GEOLOGICAL SURVEY OF CANADA

OPEN FILE 2349

Guide to aeromagnetic specifications and contracts

Aeromagnetic Standards Committee

1991

Energy, Mines and Resources Canada | Énergie, Mines et Ressources Canada

Canada

This document is being released as a G.S.C. Open File at this time in order that it may be reviewed by users of aeromagnetic survey data such as mining and oil companies, by contractors who provide the service and by government agencies. It is hoped that extensive feedback will result on both the scope and content. All comments and suggestions will be considered by the committee for a revised version to be published later.

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MEMORANDUM **NOTE DE SERVICE**

To / À: Gil Clouthier

From / De: M.F. Dufour
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Security Classification – Classification de sécurité

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Date: October 21, 1994

Subject / Objet: **Discontinuation of sample maps for Open Files**

Please note that the practice of supplying sample maps with certain Open File material has been discontinued at the GSC. In future, any client interested in map products which in the past would have accompanied a particular Open File may order them directly from the GSC Bookstore (prices may vary depending on the sheet requested).

This new measure is now valid for all GSC Open Files and therefore applies as well to D.J. Teskey's Open File 2349 entitled "Guide to Aeromagnetic Specifications and Contract Aeromagnetic Standards Committee" which in the past would have been accompanied by a sample of a GSC geophysical series aeromagnetic map.

M.F. Dufour

Canada

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PREFACE

A sub-committee on aeromagnetic mapping standards and aeromagnetic survey specifications was established at the National Geological Surveys Committee meeting May 24, 1988. The mandate of the sub-committee was to prepare a document which would serve the airborne survey industry, government and the mineral and oil industry users as a guide to survey specifications and products. An additional perceived user of the document would be foreign governments who are major clients of Canadian geophysical survey companies.

It was felt that this document should draw on as wide a base of expertise as possible. Thus the Prospectors and Developers Association, The Canadian Society of Exploration Geophysicists (CSEG) and the Canadian Exploration Geophysics Society (KEGS) were invited to nominate representatives to the committee. Dr. Norm Paterson, Mike Reford and Dave Watson were appointed to represent the respective societies. Dr. Peter Hood of the GSC, Roger Barlow, OGS and Denis Lefebvre, QMER also agreed to serve on the committee. The contribution of all committee members is gratefully acknowledged.

Because of the dynamic nature of developments in instrumentation and navigation technology, it was the opinion of the committee that this document should also be 'dynamic', that is it should be bound in such a way that updates can be provided as required to reflect advances in technology.

Operational or fiscal considerations may not permit organizations contracting for aeromagnetic surveys to adhere exactly to the optimum parameters and schedules suggested herein.

D.J. Teskey

AVANT-PROPOS

À la réunion du Comité national des commissions géologiques tenue le 24 mai 1988, les participants ont créé un sous-comité sur les normes en matière de cartographie aéromagnétique et les instructions relatives aux levés aéromagnétiques qui a reçu le mandat de rédiger un document que les utilisateurs du secteur des levés aéroportés, du gouvernement et des industries minérale et pétrolière pourraient utiliser comme guide sur les spécifications visant les levés et sur les produits obtenus des levés. Les gouvernements étrangers qui sont des grands clients de sociétés canadiennes de levés géophysiques pourraient compter parmi d'autres utilisateurs éventuels du document.

Ayant jugé qu'il faudrait faire appel au plus grand éventail possible d'experts en vue de la préparation du document, on a donc demandé à l'Association canadienne des prospecteurs, à la Canadian Society of Exploration Geophysicists (CSEG) et à la Société canadienne d'exploration géophysique (KEGS) de désigner des représentants qui siégeraient au comité. Ces sociétés ont donc choisi respectivement MM. Norm Patterson, Mike Reford et Dave Watson. M. Peter Hood de la CGC, M. Roger Barlow de la CGO et M. Denis Lefebvre du MÉRQ ont convenu de faire partie du comité. Nous tenons à remercier tous les membres de leur contribution.

Étant donné la nature dynamique des progrès réalisés quant à la technologie de l'appareillage et de la navigation, le comité a décidé de produire un document qui serait lui aussi «dynamique», c'est-à-dire qu'il serait relié de sorte d'en permettre la mise à jour, au besoin, pour refléter l'évolution de la technologie.

Pour des raisons opérationnelles ou fiscales, il ne sera peut-être pas toujours possible pour les organismes qui offrent leurs services dans le domaine des levés aéromagnétiques de respecter fidèlement les paramètres optimums et les calendriers proposés dans le document.

1. INTRODUCTION

The pursuit of geoscientific information in both hydrocarbon and mineral exploration has, in turn, expanded the use of and has continually stimulated the development of aeromagnetic instrumentation and survey methodology by resource agencies and the exploration service industries around the world. Aeromagnetic surveys were first made possible by the development of the fluxgate magnetometer which could operate within a moving platform and by military research efforts to devise methods of submarine detection from the air during world war II. This early capability of detecting hidden targets has evolved into the full scale mapping capacity we use today for the discrimination of lithological and structural trends based on the distribution and content of magnetic minerals in the upper crust. These mapping systems and techniques are particularly useful in Canada where areas of high mineral potential are often covered by glacial overburden or continental and marine sediments. In glacial terrain, it is not uncommon to have only three percent of the land surface composed of rock outcrop in prime mineral exploration territory and in oil exploration the productive formations are often capped by hundreds of metres of younger sediments. Thus aeromagnetic surveys are considered fundamental to long term geoscience mapping programs whether these are affiliated with government agencies or mining and petroleum exploration companies.

Aeromagnetic surveying practice, instrumentation and interpretation skills have been continuously improved for forty years in Canada in several ways. Firstly, by the deployment of government research initiatives which have provided both leadership and purpose to the ongoing developments. Secondly, pragmatic innovation in both contracting and consulting service companies have resulted in significant improvements in the mapping and interpretation capacity. These developments can, in turn, be indirectly linked to fundamental developments in aircraft platforms and their wide assortment of performance characteristics, to developments in the field of electronics, to developments in high speed computer processors, memory and recording devices, and finally to the development of reliable navigational positioning systems. This applied research effort in aeromagnetic technology has been spawned by the recognition of the fundamental value of aeromagnetic mapping to Canada's strategic position in world mineral markets by the mining industry together with government and university geoscience agencies.

In the 1990's, the deployment of aeromagnetic surveys is a complicated matter and entails a thorough understanding of the theoretical and practical limits of the technology and of the objectives and terrain conditions in the survey area. This report is an attempt to draw together a state-of-the-art of standards and procedure so that a current level of understanding of this geophysical method is comprehendible to those providing a service as well as to clients who provide resources.

1.1 Organization of the Report

This volume is compiled by authors with many years of experience in both the design and execution of airborne surveys and who have experienced planning surveys with a wide assortment of survey objectives. The report begins by reviewing the classical magnetic expressions as they pertain to airborne survey coverage. The types of aeromagnetic surveys based on the scale of coverage are also discussed. Chapter two covers the survey parameters and provides alternative application criteria for the reader which is fundamental to an understanding of the successful deployment of aeromagnetic surveys. Several useful examples are given at the end of the chapter and illustrate the range of survey design specifications and their role in providing the final survey objectives. The third chapter explains the importance of the field personnel in successfully executing aeromagnetic surveys. This is accomplished by reviewing the relationships, duties, and qualifications of a typical field crew. Chapter four introduces some guidelines to achieving the relevant performance requirements and traces the development and variety of instrumentation used in aeromagnetic surveys. As well, the chapter explains the role of compensation systems and data acquisition systems in both normalizing the effects of aircraft generated variations on the earths magnetic field and in recording the analog and digital data in flight, respectively. Altimeter types and uses are briefly discussed as are ground based diurnal stations. The deployment of chart recording and a suggested format for recording relevant data from both in flight and ground based magnetometers is also included. Navigation and flight path recovery techniques are documented in chapter five and, as well, an introduction is given to the combined use of navigation systems for positioning and in chapter six, calibration and compensation methods and standards are explained. Quality control and inspection topics are reviewed in chapter seven and these are fundamental to ongoing relationships between clients and contractors. Chapter eight discusses the procedures used for compiling the data onto a geographic base, the levelling of the data and diurnal subtraction, gridding and contouring and the production of colour images. The various standard products from the digital compilation are discussed in chapter nine along with suggestions for standards when contouring, profiling or producing colour images of the results. The format and content of operations reports and the enhancements derived from calculations performed on the compiled and gridded total field data are also introduced. Finally, the fundamental contractual considerations are briefly reviewed in chapter ten.

The ten chapters as set forth are intended to help introduce the complexities of modern aeromagnetic surveying to fellow earth scientists and managers who may be involved in the decision making process. The work also forms an effective review document for practising geophysicists who are involved in airborne surveying on a day to day bases. It is hoped that the document serves to promote a greater pragmatic understanding of aeromagnetic mapping and thus result in improved applications of the method.

1.2 General Magnetic Expressions

1.2.1 Magnetic Properties of Rocks

The magnetic properties of rocks give rise to changes in the scalar magnitude of the geomagnetic field as measured at or near the surface of the earth. The variation in the magnetic properties of rocks in bulk is almost entirely dependent on magnetite and its intrinsic grain size and distribution, chemistry and remanent magnetism. On a more detailed scale, concentrations of pyrrhotite in stratabound horizons may give rise to significant magnetic anomalies in base metal exploration but as a rule, these only reenforce stratigraphic trends generated by the distribution of magnetite in near surface rocks. Likewise, chromium occurrences, which occur in layered mafic intrusions, rarely influence the magnetic field as detected by aeromagnetic surveys.

The remanent or permanent magnetization effects of rocks on the induced magnetic field cannot be ignored when planning a survey. Because the remanent component will be independent of the earths current magnetic field, it may effect the simple correlation or reconciliation of the results with the geology of the area. In general, only the more mafic igneous rocks and sedimentary iron formations will display significant effects on the induced field. In addition, remanence will be more prevalent in younger rocks. Rocks of Precambrian age, which have undergone repetitive thermal overprinting through geological time, are less likely to display detectable effects of remanent magnetism which prevent simple delineation of geological trends. However, when these effects are suspected, samples suitable for palaeomagnetic determinations can be collected and used to improve interpretations.

1.2.2 Metamorphic Effects

Regional metamorphic effects on the magnetic field, which are due to folding, faulting and subsequent late intrusive activity, manifest themselves commonly in Precambrian terrains where the intrinsic magnetite chemistry and remanent magnetism has been altered from the original signature. These effects will cause problems in the interpretation stage because, depending on regional or contact metamorphic boundaries, rocks of the same petrologic classification may have wide, normal or bimodal statistical distribution patterns and yield overlapping susceptibility ranges with adjacent rocks of a different petrologic classification. Low level, high resolution surveys are desired under these circumstances because improvements in the spacial resolution of individual geological units can offset the effect of intensity differences caused by susceptibility variations. This is especially true in volcanic sequences. Alteration patterns, associated with faulting, are sometimes evident from the results and reflect the degree of fluid movement or permeability of the zone.

1.2.3 Dike Swarms

Dike swarms which angle through the area can be particularly difficult to suppress if the objective is to distinguish weaker magnetic trends at high angles to the dike-set direction. Planning the optimum line direction, spacing and flight altitude is extremely important so that trend reenforcement and shadow imaging techniques will be most effective when post processing and interpreting the results. As well, more than one dike-set direction may exist in the area and care must be taken to optimize these parameters so the survey objectives can be realized.

1.2.4 Regional Magnetic Lows

The magnetic signatures of large low-grade metavolcanic belts surrounded by granitoid domains is common to all Archean areas of the world. The metavolcanic belts in these areas commonly represent less that twenty percent of basement rock surface and yet contain more that 80 percent of the base and precious metal economic mineralization. Several authors have demonstrated a close correlation between these metavolcanic "greenstone" belts and magnetic lows within the Superior Province of the Canadian Shield. This observation can be explained by regional magnetic susceptibility depletion brought about by intense thermal and chemical alteration of magnetite during deformation when contrasted with the low temperature emplacement of surrounding regional granitoid rocks. Similar observations have been made in other Precambrian Shield areas of the world. Anomalies of this type are most likely to be observed in reconnaissance scale presentations of the earths magnetic field.

1.3 Classification of Surveys

1.3.1 Background

Large areas of the earths surface which may be composed of different structural, lithological, temporal or topographic styles should be covered using reconnaissance scale survey parameters as a first approximation to assembling the geoscience data base of an area for the purpose of encouraging resource development. Larger scales of surveying may then be gainfully instituted in order to develop more detail in relation to the mineral development objectives of mapping agencies. The reader should be aware of the important relationship between the scale of coverage desired and the line spacing/flight altitude ratio selected for the work. If the objective is to produce contoured maps of the magnetic intensity, the reader is advised to pay particular attention to chapter 2.0 when designing the scales and surveying parameters of an area.

1.3.2 Reconnaissance Surveys

In reconnaissance aeromagnetic surveying, it is most important to choose these parameters in such a way that a unified set of results over the whole of an area is realizable. This is usually an exercise in compromise and, depending on the objectives of the survey and the resources available, these sets of parameters may vary significantly from one area of the globe to another. Generally, aeromagnetic surveys having line spacings of 1.0 kilometre or better, are considered to yield reconnaissance coverage. Line spacing/flight altitude ratios for reconnaissance surveying are quite variable depending on the mapping objectives and are usually between 1.5 and 5.0.

The purposes of the reconnaissance scale survey are to map crustal features and, at the same time, highlight smaller areas of significant mineral potential or geological mapping interest for further regional-scale follow up. In addition, it is necessary to provide for a logical starting scale such that a sequence of successive approximation scales required for mapping and exploration objectives can be implemented at a later time. Presentation scales for reconnaissance survey results often are 1:100 000 and above. Small scale colour images of the result can be effectively portrayed at 1:250 000 and above. These are effective for pattern recognition purposes when selecting areas for regional surveying.

1.3.3 Regional Surveys

Upon inspection of the existing available geological mapping and/or aeromagnetic coverage in an area, a decision can be made to improve the magnetic resolution by reflying smaller sections of the above existing coverage with closer line spacing and at lower altitude. This procedure has the effect of magnifying the information to a scale more suitable for regional mineral potential evaluation or for geological interpretation. Regional surveys must be systematic but must also deal with variable strike directions, topographic variations, more stringent positioning requirements and flight line tolerances if full value from the survey is to be received. Generally, regional aeromagnetic surveys have line spacings of 2.0 to 5.0 hundred metres or better and a line spacing/flight altitude ratio of between 1.5 and 5.0 is acceptable because the along-line resolution is usually improved and the area trends are more distinctive.

This scale is usually the final coverage for systematic surveys and therefore an attempt must be made to resolve all important magnetically responsive geological features in the area. In areas of thin, steeply dipping geological units, a vertical gradiometer with a small offset between sensors can cost/effectively be deployed to provide a greater degree of definition of the geological units. Presentation scales for regional survey results are usually 1:20 000 to 1:50 000 and above. Colour images are effective at scales of 1:100 000 and above for highlighting structural trends, regional alteration patterns and areas where detailed survey coverage is required.

1.3.4 Detailed Surveys

Detailed aeromagnetic surveys are almost entirely stimulated by an exploration motive. Rarely but occasionally a geological objective is sought from the results at this scale (i.e. zoning in an intrusive or increased structural detail in volcanic stratigraphy). Detailed surveys usually consist of between one and four thousand line kilometres flown with line spacings of fifty metres or better and flight altitude/line spacing ratios closer to 1.0 than for regional or reconnaissance coverage.

The final objective in detailed aeromagnetic surveys is to map the feature or area from the air with enough resolving power so a minimum amount of effort is put forth on ground follow up. Helicopter survey platforms are almost exclusively used to carry out these tasks because of the logistics of obtaining the desired slow speed and accurate positioning of the results. Presentation scales for detailed survey results are usually 1:5 000 and above.

Colour images are usually presented at scales of 1:20 000 and above.

2. SURVEY PARAMETERS

2.1 Design Considerations

The objective of the survey must be considered first. This can generally be categorized into Reconnaissance, Regional, and Detailed, according to the definitions discussed in Chapter 1 above.

(1) Reconnaissance

If the objective is to outline the broad tectonic framework of an area at minimum cost, a set of very widely spaced profiles (e.g. 25 km) can be used or, alternatively, swaths of several profiles spaced roughly 4 times the flying height apart. For mapping the regional geology of intracratonic basin areas such as the Karroo basins of Africa and the Athabasca basin of the Northwest Territories, where the surficial geology is of little importance, useful surveys can be flown at line spacings as great as 4-6 km. Such surveys are sometimes carried out to determine the rough geophysical and structural parameters of an area before designing an optimum regional survey.

(2) Regional

As explained in chapter 1, the objective of most regional surveys is systematic geological mapping, often with mineral or petroleum exploration as its ultimate goal. The resolution required depends upon the nature of the geology and the type of target of interest. For example, a 1 km-spaced survey would be adequate for most geological mapping purposes but would fail to adequately explore for such targets as kimberlites and magnetite-rich skarn deposits. If combined radiometrics or electromagnetics are required, compromises need to be made, particularly in terms of survey altitude.

(3) Detailed Surveys

Since the objective of detailed surveys is usually a quantitative, as well as qualitative interpretation, care must be taken not only to provide adequate resolution, but to achieve a high fidelity of recorded data. Corresponding constraints are imposed on not only line spacing and altitude but other parameters including data sampling rate, diurnal tolerance and manoeuvre noise.

Other factors constraining the design considerations are: expected depth to magnetic sources; expected magnetic relief and texture; topographic relief; inclination (and declination) of the magnetic field; distance to flying base; size of area to be surveyed; nature of land forms and vegetation (visual positioning possibilities); need for electronic (non-visual) navigation and positioning means; and last but not least weather conditions.

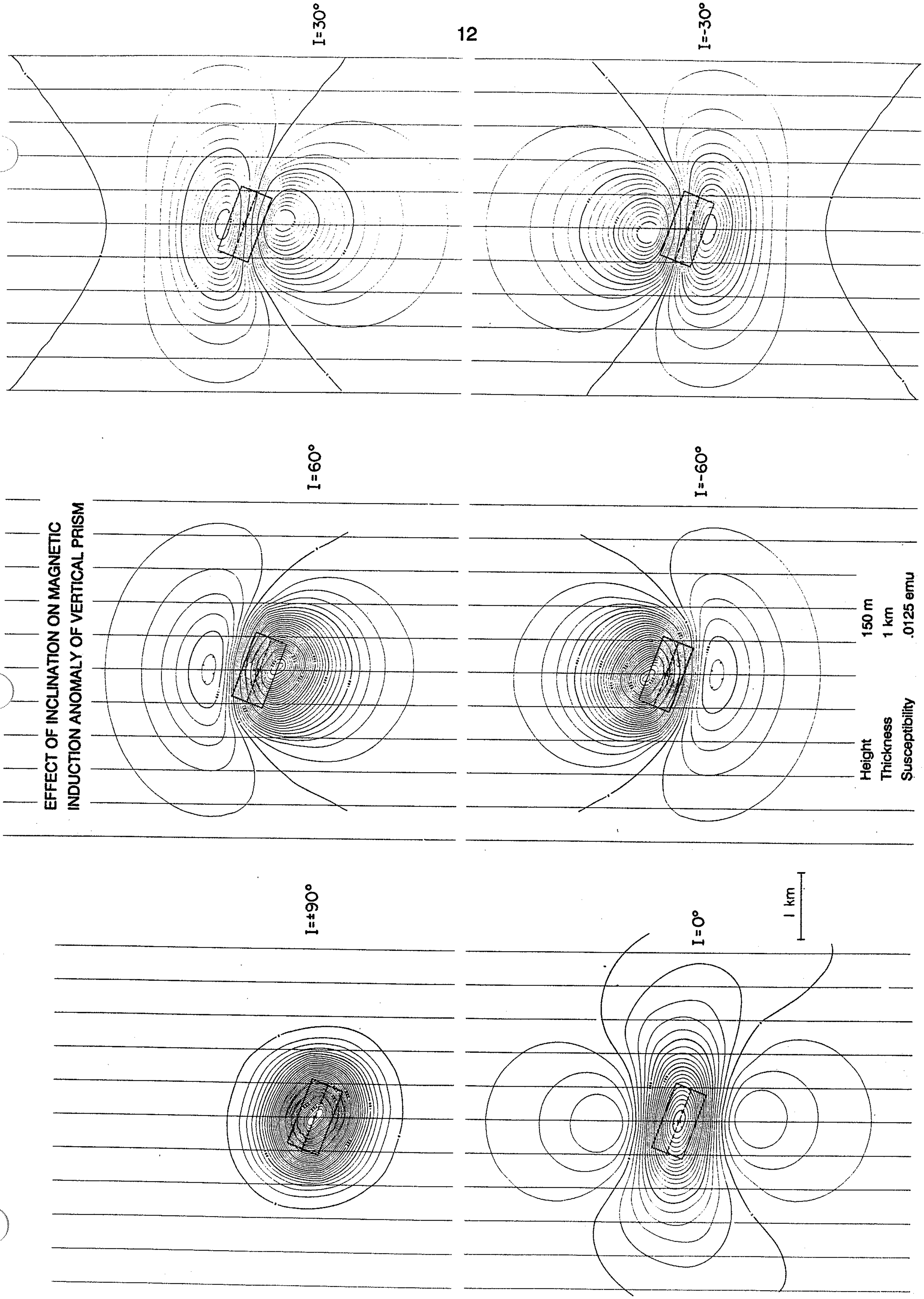


Figure 1. Effect of inclination on magnetic induction of vertical prism.

Examples of survey parameters on typical aeromagnetic surveys are given in 2.10 below.

2.2 Line Orientation

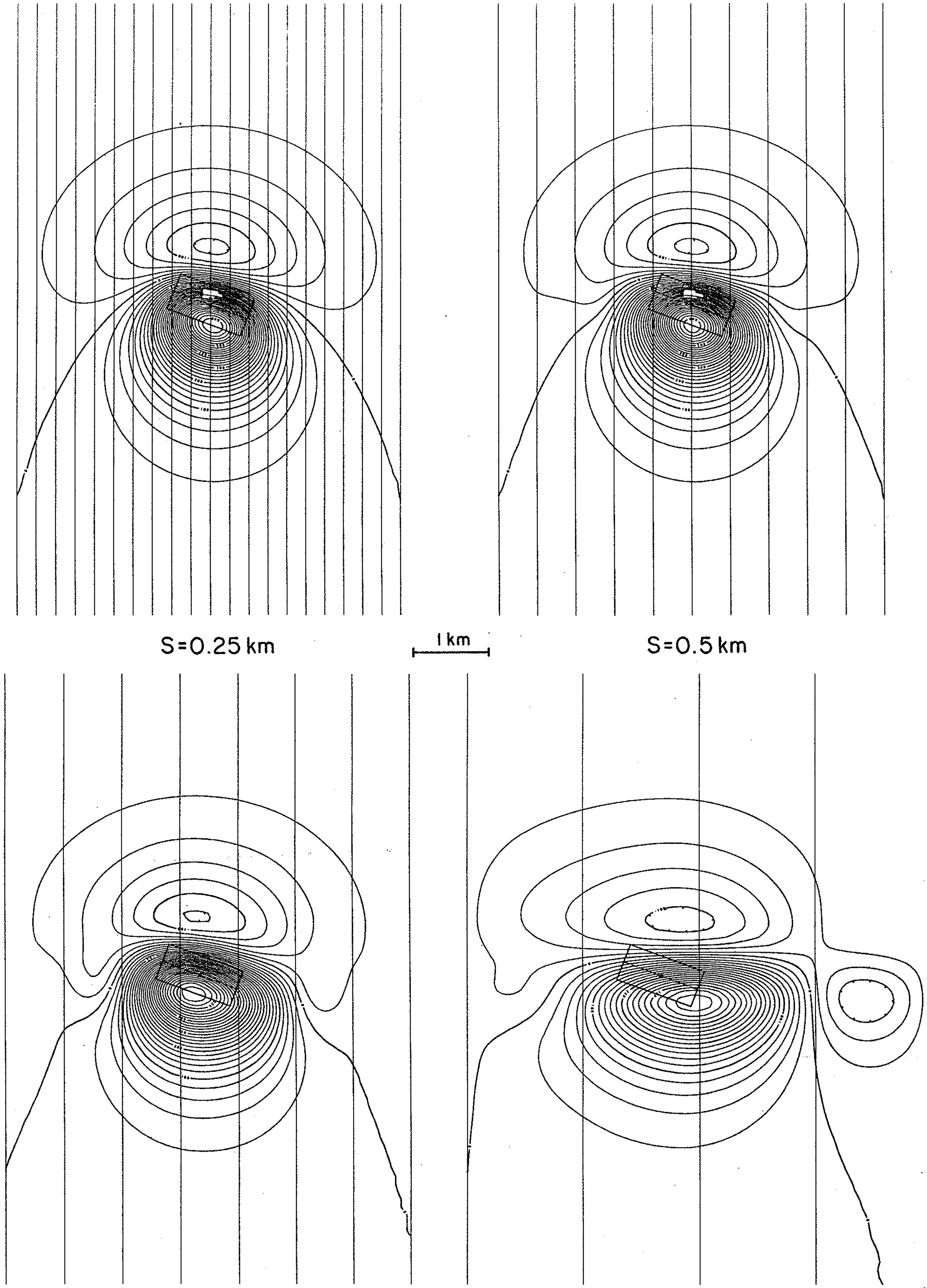
Survey line orientation is dictated by two principal factors: average strike direction of the magnetic lineation; and magnetic inclination. Optimally, lines should be flown as close as possible to perpendicular to the main magnetic lineation. Usually this is the principal stratigraphic trend in bedded geological formations, but, in some areas, it may be governed by subsequent metamorphism and/or intrusion. Very often there are two or more directions of strong magnetic lineation, and a choice has to be made as to which is the more important. Sometimes it is possible to make a compromise so that the line direction is not less than 45 to two or more magnetic strike directions.

Except at inclinations greater than about 75 degrees, more information can be gained about an anomaly with a north-south profile than with one flown in an east-west direction centrally over the body (Figure 1). Only if the survey lines are very closely spaced with respect to the body size (which is seldom the case) can this fact be ignored. As the magnetic inclination decreases this problem becomes more serious as anomalies tend to be stretched out east-west. Near the magnetic equator, surveys flown on east-west lines may detect the central low over a body, without observing the adjacent highs. A survey flown roughly north-south will obtain some expression of the entire anomaly. Contour maps prepared on the basis of east-west surveys at low magnetic latitudes can produce quite meaningless anomaly forms. For country-wide surveys conducted mainly for mapping purposes a north-south direction is often a reasonable compromise and renders the map compilation and digital archiving more straightforward.

For exploration surveys priority should be given first to the proper rendition of the magnetic fields, and secondly to the direction of geologic strike. If the geologic lineation is roughly north-south but the magnetic inclination is less than about 25 degrees it is best to keep the line direction reasonably close to north-south. Catalogues of contours over representative bodies at various magnetic latitudes are useful in guiding these considerations.

Much controversy surrounds the question of the value of surveying lines in two directions in cases where magnetic lineation is complex and/or magnetic targets may be small or of random orientation. This problem involves considerations of target size and shape, topographic relief, and survey elevation. Based on both theoretical and practical considerations, it has been found that decreasing the survey line interval and maintaining a single direction is usually preferable to flying additional lines in a perpendicular direction. The search pattern thus achieved (as well as the resolution to roughly equi-dimensional bodies) is better, and the problem of integrating the data on the perpendicular lines with the main dataset is avoided. The latter problem becomes particularly acute in areas of steep topography.

EFFECT OF LINE SPACING ON
INDUCTION ANOMALY OF VERTICAL PRISM



Height	150 m
Thickness	1 km
Susceptibility	.0125 emu
Inclination	I = 60°

Figure 2. Effect of line spacing on induction anomaly of vertical prism.

2.3 Line Spacing

Good discussions of optimum line spacing are given in the literature, but the conclusion can be summed up simply: to achieve good resolution for most magnetic body shapes and field inclinations, a spacing/height ratio of not more than 1.0 is necessary (Figure 2). For economic reasons, plus the fact that geological formations tend to be much longer in one direction than the other, this target is seldom necessary or justified. Whereas a ratio of not more than 2.0 is recommended, line spacings of four times the flying height are quite common on regional magnetic surveys, and achieve most of the required objectives. For the national aeromagnetic survey of Canada the ratio has been mostly 2.6.

Since resolution involves both flight altitude and line spacing, it is tempting to increase altitude so that lines can be flown further apart. This is only done at some sacrifice to the fidelity of information along the flight path. No matter what measurement sensitivity prevails, a greater flight altitude inevitably loses some of the shorter wavelength information that could be obtained at a lower altitude. This is particularly important on detailed surveys.

A useful guide to the correct line spacing for a given survey objective is the scale required for the final map presentation. For example, on a survey of a whole country, where the data are to be used to assist in geological mapping at, say, 1:125,000, then the important primary end product of the aeromagnetic survey will be contour and/or colour maps at the same scale. If we make the assumption that survey lines should be spaced about 1-2 cm apart on the map so as to not be too crowded nor to waste unnecessary space, then we inevitably arrive at an optimum line spacing of 1.25-2.5 km. The same argument dictates a 0.5-1 km spacing for mapping at a scale of 1:50,000 and a spacing of 5-10 km for mapping at the 1:500,000 scale. It must be remembered in the latter case, however, that to avoid aliasing of the shorter wavelength anomalies at this wide line spacing a flying height of the order of 1 km will be required. This may not be compatible with ancillary objectives of the survey which might include the resolution of shallow dykes or geological contacts of long strike dimensions. In such cases, compromises can sometimes be made by flying the survey at a lower altitude (say 500 m), presenting the data in the form of profile maps rather than contours, and performing some form of low-pass filtering in order to prepare a 1:500,000 scale contour map. It should be noted, however, that such solutions inevitably result in a degradation of the utility of the data.

On surveys over sedimentary basins, where magnetic basement is deep and the effective flight altitude is quite large, line spacing can be correspondingly increased. However, this is done to the detriment of any subsequent high-frequency enhancement, including downward continuation of the data or detection of intrasedimentary anomalies.

2.4 Flight Altitude

Survey altitude is dictated partly by considerations of line spacing (see above), but more seriously by the geological target, i.e. the objective of the survey. If near-surface and short-wavelength magnetic sources are of interest, then the survey altitude must be correspondingly small. One rule of thumb is that the altitude should not be greater than the distance between magnetic bodies to be resolved. By "resolved" we mean that the edges of the body must be defined, not just the presence of the body. This sometimes puts serious constraints on the flying height and has a domino effect on the line spacing and the survey cost. Recourse is usually made to surveying at a greater survey altitude and an appropriate altitude/line spacing ratio. The attenuation and anomaly smearing that result can be partially rectified by the use of high-pass data enhancement such as vertical derivative or downward continuation filtering.

A second consideration in the choice of flight altitude is the topography. In steep topography it is seldom possible to fly at a constant height above ground, nor is this desirable in some cases (see 2.5 below). A loose drape or a survey flown at constant barometric altitude may produce more coherent results and better data integrity.

On surveys over sedimentary basins, usually carried out for hydrocarbon exploration, it is not the height above ground that is important but height above magnetic "basement". In such cases the effective flight altitude may be quite large even if the survey is flown close to ground level. Such surveys are commonly flown at a constant barometric altitude, established as the lowest height above sea-level that will allow the aircraft to safely clear the highest peak in the area. In some sedimentary basins there is more than one magnetic horizon; for example, there may be young volcanic layers, or even dikes and sills quite close to surface. There may also be interest in locating weak anomalies of intra-sedimentary origin. In such circumstances it is the uppermost horizon of importance that dictates the survey altitude.

Finally, consideration has to be given to the method of navigation. Visual methods based on recognition of widely spaced landmarks (e.g. desert or snow cover) dictate a higher flight altitude. Electronic navigation methods involving ground-based transponders likewise may require higher altitudes in order to maintain line of sight. As discussed in Chapter 5, this will be less of a problem with the increasing availability of satellite navigation.

2.5 Altitude Mode

Except in the case of extreme topographic relief, the optimum survey mode is usually a constant height above ground. This mode provides even resolution and a roughly constant datum for carrying out quantitative anomaly analyses. Upward and downward continuations can be made conveniently to surfaces parallel to the one containing the magnetic sources. This is not the case on hydrocarbon surveys over sedimentary basins where the magnetic basement is at a variable (and usually unknown) depth below the ground surface. In such cases the survey can be flown equally well, and usually more conveniently, at a constant barometric height.

In steep topography, however, a constant height above ground is not only difficult or impossible to achieve, but it may lead to strong terrain effects from the adjacent hills. Even helicopters are unable to achieve a perfect drape, and, attempting to do so, requires changes in ground speed that complicate the problem of path recovery and interpolation of data between recovery points. This problem is becoming less serious (see Chapter 5) with the advent of satellite navigation systems which record accurately the position of the aircraft and its vertical location.

In practice, surveys on very hilly terrain are flown either at a constant barometric altitude (sometimes in discrete and overlapping blocks in various parts of the area), or by conducting a deliberately smooth drape in order to obtain a relatively uniform horizontal speed and a roughly even height above ground on adjacent flight lines. The former mode results in the most economical and accurate survey but suffers from the poorest resolution over the low ground in each survey block. The second mode suffers from problems from uneven height above ground, with consequent herringbone or line-coherent noise as a result of changes in flying height between adjacent lines.

Computer methods have been devised for reducing data flown at a constant barometric height to a perfect pseudo-drape, but, to do this, the survey must be flown at a line spacing commensurate with the final pseudo height above ground. Similar computer methods can be used to convert a loose drape to a perfect pseudo-drape by variable upward or downward continuation of each survey profile before gridding and contouring the data. These methods result in improved resolution and good data coherence, but at some sacrifice of accuracy as a result of the continuation processing.

Until these methods have been fully developed, the choice of constant barometric or drape surveying should be based mainly on the objective, namely the type of magnetic target of particular interest.

2.6 Tie Line Spacing

The primary purpose of tie-lines is to correct for diurnal variations. Tie-lines may act as supplementary flight lines but this purpose should not confuse or conflict with the objective of achieving a survey free from diurnal variations.

In the early days of aeromagnetic surveying, tie-lines were also required to correct for instrument drift; however, since the advent of nuclear precession and optical pumping magnetometers, the effect of drift is usually negligible compared with geomagnetic variation or diurnal.

In low and middle latitudes, away from the auroral zone, diurnal subtraction (using one or more recording base stations) can often be carried out and results in an almost diurnal-free record. Induction effects can, however, result in phase and amplitude changes in the geomagnetic field over survey distances. These effects are more pronounced in northern latitudes such as Canada. The technique should be used with caution and should involve careful examination of the survey records and those from, preferably, two diurnal stations to ensure that the subtraction will actually improve the record and not introduce false anomalies.

Experience has shown that, in general, a tie-line/flight line spacing ratio of about 3.0 is optimum, though ratios as high as 10 or even 20 are quite common.

Corrections made on the basis of tie-line/flight-line intersections will be subject to error if the tie-line and flight line have differing altitudes at intersections, and are also subject to error due to uncertainty of positioning in steep gradients. These problems can be partially alleviated by having the tie-lines flown in conditions of quiet diurnal and across areas of low magnetic relief, as determined by previous regional surveys or from flight lines. Methods are being tested which correct the measured field on tie-lines to the actual altitudes on the flight lines at intersections.

2.7 Diurnal Specifications

The geomagnetic variation has both long and short wavelength components. The former can be to some extent removed by base station magnetometer subtraction or tie line network adjustment (see 2.6 above and Chapter 9), the latter may produce spurious anomalies that cannot in practice be removed regardless of how tight a network of tie-lines is prescribed.

Long period variations are loosely referred to as diurnals though this term commonly includes hourly and, possibly, weekly variations. The magnitude of these variations varies from a few nT in the equatorial latitudes to several hundreds in the auroral zones. Traditionally, such variations have been removed from the survey dataset by the use of tie-lines, and a levelling process referred to as network adjustment (see 2.6 above). Given some prior knowledge of the magnitude and period of such variations, a tie-line network can be designed such that the residual errors are within the required accuracy of the survey. If these procedures are followed, it is necessary to specify a curvature, usually in the form of a departure from a linear chord, commensurate with the spacing of the tie-lines. For example, if a final accuracy of 2.5 nT is required, and tie-lines are spaced 10 km apart, then a curvature specification might read: "Diurnal will not exceed 2.5 nT when measured from any linear chord of 2.4 minutes (assuming an aircraft ground speed of 250 km/hr)". Diurnal gradient, if linear, should be removable by the levelling process. However, a strong gradient occurring at tie-line/flightline crossings can increase the possibility of errors in the network adjustments. For this reason it is common to specify a maximum allowable gradient. The allowable diurnal gradient will depend upon the navigation method and the local magnetic relief but the criterion is usually based on common sense. Too tight a specification will result in an inefficient survey and/or difficulties with the contractor. The diurnal gradient is seldom the deciding factor in the acceptance or rejection of a tie-line/flight line network adjustment; horizontal magnetic gradients and/or height changes are more commonly the deciding factor.

When using recording base-station magnetometers to correct the airborne survey measurements for diurnal variations close time-synchronization is required and must be specified. Both analogue and digital recording is recommended, preferably with the same recorder that is employed in the aircraft. If an array of ground magnetometers is used, criteria must be established for the allowable differences between magnetic stations, above which interpolation procedures must be used to derive x, y, t corrections to be applied to the survey lines.

Short period geomagnetic variations pose a difficult problem. In the higher magnetic latitudes variations with periods from a few seconds to several minutes are quite common and can vary in amplitude up to several tens of nT. Such variations are commonly referred to as micropulsations. Bursts of such pulsations are also common and are termed magnetic storms. These are often accompanied by steep geomagnetic gradients. Such variations cannot be removed in practice by any reasonable network of tie-lines, nor can they be reliably corrected for by the subtraction of base-station magnetic readings. Magnetic storms are usually of local origin and there is a significant spatial as well as time variation in the magnetic field. The diurnal specification that is appropriate in such circumstances must, again, take into consideration the objective of the survey. If the anomalies of interest are broad, short-period magnetic variations can be filtered out without serious detriment to the final data accuracy. If, on the other hand, near-surface geology is the objective, short period variations cannot be tolerated if they are comparable in amplitude to the target anomaly.

There are no simple rules for establishing limits for tolerance to magnetic storm activity but data obtained in such periods will be rejected by using the chord criteria. The USGS has attempted to establish limits with the "K-index" which is a measure of geomagnetic activity of all wavelengths, averaged over eight 3 hour periods each day. Tolerances based on K-index activity, however, fail to take into account the survey objective or the tie-line interval. They are also inefficient as they preclude surveying during quiet periods of the day.

Short-period magnetic pulsations of amplitude greater than the allowed departure from a linear chord are automatically outside tolerance, given the normal diurnal specification for surveys with tie line levelling control. On surveys where tie-lines are not used for levelling it is common to establish a specification such as: "Lines or parts of lines wherein the corresponding diurnal record shows departures from a linear chord greater than 2 nT over a period less than 2 minutes will be reflown".

2.8 Sampling Rates

The sampling rate specified for the magnetometer is dictated by the desired resolution of the target anomaly and the flying speed of the aircraft. Knowing the objective of the survey it is usually possible to establish the maximum allowable sampling distance necessary to achieve proper resolution. For surveys flown in areas of crystalline rocks the necessary resolution is about 0.25 of the flying height, or 75 m in the case of surveys flown at 330 m elevation. At an aircraft speed of 4 km per minute, the equivalent sampling rate works out to 1 second. The bulk of aeromagnetic surveys flown world wide over the past 20 years has been carried out at this sampling rate.

With the advent of optical pumping magnetometers wherein sampling rates of two or more per second are standard, a better resolution is easily achieveable. New methods of dataprocessing and enhancement can take advantage of the 25 metre or better resolution thus obtained, and lower elevations can be accommodated.

Since the sampling rate with most magnetometers is a trade-off with sensitivity, care must be exercised not to specify too close a sampling interval at the expense of the required sensitivity. With the increasing use of optical pumping magnetometers this is seldom the case.

Where multiple geophysical systems are operated simultaneously in the aircraft a problem of interference may arise requiring the systems to be sampled successively rather than together. This is solved by time-sharing at the data acquisition interface, sometimes with a resulting loss of data density.

2.9 Tolerances

Tolerance is the term applied to the allowable error in any of the above parameters, beyond which the survey fails to meet required specifications and should be reflown. Normally, line spacing and flight altitude are the only two parameters for which rigid tolerances are given, with the exception of the diurnal tolerance which has already been discussed.

Line spacing tolerance is usually stated as a function of distance along the flight line and as a percentage of the nominal line spacing. For example, a common tolerance might be: "Line spacing shall not exceed 1.5 times and not be less than 0.25 the nominal spacing for distances greater than 2.5 km along the flight path". Both the spacing error and the distance along the flight path are governed by the desired survey resolution which, in turn, is dependent upon the survey objective. To prevent short gaps of still greater width, it is usual to also specify a maximum line spacing that will be tolerated at any point, for example: "The line spacing shall not exceed 1.75 times the nominal spacing at any point along the flight path".

Flight altitude tolerance is relatively simple to specify in the case of constant barometric surveying, since it is decided mainly by aircraft flight characteristics and instrumentation rather than by geophysical objective. Since the pilot is maintaining altitude on the basis of a barometric altimeter readout (or by autopilot), the altitude tolerance is normally set at the practical limits within which altitude can be maintained under normal survey conditions. A tolerance of $\pm$20 m is normally achievable and will seldom affect the quality of the geophysical data. A larger tolerance would normally imply conditions of severe turbulence under which survey could not, for other reasons, proceed. Occasional departures from this specification may be tolerated in the interests of survey production and economy.

In the case of drape-flown surveys, altitude tolerance is much more difficult to specify since, in the final analysis, the pilot must decide what is feasible and what is prudent in any given topographic situation. The specification normally reads something like: "Flying height above ground will be maintained at 150 m ±20 m where feasible, depending upon the pilot's judgement with respect to safety considerations".

Failure to adhere to the specified tolerances normally requires a flight line or part of a flight line to be reflown and the earlier line to be deleted from the final dataset. If tie lines are specified, all reflights are required to intersect a minimum of two tie lines so that they can be levelled to the surrounding data. In the case of surveys where tie lines are not used for levelling, the reflight should be of sufficient length that any error in base level will be readily apparent in a verification contour plot or by shadowing on a workstation. Final level adjustments are normally made by trial and error.

2.10 Examples of Survey Parameters on Typical Aeromagnetic Surveys

2.10.1 Reconnaissance

Area and date: Eastern Hudson Bay, 1977.

Sensor(s): Magnetometer.

Purpose: Solve major basement structure for assessment of hydrocarbon potential.

Line pattern: Five blocks of seven lines each, spaced 1 or 2 mi. apart, average block length 130 mi., oriented roughly perpendicular to shoreline and basement lineation.

Total mileage: 3180 mi.

Flight altitude: 1250 ft. above sea-level.

Navigation system: Doppler and VLF (GPS would be used now).

Presentation: Contour maps and profile maps of each block, at scale 1:100,000.

2.10.2 Regional

(a) Area and date: Thailand, 1984-85.

Sensor(s): Cesium vapour magnetometer.

F.O.M.: 4 nT.

Sensitivity: 0.01 nT.

Data sampling: 0.25 sec.

Purpose: Geological mapping and regional mineral exploration.

Line pattern: Fifteen blocks, line direction N-S, spacing 1 km.

Tie-line spacing: 14 km.

Total kilometers: 439, 538 line km.

Flight altitude: Thirteen blocks at constant barometric altitudes varying from 1500 ft. to 7500 ft. above sea-level, as dictated by topography. Two blocks at 1000 ft. mean terrain clearance.

Navigation system: Doppler-assisted visual navigation; 35 mm frame camera path recovery.

Presentation: Contour maps at scales 1:50,000 and 1:250,000; colour maps at 1:1,000,000; and digital archives.

(b) Area and date: Northern Yukon Territory, 1988-89.

Sensor(s): Magnetometer.

Purpose: Geological mapping and regional hydrocarbon/mineral exploration.

Survey pattern: Three areas (two contiguous). Area 1- N-S lines 2 km apart, 9000 ft. above sea-level.

Area 2- E-W lines 3 km apart, 7000 ft. above sea-level.

Area 3- N-S lines 2 km apart, 1000 ft. mean terrain clearance.

Tie-line spacing: 8 km.

Total kilometers: 57,000 km

Flight altitude: Given.

Navigation system: GPS (Ground Positioning Satellite), 35 mm frame camera and Doppler.

Presentation: Contour maps at 1:250,000 and 1:1,000,000; and digital archives.

2.10.3 Detailed

(a) Area and date: Lesotho, 1975.

Sensor(s): Magnetometer and gamma-ray spectrometer.

Purpose: Exploration for kimberlites and coal.

Survey pattern: Lines flown N-S, 275 m apart.

Tie-Line spacing: 15 km

Total kilometers: 20,500 line km.

Flight altitude: 150 m mean terrain clearance.

Navigation system: Doppler-assisted visual navigation; 35 mm frame camera path recovery.

Presentation: Contour maps of total magnetic field and profile maps of radiometric total count at 1:25,000 and 1:50,000; stacked profiles of 4 radiometric channels; and digital archives.

(b) Area and date: Whitehills, N.W.T., 1988.

Sensor(s): Magnetic gradiometer and VLF EM.

Purpose: Geological mapping and mineral exploration.

Survey pattern: Lines flown NW-SE, 300 m apart.

Tie-line spacing: 5 km

Total kilometers: 6,855 km

Flight altitude: 150 m mean terrain clearance.

Navigation system: Film, Doppler, GPS

Presentation: Colour/contour maps of total magnetic field and vertical magnetic gradient at 1:20,000; profile maps of two VLF EM components at 1:20,000; and digital archives.

3. QUALIFICATIONS, EXPERIENCE AND DUTIES OF PERSONNEL

Demonstrated experience by the airborne geophysical contracting company as a whole, in addition to individual personnel, is important in evaluating the capabilities of the company. Chapter 10, will deal with the evaluation of the company as a whole, but it should be emphasized here that the individuals need the support and backup of the company in order to have a smoothly running operational team. The following is offered as a guide to evaluating personnel and will explain in general terms the duties of each member of the team. Some duties may be shared and different contracting companies may delegate responsibilities differently however all aspects must be covered. Overall responsibility for the successful completion of the project must rest with the project manager. The daily field operation with some companies may be handled by the captain of the aircraft, however for large projects it is recommended that a field operations manager be appointed.

3.1 Project Manager

The project manager will be responsible and have authority for all aspects of the survey, including initial planning and proposal, instrumentation, flying, compilation and reporting. The project manager will be responsible for signing off all reports and products delivered, and certifying that work was carried out in accordance with the specifications of the contract. He/she must be a geophysicist, with a degree from a recognized university, and have a minimum of five years experience in aeromagnetic surveying and should have worked as a field operations manager at some stage in his/her career.

3.2 Field Operations Manager

The field manager will be responsible for daily operational procedures, keeping abreast of and maintaining a log of the survey production and ensuring data quality and navigation. He is responsible for ensuring that all products are properly catalogued and transmitted or shipped to the office. He/she will inform the aircrew of any fill-in lines required so that complete flight coverage is maintained. The field operation manager should have full field responsibility, however, the pilot in command will obviously make the flying decisions i.e. weather conditions, etc. The field operations manager will have 5 years experience in data compilation and/or data acquisition of aeromagnetic data. He/she should have received formal training in geophysics, however further experience in lieu of education would be acceptable. Either the field operations manager or the project manager will be on site for the duration of the contract.

3.3 Pilots/Navigators

On aircraft that require both a pilot and copilot, the pilots must have a valid commercial pilot licence for the aircraft being flown. The pilot in command should have a minimum of 1500 hours total time with a minimum of 1000 hours of low level geophysical surveying, and be experienced with visual and electronic navigation techniques. The copilot must have a minimum of 500 hours of low level airborne geophysical flying.

Even when only one pilot is required to safely operate the aircraft it is recommended that at least one other person be on the aircraft to assist with positioning and ensuring quality control, thus reducing reflights.

In most cases insurance companies require more experience than that asked for here, so the safety requirements are satisfied. However from the geophysical survey standpoint it is important that the pilots stay within the altitude and line deviation limitations as specified in the contract, and therefore low level geophysical surveying experience is important.

The pilot in command must make decisions of a flying nature and he/she should not be overruled by the field operations manager in that respect. Some airborne geophysical survey companies give the pilot-in-command the duties of the field operations manager. However, for large projects this is not recommended procedure, because he/she is usually not aware of all the geophysical survey requirements.

3.4 Maintenance Engineer

The inclusion of an aircraft maintenance engineer is especially important when the survey will take many weeks or months to complete. The engineer can therefore perform inspections on an ongoing basis and perform preventative maintenance. He/she should have a valid aircraft maintenance licence endorsed on the aircraft being used. This person's duties are regulated by the airborne company's flight operations manual which has been certified by the Ministry of Transport. Even though this person may not be required in a legal sense it is recommended that one be on site particularly in remote areas.

3.5 Instrument Operator

This person should be a graduate electronic technician with a diploma from a recognized technical school. He/she must have at least three years experience with the airborne geophysical and ancillary equipment specified in the contract. The instrument operator will be on board the aircraft monitoring the geophysical instruments and recording devices. He/she must be familiar with the contract specifications that pertain to noise levels, recording specifications, etc. This person should also be able to trouble shoot the instrumentation and make minor repairs where necessary.

3.6 Field Data Technician and Quality Controller

This person is usually an assistant to the field operations manager and carries out routines necessary to ensure that flight path is complete and accurate including the visual flight path recovery where necessary and will look after things such as the diurnal monitoring, copying tapes etc. This individual will normally carry out all quality control work under supervision of the field operations manager and in some cases will carry out initial editing and compilation of the data on the field system. He/she should have an interest in airborne magnetics, and have had experience in at least two airborne survey projects and experience in operating the type of quality control equipment to be utilized in the survey.

Note: For the smooth running of an airborne geophysical survey it is necessary that all members of the crew work together for the common purpose of successful completion of the survey in addition to the economic benefit of the survey company, therefore each member should respect and be aware of the others duties and help out wherever necessary. Duties therefore should be flexible enough to allow for this interaction.

4. INSTRUMENTATION

Aircraft Characteristics

Aeromagnetic surveying activity commenced shortly after the end of World War II and the aircraft utilized were mostly the military transport and reconnaissance aircraft of that period, particularly the Douglas DC-3 aircraft. These aircraft were utilized for more than a decade with the magnetometer being trailed in a towed bird so that the magnetic effects of the ferrous portions of the aircraft, such as the engines, were minimized. In Canada, trailing a towed bird in icy conditions often led to dangerous flying conditions and the consequent loss of the magnetometer. This situation resulted in inboard installations being utilized in which the magnetometer was installed in a boom which extended from the tail of the aircraft to remove the magnetometer as far from the magnetic field-producing components of the aircraft as possible. It was found that these magnetic effects would produce a noticeable signal hash on the chart record that was more pronounced with aircraft manoeuvres. It was realized that these magnetic effects could be minimized by suitable compensation techniques. As skill in these compensation techniques improved, it became feasible starting about 1960 to use smaller twin-engined aircraft such as the Aero Commander which resulted in acceptable quality data being produced at lower line mileage costs. Other twin-engined aircraft that have been utilized have included the Piper Aztec and Navaho, the Britten-Norman Islander and Beechcraft Queenair aircraft. In recent years, the Cessna Titan 404 with its longer range has been much utilized by aeromagnetic survey contractors throughout the world. Small single-engined aircraft have been used for small detailed surveys in suitable areas with a minimum crew.

The desirable characteristics of fixed-wing aeromagnetic survey aircraft for regional surveys are as follows:-

(1) It should be a well-designed reliable aircraft from a well-established manufacturer with a good reputation, structurally strong with no record of metal fatigue problems.

(2) For safety reasons, the aircraft should be twin-engined with a good single engine capability with full fuel load. It should have a high power-to-weight ratio with rapid throttle response for mean terrain clearance flying.

(3) The aircraft should have an endurance in excess of 7 hours to permit a cost-effective survey operation and be able to cruise in excess of 120 knots. With the use of optical absorption magnetometers having a much higher sampling rate, aeromagnetic surveys could easily be flown at 200 knots and even faster.

(4) The aircraft should preferably be able to carry a pilot, copilot/navigator, instrument operator and have an extra seat for the client representative (inspector) or security officer as well as the geophysical instrumentation and a survival kit. This is a volumetric requirement found usually in an eight-passenger aircraft.

(5) The aircraft should be easy for the pilot to navigate along predetermined flight lines with good forward and downward visibility and be suitable for operation from gravel strips.

(6) The aircraft should be easily maintainable, refuelled and serviced in the field with adequate electrical power generation for the geophysical and navigation instrumentation.

(7) The aircraft should be economic to fly. Up to the present time contractors have utilized piston-engined aircraft that require 100/130 gasoline because turbo-prop aircraft are not so fuel efficient at low altitudes. Another consideration is that their capital cost is much higher and good second-hand piston-engined aircraft are relatively cheap to buy. However 100/130 aviation gasoline is becoming scarcer and more difficult to obtain so the situation may change in future years.

Helicopters are normally only utilized in aeromagnetic gradiometer surveys of mountainous terrain using towed-bird systems because the costs of such surveys are generally much higher. Nowadays the helicopters utilized are turbine powered for increased lift and examples in common use are the Aerospatiale A Star 350D and the Bell 412. Their range is significantly lower than fixed-wing aircraft although they can be refuelled in the field.

4.2 Airborne Magnetometers

4.2.1 Definitions

In describing the specifications required for aeromagnetic survey instrumentation, various terms are utilized that while in common usage are often loosely employed by geophysicists. It is therefore appropriate to begin this narrative by a discussion of those terms in order to arrive at a definition.

4.2.1.2 Sensitivity or Resolution

These terms are often used interchangeably for magnetic survey instrumentation. With present digitally-recording instrumentation, the sensitivity refers to the least incremental change in the magnetic field parameter (at the detector) that can be recorded i.e. resolved and so it is instrument sensitivity or resolution that is really meant. This however takes no account of the background noise imposed on the magnetic signal that is always present under operational survey conditions. The amplitude of the background noise level in actual survey conditions which appears as a swath of noise will depend on the various factors pertaining to the quality of instrument installation and flying conditions. Under normal turbulence conditions, the noise swath is directly dependent on how well the survey aircraft is compensated for its own magnetic properties. Thus the instrument sensitivity will differ from the effective recording sensitivity due to background noise. The effects of such noise can be minimized by judicious post-flight filtering which is most effective when the wavelength content of the signal is much longer than the much shorter wavelength of the background noise which is controlled by the sampling interval.

4.2.1.3 Accuracy or Precision

These terms are often mistakenly used instead of sensitivity or resolution. The accuracy of a measurement is the total error, often expressed as a percentage, of the recorded value from the true value of the quantity measured. It is usually ascertained in practice by obtaining the mean deviation of a set of measurements from the average value. Precision is a term that relates to the reproducibility of a measurement. It should be appreciated that a magnetometer can have a sensitivity of 0.1 gammas and yet only have an accuracy in measuring the total field of 10 gammas.

4.2.2 Types of Magnetometers

There are three varieties of airborne magnetometers that have been utilized in aeromagnetic surveying, namely

(1) Fluxgate

(2) Proton precession-free and spin-precession

(3) Optical absorption

All measure the total field value of the earth's magnetic field whose background value varies from about 24,000 to about 70,000 nanoteslas.

4.2.2.1 Fluxgate Magnetometers

These were the first practical airborne geophysical instruments utilized and were developed immediately after the end of World War II from the airborne magnetometers used in antisubmarine warfare.

The sensitive element of a saturable-core or fluxgate magnetometer consists of a short length of high-permeability ferromagnetic material having a narrow hysteresis loop which acts as a core for one or more windings connected to AC exciting and indicating circuits. The field component along the axis of the fluxgate element is measured and so it is necessary to keep the axis accurately aligned in the direction of the earth's magnetic field. This is accomplished by the use of a three-axis moveable platform in which are mounted additional orthogonal elements which control the orientation of the measuring elements.

For the device to work most of the ambient field is bucked out by the use of an additional winding through which is passed an accurately controlled DC current. Thus the fluxgate magnetometer is a vector variometer in which the variations of the earth's magnetic field from a fixed datum is measured. The output of a fluxgate magnetometer may be recorded as a continuous trace i.e. without steps, on an analog record. When first introduced fluxgate magnetometers were considered to have a sensitivity of one gamma but with improved compensation the latter models could achieve sensitivities approaching 0.1 gamma. Although these magnetometers were utilized for many years up to the 70's they are not much utilized now and can be considered to be obsolescent being replaced by the simpler and less costly proton precession magnetometers.

4.2.2.2 Proton Free-Precession Magnetometers

The proton free-precession magnetometer has been the most commonly utilized airborne magnetometer in recent years and was developed during the middle 1950's. The sensor is much simpler than the relatively complicated fluxgate magnetometer consisting essentially of a bottle of a hydrogen-rich liquid, such as water or kerosene, around which is wound a coil of copper wire. The principle of operation depends upon the fact that hydrogen (but not the oxygen) protons have a magnetic moment due to their spin. First an external field is applied to the bottle of hydrogen protons by passing a DC current through the coil for a short period of time, typically one half-second or so. Then the field is switched off allowing only the earth's magnetic field to act. The effect is somewhat like kicking a child's spinning top, and the spinning hydrogen proton begins to wobble i.e.precess. The frequency of precession (f) is directly proportional to the ambient earth's field (T) and is related to it by the following formula $T = Kf$ where $K = 2\pi$/gyromagnetic ratio of the proton = 23.4874.

The hydrogen protons which are precessing in unison will induce an audio signal into the surrounding copper coil. This audio signal decays exponentially to zero within several seconds. The audio signal is amplified and in the most commonly utilized instruments multiplied in frequency to increase the sensitivity of the reading before being counted for a set period of time to yield the earth's magnetic field value directly in gammas. The sensitivity of direct-reading proton free-precession magnetometers ranges from 0.1 to 1.0 gammas; the sampling rate is usually 1 second, and their range is typically 20,000 to 100,000 gammas to permit their use worldwide.

Proton precession magnetometers have a number of disadvantages. The rate of decay of the proton signal is dependent on the magnetic field gradient across the sensor although that is more of a problem in ground magnetometers. The amplitude of the precession signal is dependent on the angle θ between the axis of the sensor coil and the direction of the total field. It is actually proportional to $\sin^2\theta$ so there is a dead zone along the axis of the sensor coil. At high latitudes, the sensor coil should therefore be oriented in a horizontal position and at low latitudes in a vertical position. For surveys where the inclination of the earth's field is 45°, it is clearly advisable to orient the sensor coil horizontally transverse to the longitudinal axis of the survey aircraft if north-south lines are being flown.

A further difficulty with proton precession magnetometers is that if the head rotates during the count period, the apparent precession frequency will be either increased or decreased depending upon the sense of the rotation with respect to the coil system. This will clearly be a more serious drawback for towed bird systems than for inboard systems contributing to the background noise especially in more turbulent flying conditions.

Perhaps the most serious drawback of proton free-precession magnetometers is the necessity to polarize the sensor and then measure the frequency of precession. This puts a limitation on the rate at which measurements can be recorded and also the instrument sensitivity. For instance for the popular Geometrics G803 proton magnetometer, sensitivities of 0.5 gamma for a 0.8 second sampling, 1 gamma for a 0.5 second rate and 2 gammas for a 0.33 second sampling rate are achievable.

4.2.2.3 Spin-Precession or Overhauser Magnetometers

Spin-precession magnetometers are somewhat similar to the proton free-precession type in that the sensor consists of a coil system enclosing a liquid sample containing hydrogen protons. However a parametric salt is dissolved in the liquid sample which has the special property that the spin energy of the orbital electrons can be transferred to the proton to keep them precessing continuously by the use of high-frequency fields. This is called the Overhauser effect after the discoverer. The output from the sensor is however continuous and the resultant audio frequency is measured utilizing similar techniques as for the proton free-precession magnetometer since the constant of proportionality (K) is the same between the measured field and the output frequency. Because the output is continuous, the sensitivity can be made to exceed 0.1 gammas, so they are well suited to medium sensitivity surveys. Overhauser magnetometers have not however been much utilized in aeromagnetic surveying except in France.

4.2.2.4 Optical Absorption Magnetometers

Optical absorption magnetometers were developed during the 1960's and have an order of magnitude better sensitivity than the proton precession magnetometer that is around 0.01 nanotesla. They have not been greatly utilized in aeromagnetic surveying for a number of reasons up to the 1980's although that situation is now changing. The first reason is that their use has been restricted by patents (up to September 10, 1987 when the important Dehmelt patent expired) so that only a few contractors have been licensed to provide surveys using such magnetometers. The second reason is that for regional aeromagnetic surveys, the sensitivity of the proton precession magnetometer is adequate for the purpose. However the use of optical absorption magnetometers has increased considerably by their being utilized in aeromagnetic gradiometer systems consisting of two optical absorption magnetometers vertically separated by a short (2 metre or so) distance. Such aeromagnetic gradiometers require the higher sensitivity that optical absorption magnetometers possess. Optical absorption magnetometers can also sample the magnetic field at a much higher rate than proton precession magnetometers at high sensitivity - up to 10 times per second.

At the heart of an optical absorption magnetometer is a glass cell containing an alkali vapour such as cesium or rubidium which is irradiated by radio frequency light corresponding to a specific line in the alkali vapour spectrum. The effect of the irradiation is to pump alkali vapour electrons to higher energy orbits from which they will fall spontaneously to lower energy state. When they absorb light the glass cell becomes opaque to the incident light and when the electrons fall back to the lower energy state they actually emit light and the cell is transparent. The effect is that the light passing through the cell flickers at the Larmor precession frequency of the electron which depends on the ambient field. For cesium the Larmor frequency is 3.498 hertz per gamma. Thus the resultant output frequency is much higher than that produced by the proton precession magnetometer for the same magnetic field and falls in the range 100-200 KHz.

Cesium magnetometers have a number of drawbacks. The first of these is that there are actually eight spin states for Cesium 133 that gives rise to eight closely spaced Larmor frequencies of varying amplitudes producing a composite output frequency. The relative amplitudes of the eight Larmor frequencies change as the angle of the optical axis of the magnetometer changes with respect to the ambient field. This orientation error ranges up to about 8 nanoteslas for a single cell instrument.

The orientation error is reduced considerably (to less than 1 nT) by the use of split beam instruments in which the circular polarization of the light passing through one half of the cell is made to be in the opposite sense to that passing through the other half of the cell. After passing through the cesium cell, the split beams are focussed on a photoelectric cell producing an averaged frequency and giving a flatter response for the combined effect of the eight Larmor frequencies mentioned earlier.

The second drawback is that the instrument has an active zone of orientation of about 65° in which it will operate, and polar dead zones of 30° and 210° from magnetic north in which the magnetometer will not work. For optimum operation, the cesium magnetometer is set at an angle of 45° from the total field vector.

To avoid the heading error and dead zone problems the NRC National Aeronautical Establishment developed a two-axis orienting method based on the minimization of a small audio frequency signal superimposed on the ambient field. The technique was utilized in the military ASQ-501 and ASQ-502 magnetometers built by Canadian Aviation Electronics Ltd. and adopted by the GSC in magnetometers built for its Beechcraft B-80 Queenair survey aircraft. Such two-axis orienting magnetometers have now seen considerable commercial airborne geophysical use and it is clear that the orientation error is minimal and there are no dead zone problems.

A second technique for minimizing the orientation error is in the use of a so-called strap down magnetometer which employs a non-oriented split-beam cesium magnetometer. The orientation errors are minimized by incorporating the necessary corrections into the algorithm of the active magnetic compensation system used in the magnetometer installation. In such microprocessor-based compensators aircraft manoeuvres are sensed using a triaxial fluxgate sensor. The technique appears to work reasonably well at magnetic latitudes higher than about 60° when the optical axis of the cesium sensor should be mounted at a 45° dip angle from the longitudinal axis of the survey aircraft. At middle magnetic latitudes, the cesium sensor should be mounted vertically. Significant east-west rolls and north-south pitches of the aircraft will cause the ambient field direction to fall into the dead zone of operation of the magnetometer. At low magnetic latitudes, the cesium magnetometer is again best oriented dipping at an angle of 45° along the longitudinal axis of the survey aircraft. However there is a much greater propensity to lose signal completely with heading changes and pitch of the aircraft because of the dead zone problem that would make the compensation of the aircraft difficult to carry out.

Helium magnetometers neither have an orientation error nor do they have polar dead zones although there are 30° equatorial dead zones. Furthermore the higher Larmor frequency ratio (28.02468 Hz/nT) of the He magnetometer as compared to the lower (3.498 Hz/nT) of the cesium vapour magnetometer, provides significantly higher resolution at a higher field sampling rate. However helium magnetometers have been utilized far less than cesium magnetometers for aeromagnetic survey work up to the present time in part because of the commercial availability. One reported difficulty in the earlier helium magnetometers was the ready diffusion of helium gas through the glass walls of the optical cell that gave them a rather short operating life. Thus cesium magnetometers have had a much longer history of usage in aeromagnetic surveying and have a demonstrated reliability of operation.

4.3 Compensation Systems

Actually inboard installations of the magnetometers were made possible by improvements in the magnetic compensation of aircraft. There are three different sources of interference produced by the aircraft itself. The first is the permanent magnetism of the various components made of steel, such as the engines, whose direction remains fixed with respect to the aircraft. The second source is the induced field due to the magnetic susceptibility of these same components and the earth's field. Its polarity and magnitude depend upon the orientation of the aircraft with respect to the earth's magnetic field. The third source of interference is that caused by the magnetic effect of eddy currents generated in the skin and other conducting parts of the aircraft by their motion in the earth's magnetic field.

In earlier passive compensation systems, the permanent magnetism was eliminated by the use of a set of three-orthogonal compensating coils mounted near the magnetometer head and on the roll axis of the aircraft through which the appropriate DC current were passed. The induced components were eliminated by the use of permalloy strips, and the eddy currents were compensated for by the use of coils of wire mounted in close proximity to the sensitive element. It was necessary to carry out a set of rolls, pitches and yaws of the aircraft in low gradient areas in order to separate the effects of the various components. The excellence of magnetic compensation of a given survey aircraft is measured by its "figure of merit" (FOM). This index is obtained by summing, without regard to sign, the amplitudes in gammas of the 12 magnetic signatures recorded when the aircraft carries out ± 10° rolls, ± 5° pitches, ± 5° yaws peak-to-peak on north, east, south, and west headings over periods of 4 to 5 seconds.

In recent years, active 9-term aircraft magnetic compensation systems have been manufactured by three companies in Canada. The use of these active compensation systems improve the "figure of merit" of a given aircraft considerably, and drastically reduces the time required for aircraft compensation.

It is necessary to ensure that magnetic compensators are well proven under actual flying conditions in removing the effects of manoeuvre noise due to the aircraft itself. In particular it is essential that the frequency response of the compensator is sufficiently wide that it will not adversely affect the recording of the geological signal. Thus a description of the frequency response of a given instrument should be contained in the manufacturer's documentation.

Up to the present time post-flight magnetic compensation of the resultant data has not been well-proven in a variety of survey conditions. The technique has a number of drawbacks perhaps the most important being that the actual noise level cannot be easily ascertained during a given flight to ensure that the survey specifications are being met. Indeed the noise level is generally reduced by an order of magnitude by inboard compensation techniques. If, for instance, there is a magnetic inclusion near the sensor particularly one that moves in some regular fashion, then no amount of post-flight compensation will remove their adverse effects. The presence of such inclusions will be immediately obvious in a well-compensated inboard system.

4.4 Data Acquisition Systems

Data acquisition systems normally consist of both digital and analog recording systems. The digital acquisition system records the digital data on a suitable medium that has traditionally been magnetic tape on reels but data cassettes and discs are also acceptable. It is desirable that the digital recorder has a read-after-write capability so that the recorded data can also be displayed in analog form on a chart recorder (or scrolled on a CRT display) so the instrument operator can ensure that the data is being properly recorded throughout the survey flight. The parameters that are digitally recorded include the magnetic field readings, radar and barometric altitudes, time, fiducial numbers and navigational information. Information such as aircraft registration, date, line number, line segment number, direction, flight number, start time of line and any relevant scale factors or datum levels should be included in a header record which precedes the relevant data. Such pertinent information should also be included on the analog records and on the flight log to be maintained by the instrument operator.

Each gate of the data record which contains one variable being recorded must have sufficient digits to cover the dynamic range of the variable. Free choice of recording scale and datum is allowed provided that:

(1) this does not conflict with any stated specifications,

(2) no change of scale or datum occurs in any variable unless the change is immediately preceded by a header record containing the new scale and/or datum.

The only exception to the above provision are those data (i.e. time) which are always positively increasing quantities. For those data, a "cycling" gate is allowable. In this case the number of digits within the gate must be sufficient to cover the range of variations over at least ten physical records but need not be greater.

If in the case of time data, a gate is used which contains insufficient digits to cover a range of 24 hours to a 1 second accuracy, then every discontinuity in recording must be preceded by a header record containing the full 24 hr-min-sec time (GMT or local) of the instant at which recording commenced.

A digital tape log book must be maintained in the field to record the following information for housekeeping purposes:

(1) external tape label code,

(2) tape content (start and finish date/time of recording and flight numbers),

(3) dates of verification and copying,

(4) results of verification (i.e. any read errors, or re-reads required),

(5) data original tapes shipped to compilation laboratory. Action taken if lost or damaged in transit.

If a suitable personal computer is available in the field such a log could be maintained as a computer listing that could be printed out for the monthly report.
Chart recorder parameters are discussed in Chapter 6 of this document.

Some flexibility to change the scale sensitivities in the field preferably with the approval of the client inspector should be permitted as the magnetic activity in the survey area warrants.

Fiducial System and Clock

It is necessary to be able to tie the data recorded to a ground position in order to produce a contour map with geographic co-ordinates. Thus it is necessary to have a synchronized numbering system that puts a sequential series of numbers on the positioning film (or video tape) and that is also recorded along with the magnetic field and other recorded parameters by the data acquisition system. Time for a digital clock is often utilized for this purpose but it is necessary in any case to record time to ensure that the magnetic diurnal specifications are not exceeded along a given line.

4.5 Altimeters (Radar and Barometric)

Both these type of height measuring equipment are employed in aeromagnetic survey operations. Barometric altimeters which are standard equipment on all aircraft contain a pressure-sensitive metal capsule from which the air has been removed. The sealed metal capsule expands as the air pressure decreases and this small movement is multiplied through a linkage system and gears to rotate the needles (indicators) on a dial. The dial normally shows 100's, 1,000's and 10,000's feet.

The altitude of the airport or sea level pressure is normally set in to the altimeter by a knob to establish the datum so that height above mean sea level of the aircraft will be indicated. To record the output of the barometric altimeter digitally, sensitive capacitance circuitry is utilized.

Radar altimeters are active systems which utilize electromagnetic energy reflected from the ground. Two main types have been utilized namely (1) frequency-modulated altimeter; (2) pulse-type altimeter. In the first type which is generally more suited to slow-moving low altitude aircraft, the output of the transmitter is frequency-modulated and the resultant frequency shift between the transmitted and reflected energy used to obtain the terrain clearance. The pulse-type measures the transit time of the reflected pulses to calculate the height.

In field operations, the accuracy of radar altimeters is normally checked by flying at various heights using barometric altimeters above the airport being used.

Laser altimeters are coming on to the market that provide highly accurate heights. However they do not penetrate cloud or falling snow.

4.6 Ground Verification Systems

The digital data tapes must be verified in the field to prevent unnecessary reflights if faulty recording has taken place. Continued in-flight verification by employing a read-after-write system plus a ground based verification system are required.

The ground based verification system should consist of a tape reader with a programmable microcomputer and printer or plotter. It must be capable of plotting the recorded values back at enlarged scales suitable for detecting any problems, to ensure all data are within specifications.

After every day's flying the contents of the day's production of digital magnetic tapes must be verified using the ground based verification system. It would be desirable if digital tapes were also copied prior to shipment to avoid the possibility of loss of the data and provide a back-up tape that can subsequently be placed in storage as insurance against catastrophic happenings e.g. theft in the home office.

4.7 Ground Diurnal Stations

In order to monitor the daily (diurnal) variation of the earth's magnetic field, it is imperative that a ground station be continuously operated at the base of operations. Because the resultant data should be free of interference from vehicular traffic etc., the sensor itself has to be located in a magnetically quiet location. The resultant data is normally digitally recorded at a one-second interval during survey operations but an analog recording is required on a continuous basis so that the general state of the diurnal activity can be ascertained over the previous few hours by the flight crew prior to the start of flying. Clearly if a magnetic storm is in progress or if the activity is unusual, there is no point in flying. Control lines are also best flown on quiet days.

For the analog chart recorded, a scale of 2 gammas per vertical centimetre is normally specified with a chart speed of 50 cm/hour during survey flights. Fiducial timing marks every minute should appear on the analog chart which should be synchronized to within 1 second with the aircraft clock.

4.8 Chart Recorder and Chart Parameters

4.8.1 General Remarks

The primary reason for a chart record is to evaluate the operation of survey equipment during flight. All the data must be visually examined, annotated and evaluated by qualified personnel before data leaves the job site. The chart record should be the reproduction of the digital data recorded on tape in the aircraft. Sometimes the chart record is used for preliminary interpretation and ground follow up.

All trace values must be presented at useful scales on each line recorded. The values given in the following paragraphs are useful as a guide, but consideration must be given to variable conditions of activity. In the field, some flexibility to change vertical scales must be made available as magnetic activity demands.

4.8.2 The Type of Chart Recorder

The chart recorder should be of good quality with a recommended paper width of 30 cm. This width gives enough room to clearly register all the traces. All charts must be easily reproducible by photographic means and have rectilinear coordinates. In order to record the data at a convenient scale and a good precision, the chart speed should be approximately 3 cm on paper per each kilometre of ground distance (given by the navigation system used).

4.8.3 The Recorded Data and Format

A well balanced display format is important to obtain a clear and rapid check of the data at the sensitivity recorded. A typical example of fields and scales is presented below. Each survey will however require careful consideration to optimize the utility of the display.

Data	Full Scale Deflection	Width of Trace
Fiducial times - along top edge of record	---	---
Total field - high sensitivity	20γ	10 cm
Total field - low sensitivity	500γ	10 cm
Fourth difference (÷ by 16)	2γ	2 cm
Navigational data	150 m	2 cm
Radar altimeter	300 m	4 cm
Barometric altimeter	60 m	2 cm

All charts should be clearly annotated with the relevant survey information at the start of the roll, i.e. date, line number, sensitivities utilized, operators name, flight number, direction, start time of line, any relevant scale factors or datum levels. The fiducial marks are synchronized with the flight path camera and digital positioning information.

4.8.4 The Magnetic Ground Station Chart Record

The chart recorder of the ground magnetometer should be set at approximately 2 gammas per vertical centimeter. Fiducial marks should be recorded at regular intervals of one minute with 1 sec. accuracy on the rectilinear coordinate chart, preferably triggered by a crystal clock mechanism which will be synchronized with a similar clock on board the aircraft.

For good precision and easy reading, the chart speed for the ground magnetometer should be approximately 50 cm per hour during survey flights.

To facilitate checking by the technical Inspector after the survey, the ground station charts should be dated and time marked with respect to the beginning and end of each identified traverse and control line. Any change in the recorder sensitivity should be clearly noted on the chart and pen repositioning will be indicated. The total field trace must be labelled with a minimum of 1 field value per flight line.

4.8.5 Multi Parameter Airborne Surveys

The same principles given above apply as in magnetometric surveys. The chart has to display all the parameters measured and recorded digitally during the flight survey.

5. NAVIGATION AND FLIGHT PATH RECOVERY

5.1 General Considerations

It is important to recognize three distinct steps in the process of positioning aeromagnetic surveys. First is navigation, guiding the aircraft along each flight line. Second is path recovery, determining the location of the aircraft when each geophysical measurement was made. Finally, there is mapping, the location of the flight path on a useful set of base maps. The technology of all three steps has developed rapidly in recent years, and the airborne survey industry has quickly put new techniques to use. This has required adaptations, because the normal requirement for aircraft navigation is to arrive at a destination, not to determine the precise path followed in getting there.

Electronic navigation is an area of survey technology that is changing rapidly. In particular, the advent of Global Positioning Systems has the potential to revolutionize both real-time navigation and post flight-path recovery to provide a degree of accuracy worldwide not previously attainable. More reliable flight path recovery will significantly reduce the need for laborious point picking from film and transferring to stable material, and the digitizing of the flight path thus significantly improving delivery schedules and reliability. At the end of 1990, there was still an incomplete GPS satellite constellation, delayed by the Challenger accident, however the full array is expected to be in place by the end of the year. Despite this progress, gaps in GPS coverage and uncertainty concerning the intentions of the military to reduce the reliability available to civilians still exist. There is still a requirement and a considerable amount of research taking place in industry and government on the integration of navigation systems, primarily in the use of inertial guidance to correct or bridge gaps in GPS coverage and to arrive at the 'best' flight path by real time averaging techniques such as Kalman filters. One of the more interesting phenomena which will affect geophysical surveys is the possibility that electronic navigation will soon become more reliable than the topographic maps themselves.

An excellent review of current techniques of navigation and flight path recovery has been presented by Bullock and Barritt (1989), and the reader is referred to this article for technical details. Here we wish to present only a brief summary.

5.2 Visual Methods

The traditional, and still the most common approach for aeromagnetic surveys has been to locate the proposed flight lines on topographic maps or photo-laydowns, to navigate the aircraft visually along these lines, recording the actual flight path by 35 mm film photography or on video tape, which is then used to identify points along the path, and finally to transfer these locations onto a base map. Colour video systems are now common and eliminate the necessity for developing film, however it is difficult to establish cross-overs as can be done with film. An essential element is a fiducial system which sets simultaneous marks on the flight path and the geophysical recordings to tie them together.

The method is time consuming, but works well. There are two necessary conditions, namely that the terrain has enough features that a point can be picked about every 3 km, and that it is reasonable to assume a constant groundspeed between the picked points. The method is not recommended for featureless terrain or for helicopter surveys in mountains.

5.3 Self-Contained Systems: Doppler and Inertial

Both Doppler and Inertial navigational (INS) systems are self contained in the aircraft. Installation of a Doppler system is more difficult, since an external antenna must be mounted on the aircraft for the radar beams. The Doppler measures the groundspeed and track direction of the aircraft by means of radar signals reflected from the underlying terrain. Accuracy is reduced over water, since the surface of the water is moving as a result of currents and waves. The Doppler measurements are integrated in real time for navigation purposes to give distances travelled along and across the desired track. The system is subject to drift through inaccuracies of the reference direction, measured by a compass. Both for navigation and path recovery, the Doppler data must be tied in to recognizable points or to the known coordinates from an electronic positioning system.

An inertial navigation system uses accelerometers and a gyroscope to measure the movement of the aircraft, with double integration to compute the latitude and longitude, starting from a known location. The computed positions are subject to drift, principally caused by the so-called Schuler oscillations, which have a period of 84.4 minutes and an amplitude which may reach a few kilometres. Therefore update points are required both for navigation and path recovery, just as for a Doppler system.

Because of the inherent drifts of these systems, special flying procedures must be established to ensure accurate navigation, with updates over known points at intervals of 10 to 15 minutes. When the navigation data is updated, it is desirable to avoid any corresponding shifts in the recorded data, since such discontinuities complicate subsequent data processing.

The long-term drifts are disadvantages in these systems. Their great advantages are their accuracy in short term measurements, which provide a continuous set of positions between fixes, whether these be from picked points or an electronic positioning system. Doppler or INS data will readily identify errors in such points, since they cannot be fitted into a smooth pattern of drift.

Another great advantage is the ability to use the recorded Doppler or INS data in the field to make a plot of the aircraft track of the entire flight immediately upon its return. This can make checking the flight path both quicker and more accurate than relying solely on visual path recovery. To make the most of this technique, continuous recording of the Doppler or INS data is necessary, including turns between lines, and also to have the necessary data processing and plotting facilities in the field office.

5.4 Radio Navigation Systems

On the basis of cost, two different types of radio navigation systems are distinguished. The first group are the VLF/LF systems which provide permanent coverage over large parts of the earth and oceans. To use these systems, it is only necessary to install a receiver in the aircraft. In contrast, it is much more expensive to use the more precise higher frequency systems, since transmitters must also be set up and operated. Positions are determined with these systems in one of two ways, either by measuring the difference in time between signals arriving from pairs of transmitters (hyperbolic mode), or by measuring the times for the signal to travel between the aircraft and the ground station (range-range mode). With the higher frequency systems, signals are transmitted along lines-of-sight, so that it is important to locate the ground stations on high points and to beware of shadow zones within the survey area. With the lower frequency systems, range is increased because the signals follow the ground, but the signal patterns are distorted by changes in the electrical ground conductivity, especially by contrasts between land and sea. Difficulties can also arise from confusion between ground and sky waves, the latter being reflected from the ionosphere.

It has been common to use the longer range low-frequency systems for offshore surveys where coverage exists, especially Loran C. Microwave systems are used for relatively small and detailed surveys, especially those requiring helicopters. Their ground stations are light and easy to install.

Many of the radio navigation systems were designed for navigation purposes, and some for ships rather than aircraft. Special adaptations have been required to provide adequate guidance for a pilot to fly a regular grid of lines, and to provide signals suitable for digital recording of the actual flight path.

Bullock and Barritt (1989) have prepared convenient tables (17.3 and 17.4) comparing the basic characteristics of radio navigation systems, and these are reproduced below:

System	Frequency	Measurement	Range (Propagation)	Accuracy	Transmitters (Power Output)	Remarks
OMEGA	10-14 kHz 5γ's	Hyperbolic C.W. Phase	Global (Skywave)	4-7 km Diff 1 km	Permanent All Tx's in sync 8 stations world wide Spacing 8000-10000 km (50k W)	Diurnal Skywave correction. Propagation varies with seasons, solar activity, etc.
LORAN-C	100 kHz	Hyperbolic Pulse Timing Range-Range	1000-2500 km (Groundwater)	50-200 m	Permanent. Many chains. Spacing 1000 km All Tx's in sync (150-1500kW)	Skywave effect removed by pulsing. With atomic clock timing.
PULSE-8	100 kHz	Hyperbolic Pulse Timing Range-Range	800 km (Groundwave)	20-40 m	Permanent/ Semi Permanent Many chains Spacing 300-500 km All Tx's in sync (1 kW)	Modern Loran-C Designed for survey work. Monitor station to correct to diurnal errors. With atomic clock timing.
DECCA Main Chain	70-130 kHz	Hyperbolic C.W. Phase	150-300 km (Groundwater)	50-200 m	Permanent Many chains Spacing 100 km (1.2kW)	An old system Problems with skywave

rom: **Exploration '87 Proceedings - GEOPHYSICAL METHODS: ADVANCES IN THE STATE OF THE ART**
Bullock and Barritt: TABLE 17.3 VLF/LF SYSTEMS.

Frequency	Systems	Measurement	Range (Propagation)	Accuracy	Portability (Power Output)	Remarks
MF 2 MHz (1.0-3.4 MHz)	ARGO GEOLOC HYDROTRAC HYPERFIX RAYDIST SPOT TORAN	Hyperbolic C.W. Phase Some spread spectrum systems. Also active Range-Range	200-500 km Greater during daylight hours (Groundwave)	5-25 m	Large permanent antennas. (100-300 w)	Skywave problems at night. Lane count errors. Propagation velocity errors. Best choice when distances >150 km.
UHF 400 MHz (200-450 MHz)	MAXIRAN SYLEDIS TRIDENT TRISPONDER SHORAN	Hyperbolic Range/Range Pulse	200-400 km (surface "ducts")	2-10 m	Systems semi-portable. Large antennas required for longer ranges (100-1000w)	Errors increase when distance is 2 to 3 times LOS Suitable for airborne survey.
Microwave (3-10 GHz)	ARTEMIS AUTOTAPE CR-100 MAPS TELLUROMETER MICRO-FIX MINIRANGER TRISPONDER	Range-Range Pulse envelope Phase modulation.	50-200 km (LOS) (Depends of Tx height.)	1-3 m	Very portable (1-100w)	Suitable for airborne survey. Errors caused by multipath reflections. Pulse more flexible. Phase more accurate.

From: **Exploration '87 Proceedings - GEOPHYSICAL METHODS: ADVANCES IN THE STATE OF THE ART**
Bullock and Barritt: TABLE 17.4. PRECISE POSITIONING SYSTEMS.

5.5 Global Positioning System (GPS)

Full implementation of the Global Positioning System (GPS) will lead to a revolution in positioning airborne surveys. When the complete set of 24 orbiting satellites are in operation in the early 1990's, it will be possible to determine the position of the aircraft (latitude, longitude and altitude) at all times and anywhere in the world with a potential accuracy of 3-5 m, and perhaps even better. In principle, the system measures the distance from the aircraft receiver to a satellite. By measuring from four satellites that will be above the horizon at any given time, four equations are established to solve for the three unknowns of position and the fourth unknown, which is the time difference between the receiver and satellite clocks. GPS has been successfully used for aeromagnetic surveys since 1985 even though the network of satellites was incomplete. Careful planning has been required to make the best use of time windows when signals from four satellites were available. When the time difference had been established, three satellites could be used to fix the position. Accuracy has been considerably improved by operating in a differential mode, with an extra GPS receiver at a fixed position on the ground to establish error corrections for the satellite signals.

5.6 Combined Systems

It is common practice to use a combination of systems, especially for path recovery. For instance inspection of the adjustments necessary to fit Doppler or inertial measurements to the co-ordinates of visually picked points will demonstrate the noise level of the point picking process. It will also reveal adjustments which are so large and erratic that errors are implied. In a similar way, the accuracy of Doppler or inertial data over short times can be used to detect erratic drifts of the lower frequency radio navigation systems, which happen occasionally, perhaps as the receiver loses signal from one of the transmitters or confuses ground and sky waves.

It is desirable that the positioning data be recorded in a form as close as possible to the original measurements. For instance to record Doppler data as track and groundspeed rather than the positions computed from them. This makes it easier to detect errors and process the data with maximum accuracy. However recordings of the computed positions may also be desired for field plotting purposes.

Various approaches have been made to combine systems in the aircraft in order to improve navigation. For instance Loran C data has been calibrated in flight against GPS positions so that loss of satellite data could be automatically replaced by Loran C data. Attempts have also been made to apply the data processing techniques of Kalman filtering in order to predict in real time the drift of an inertial guidance system, and so to improve navigation.

It may be noted that several navigation systems involve the use of their own clocks, notably GPS. This clock will generally be independent of the clock which controls the magnetometer, introducing a question of synchronization, and hence of uncertainty in correctly locating the geophysical data points. Procedures must be set up in the field to limit this uncertainty.

5.7 Mapping

Aeromagnetic surveys are followed up on the ground, and it is important to make aeromagnetic maps which provide useful ground locations. When available, topographic maps are generally used as base maps and at a scale of 1:50,000 or 1:25,000, give good results. Satellite images have improved enormously in quality and can provide excellent bases. Enlargements have been made to 1:25,000 scale.

Problems of inaccuracy arise when using smaller scale topographic maps. Also for low level and detailed surveys, laydowns of aerial photographs have commonly been used and these inevitably involve some distortion and mismatches. In these situations it is necessary to decide whether to fit the flight path to the base maps, which should assist ground follow up, or to avoid distortions of the flight path recorded by an electronic system, and so avoid distortions of the aeromagnetic data. Bullock and Barritt (1989) have suggested the eventual solution, that small portable GPS receivers will eventually be more accurate and easier to use than aerial photographs for ground follow-up.

Conclusion

It is evident that the accuracy of all of the systems can be quite variable. Accurate positioning depends to a great deal on the conditions under which a system is used. Results can be improved dramatically by the use of integrated or improved systems (i.e. differential GPS) and by careful processing.

Prospective contractors should be requested to clearly describe their rationale for the proposed system, the type of processing which will be used and the accuracy expected.

6. CALIBRATION AND COMPENSATION OF AEROMAGNETIC SURVEY AIRCRAFT

6.1 Introduction

In considering the influence of the survey aircraft itself on the magnetic field recorded by an inboard magnetometer, the interference can be divided into static and dynamic effects as follows:

(1) the static effect is due to the permanent and induced magnetic fields produced by the ferrous components of the aircraft, by eddy currents induced in the skin of the aircraft and by DC current loops in the electrical system which slightly change the base level of the magnetic readings. The amplitude of the static effect will depend on the heading of the aircraft with respect to magnetic north because the induced magnetization direction of the various ferrous components will change as the earth's magnetic field vector changes with respect to the aircraft flight direction.

(2) the dynamic effects are produced by the various oscillatory movements that all aircraft experience as they fly and by electrical interference from within the aircraft. These dynamic effects show up as noise on the resultant recorded data.

Thus the total field value recorded at any instant by an inboard magnetometer will differ somewhat from the true value due to the magnetic properties of the aeromagnetic survey aircraft itself. In any discussion of whether the measured total field values correspond to the actual total field values, there is also the question of the accuracy of the basic magnetometer circuitry utilized in measuring and frequency. Frequency measuring devices invariably require an accurate internal clock or timing device whatever the actual technique that is utilized. Consequently it follows that some form of calibration is required for an airborne magnetometer system.

6.2 Noise on Aeromagnetic Survey Data

There are several different types of noise that are recorded in aeromagnetic survey operations which may be divided into two main categories - continuous and discontinuous noise. Discontinuous noise occurs as isolated spikes or a series of closely-spaced spikes forming a wavetrain in the magnetic field data usually as a result of some action of the flight crew although there can be external causes. These external causes would include close lightning bursts, the presence of a DC train, street car (tram) or power line system in the survey area, and in the case of optical absorption magnetometers, the passing of the aircraft through a radar or TV repeater beam. The actions of the crew that would cause discontinuous noise include

(1) radio transmissions particularly HF,

(2) the switching of equipment drawing DC current, e.g. auto pilots,

(3) relocation of ferrous objects in the cabin of the aircraft such as tool boxes.

Continuous noise for inboard installations is produced both by the flexing of the aircraft during turbulence and by its overall manoeuvre pattern relating to the attitude of the aircraft as it flies. The flexing of the aircraft will produce a (high frequency) noise swath on the magnetic field signal while the overall manoeuvre pattern (rolls, pitches and yaws) will tend to modulate the magnetic field signal at a somewhat lower frequency. A lower frequency modulation can also be produced by bird swing if the magnetometer is towed such as in helicopter-borne vertical gradiometer systems. The period of oscillation depends on the length of the cable and is usually of the order of 10 seconds. In high sensitivity survey installations, the use of a flight path camera that has a DC motor can produce a small spike every time the shutter is activated. One of the most effective ways of measuring the noise swath is by computing the fourth difference of the digital data. The noise at value ΔT_0

$$= \frac{\Delta T_{-2} - 4\Delta T_{-1} + 6\Delta T_0 - 4\Delta T_1 + \Delta T_2}{16}$$

where ΔT_{-2}, ΔT_{-1}, ΔT_1 and ΔT_2 are respectively the four recorded values located symmetrically with respect to the central value ΔT_0. Thus by calculating the fourth differences of the recorded data in flight using in turn five adjacent values, the noise level can be monitored by the instrument operator continuously using an analog chart recorder. Any spikes or changes in the datum level of the data will also be readily apparent to the operator, because these appear as a distinctive wavetrain on the fourth difference trace.

6.3 Acceptable FOM Levels

Under normal turbulence conditions, the noise level appears to be linearly dependent on the figure of merit (FOM) of the survey aircraft (see Section 4.3 for definition). In fact as a rough guide, the empirical relationship appears to be

$$\textit{Noise Level} = \frac{\textit{FOM}}{15} \quad (\textit{Hood}, 1986)$$

which is slightly less than the average for the FOM manoeuvres as would be expected. But in very calm air, the noise level would be somewhat less.

Thus for the 1 gamma regional surveys of the 1970's, the FOM specified was 12 gammas. With improved compensation the specified FOM has been reduced to 4 gammas for a concomitant 0.25 gamma noise level.

In gradiometer systems, the noise output from the two magnetometers is additive. The separation between the sensors usually about 3 metres is also a factor in the required instrument sensitivity. Presently the GSC requires for gradiometer surveys, an FOM of 1 gamma for each sensor to obtain noise levels of 0.1 gamma for the total field and 0.025 gamma/metre for the gradient.

6.4 Calibration of Aeromagnetic Survey Systems

6.4.1 General

The calibration of aeromagnetic survey systems should preferably be carried out immediately before and at the close of survey operations. In addition, if there are major repairs or changes to aircraft instrumentation during the course of a survey, then the calibration should be repeated to check that the units of the geophysical parameters recorded are accurate. If several survey aircraft are being utilized to survey adjacent areas, then the calibration of each will avoid the possibility of level shifts in the measured geophysical parameter across the common boundary of the survey area flown by the different survey aircraft. In addition to establishing that the geophysical parameter indicated by the airborne instrumentation corresponds closely to that existing at the geophysical sensor, a check should also be made that the background noise of the geophysical system has also been reduced to an acceptable level using the fourth difference technique.

6.4.2 Bourget and Meanook Calibration Ranges

As was stated earlier, the calibration of aeromagnetic survey systems should preferably be carried out immediately before and at the close of survey operations. The first step is to compensate the survey aircraft as described earlier to obtain the lowest figure of merit possible. A check should then be made that the background noise of the geophysical system has also been reduced to an acceptable level.

It is also necessary to establish that the measured total field values recorded by an aeromagnetic survey system correspond accurately to those actually existing at the magnetometer sensor. In Canada, for government aeromagnetic surveys utilizing proton precession or optical absorption magnetometers, an aeromagnetic calibration range has been set up in a low gradient area at a crossroads near Bourget, Ontario which is approximately 45 km east of Ottawa and easily recognizable from the air and in Meanook Alberta, north of Edmonton. The values at the ground level at the crossroads have been tied to the Blackburn or Meanook Magnetic Observatory using calibrated proton precession magnetometers. The values at 150 m and 300 m elevation above the crossroads have been measured by flying a survey aircraft at various heights across the crossroads to ascertain the vertical change which is about 12 nanoteslas in 300 m positively upwards. Thus the total field values at the two levels above the crossroads have been tied to within a few nanoteslas to the continuously recording magnetometer at the Blackburn or Meanook Magnetic Observatory. Because the diurnal variation at the crossroads can be expected to follow closely the diurnal variation at the observatory, the value can be calculated at any instant of time by subtracting a constant difference value from the Blackburn or Meanook Observatory value.

Aeromagnetic survey aircraft are normally flown along the four cardinal headings across the Bourget, Ontario or Meanook, Alberta crossroads with their flight path cameras operating and the field values for each cardinal heading are ascertained at the crossroads. The difference value is subtracted from the Blackburn reading at the exact time that the survey aircraft crossed the Bourget crossroads to get the true reading. The heading errors for the survey aircraft are also calculated as part of the same calibration procedure.

In general the calibration errors should not exceed 10 nT and the heading errors should be within 5 nT in an acceptable aeromagnetic survey system. For fluxgate magnetometers which measure the total field above an arbitrary datum, Helmholtz coils can be utilized to check the sensitivity of the aeromagnetic survey system in a similar way that ground systems are calibrated.

Some trimming of the calibration will be necessary when the dip and strength of the magnetic field in the survey area differs somewhat from that where the survey area is normally based. For recently developed active compensation systems, a complete recompensation is easily carried out in a short survey flight.

6.5 Lag Tests

It is usually found that there is a difference in time between the instant that a flight path photo is taken and the magnetic value recorded. This results from, for instance, inertia in the camera motor, non-vertically of the camera, the fact that the magnetic reading is actually an average over a short period of time, etc. In order to ascertain what this time difference, usually referred to as lag, is it is necessary to fly over a sharp anomaly such as a bridge in both directions and plot the location of the peak of the anomaly with respect to its position on the ground from the film. The resultant displacement in the position of the peak of the anomaly will give twice the lag that is normally expressed in seconds. A typical value might be 0.5 seconds. Some care should be taken in the resultant compilation process that the lag is removed in the correct sense. If this is not done correctly, it will appear as so-called "herring boning" in the contouring across adjacent lines flown in the opposite direction.

6.6 Altimeter Calibrations

Normally the calibration of the radar altimeter is checked against that of the barometric altimeter by flying at a series of heights above a suitably flat area such as the base air strip or a lake. For a survey flown at 305 m (1000'), it would be appropriate to fly at 305 m (1000'), 457 m (1500'), 610 m (2000'), 762 m (2500'), 915 m (3000'), 1220 m (4000') and 1524 m (5000'). Because the barometric altimeter is a mechanical device that is basically an aneroid barometer, its calibration is based on the fact that the density of air changes in a known regular fashion with height. Using the units still in common use in aviation the standard pressure at any altitude under standard temperature conditions can be found approximately from the formula:

$$H - 221.152 T_m \log \frac{29.92}{P}$$

where H = altitude in feet,
T_m = mean temperature of air column in °K (= 0°C + 273°),
P = air pressure in inches Hg at altitude H.

For the radar altimeter an accuracy of 1% is normally expected in the digitally recorded values. This translates to 10 feet at a flying height of 1000 feet.

7. CLIENT INSPECTION

7.1 Quality Control

Day-to-day quality control of the survey data is the responsibility of the contractor. Given a well prepared technical specification there should be no need for continuous client inspection since the contractor is aware both of what is required and of what the penalties are for non-compliance with specifications.

There are, however possibilities for misinterpretation along the way and, besides, changes in specifications are sometimes necessary in the interests of efficiency or, for example, if the magnetic characteristics of the area turn out to be different than they were originally conceived. For these reasons a Technical Inspector or Quality Control Supervisor is usually assigned to inspect the field operation either continuously or at certain key points during the survey.

7.2 Field Inspection

Continuous field inspection is favoured by some organizations when:

(1) preliminary interpretation is required for purposes of in-fill surveying, land acquisition or early ground follow-up;

(2) the survey is partly experimental and the results need evaluation, following which new specifications may be in order;

(3) the contract is badly written and/or the contractor has only a general idea of what is required;

(4) the survey is a very short one so that it is more efficient to stay than to incur additional travel costs; or

(5) the technical inspector can perform other functions in the field such as mapping, training etc.

Normally, however, field inspection is carried out periodically throughout the survey, for example as follows:

(1) An initial visit when the survey unit has completed the first four or five sucessful sorties.

(2) An interim visit or visits at intervals throughout the survey, largely for liaison but also to verify that the survey and data tolerances are indeed within specified limits. As a rule, it should not be necessary to carry out such visits more than about once per month.

(3) A final visit just before the flying unit demobilizes, in order to verify that all reflights have been conducted as required.

The field inspector should be given the authority to accept or reject data and to advise the survey manager if, in his opinion, specifications are not being met. The survey manager may, if he wishes, refer to a senior authority, but it is important that the initial communication be made in the field between the specialists primarily involved. Usually any differences that occur can be worked out on the spot. Careful records and reports are necessary in order to validate rejected data and reflights.

7.3 Compilation Inspection

An inspector is usually assigned to monitor the compilation process, partly to ensure that the quality is satisfactory before it becomes inconveniently late in the process to make retroactive changes. It also happens that modifications to the technical specifications may be necessary. For example, vertical scales on profile maps or charts may require re-specifying if the magnetic relief is greatly different than was originally conceived. During the compilation process data errors may come to light that require decisions as to how they are handled. The removal of cultural anomalies might be one such problem. The compilation inspector can discuss such problems with the contractor's compilation supervisor either by telephone or during an inspection visit.

The timing of inspection visits to the compilation centre depends mainly on the length of the project. An initial visit should be made shortly after the first batch of data arrives from the field. Periodic visits should then be made at roughly one-month intervals, and perhaps more frequently towards the end of the compilation program. The number of visits can be minimized if the inspector is resident close to the compilation centre and interim and final products can be forwarded to him by mail or by courier.

As in the case of the field inspector, the compilation inspector (preferably the same person) should have the authority to request changes, within the financial constraints of the survey contract. Changes involving a modification of the budget would of course have to be approved between the parties to the contract before they are implemented.

7.4 Scientific Authority

On government-funded national and international aeromagnetic survey programs it has been the practice to appoint a Scientific Authority who has the ultimate authority to approve or disapprove products as well as survey practices. It is important that the Scientific Authority have the background and experience to fully understand the acquisition and compilation phases, otherwise decisions may cause unnecessary delays and, in extreme cases, be detrimental to the final outcome of the survey. An example might be a recommendation by the inspector or the survey manager to switch from one analog recording scale to another as a result of unexpected magnetic relief. Such changes should be routinely approved but, in practice, they have been known to cause serious delays. If the Scientific Authority is a committee rather than an individual, the problem is sometimes magnified.

If it is necessary to have a Scientific Authority on a project, the following rules are recommended:

(1) The Authority should be an individual rather than a group of people.

(2) He/she should be highly experienced - preferably with 15 or more years in the quality control of aeromagnetic surveys.

(3) He/she should have the ultimate technical authority, any disputes arising with the contractor being subject to arbitration by an independent, technically qualified third party.

(4) He/she should be protected from personal liability by appropriate contractual arrangements.

8. COMPILATION AND MAP FORMATS

Compilation includes all processes that are applied to the recorded data, including the magnetic total field and gradient, radar and barometric altimeters and navigation systems to produce a digital data set suitable for production of maps, derived products and interpretation.

The processes to be followed are:

(1) Editing of recorded data

(2) Filtering of profile data for noise discrimination

(3) Recovery of flight-path from film and aerial photographs

(4) Integration of picked points and electronic navigation and finalization of flight path

(5) Levelling (may include diurnal subtraction)

(6) Gridding

(7) Regional subtraction (if required)

(8) Contour Maps

(9) Colour interval maps

(10) Other products (e.g. profile maps)

8.1 Editing of Recorded Data

Because of the importance of digital products and the desirability of integrating with other data sets, an accurate and complete digital data set is essential.

Editing of data and quality control are closely related and interdependent. It is now common to have computer and plotting systems at the field office so that all parameters including electronic navigation data and recorded fields can be plotted to determine acceptability. Preliminary editing can also be done in the field in many cases and several companies are now actually carrying out most of the compilation in the field.

8.1.1 Magnetic & Gradient Data

Editing should be limited to removal of noise spikes with a maximum duration of two recorded values. The preferred method for removal is by interactive techniques since automated spike-filtering cannot always distinguish between spikes and sharp anomalies. Automated techniques can be used, however to locate potential spikes. Spikes should occur in less than 0.1 percent of the data and segments where errors occur more frequently should be reflown. Judgment must be used however to avoid incurring additional costs when the signal can easily be distinguished from the noise spikes. If frequent spikes are occurring it is an indication of a faulty recording system, thus it is important that data be examined in the field and office as soon as possible.

In some cases it is difficult to distinguish between noise spikes and sources (e.g. kimberlites), however this can be avoided if the sampling interval is adequate (a minimum of four samples in a distance corresponding to height above ground.)

Other types of errors that can occur are level shifts due to equipment such as heaters switching on and off and operation of other aircraft equipment. These problems should be identified and corrected at the source as soon as possible. Although it is possible to correct these problems to some extent with postprocessing, the data is always somewhat degraded. Noise bursts due to radio transmission cannot always be avoided and thus must be edited from the data.

Anomalies due to cultural sources which are permanent such as bridges or buildings should be left in the data. Anomalies due to non permanent sources i.e. drilling rigs, should be edited from the data.

8.1.2 Barometric and Radar Altimeters

These should be treated in essentially the same fashion as the magnetic data, however since they are in general more slowly varying, spike sequences of up to four recorded values can be tolerated.

8.1.3 Electronic Navigation

The amount of editing will depend to a great deal on the navigation system used. Systems depending on a transmitted signal can be subject to noise bursts or the inability of the aircraft system to track the signal, resulting in gaps. Since the actual flight path is usually a smoothly varying curve, it is possible to interpolate the erroneous data over distances up to several kilometres for fixed wing aircraft. For helicopter surveys this limit would be a few hundred metres. In order to carry out this interpolation, the recorded navigational data would have to be within the specified noise limits. If possible confidence levels for the electronic navigation should be established based on variances, number of stations for satellite, or range-range systems, etc.

8.2 Filtering of Profile Data

Filtering of profile data should only be applied to remove high frequency noise. The filter applied should not affect wavelengths greater than .65 of the altitude above sources. If the survey data is to be later artificially draped, the filtering must not exceed that appropriate for the draped altitude. Filtering to remove low frequency components in order to level gradiometer data will be discussed in section 8.5.

8.3 Recovery of Flight-Path from Film and Aerial Photographs

Picked points should be recovered from aerial photos and transferred to controlled topographical maps. Points should be picked on clearly identifiable features and rated according to reliability in order to ensure maximum accuracy of the final flight path after amalgamation with doppler, inertial guidance or other navigational systems. In some areas where detail is such that film (including video) can be accurately recovered, electronic navigation may not be necessary, however, for helicopter surveys electronic navigation is necessary to guarantee accurate flight path. Speed checks, in which the 'speed' of the aircraft is calculated from the recovered position should be run for fixed winged aircraft and can be quite useful for identifying inaccurate picked points in the flight line direction. The technique is of limited use for helicopter surveys where the speed can vary drastically. With the continued development of accurate satellite positioning, film points will tend to be used more for quality control and backup than as a primary flight path recovery system.

8.4 Integration of Picked Points and Electronic Navigation

The procedure to be followed will depend on the systems used and the relative confidence. In general relative systems such as doppler and inertial guidance must be tied into an absolute system such as film points, range-range systems or GPS. The probable accuracy of picked points in which errors can be produced by aircraft attitude must be considered relative to the expected behaviour of the system, for example, doppler or inertial guidance should not be distorted over short distances in order to force the flight path through picked points. Continued improvement of absolute systems such as GPS will result in such systems having a higher resolution and accuracy than existing topographical maps. It is now common for multiple navigation systems such as GPS and doppler or inertial guidance to be used as the primary mode of navigation and positioning. Techniques using Kalman filters have been developed to give highly accurate positioning and velocity information in flight. These techniques can also often be used in post flight processing to provide an accurate positional data set without excessive delays for film flight path recovery.

A problem can exist due to differences in reference systems used by the navigation system such as GPS and the topographical maps. A program is under way to transform all existing maps from the NORTH AMERICAN DATUM 1927 (NAD27) to NAD83 based on the WGS 84 geoid model. Software exists to transform between systems and is available from the Mapping and Surveys Sector, EMR. Adoption of the new reference system was announced on May 23, 1990. Information on progress and availability can be obtained by contacting G. Babbage, Canada Centre for Surveying (613) 996-2817.

8.5 Levelling and Diurnal Subtraction

8.5.1 Total field

Diurnal subtraction can sometimes be used when it can be shown to be effective. However the flight record should be carefully examined along with diurnal records from two or more stations to ensure that the segments are in phase and of the same amplitude, in order to not introduce false anomalies into the record.

Levelling adjustments should be applied to lines and control lines in such a way that the overall adjustment is minimized while not introducing slope differences between successive control lines that exceed the diurnal specification. For example, if the diurnal specification is to not exceed 2nt from a chord equivalent in length to the average control line spacing, say 10km, the difference in slope should not normally exceed 0.4 nt/km. The diurnal record for the time of flight should be consulted to ensure that the correction applied is consistent with the diurnal activity keeping in mind that phase differences and even reversals can occur. Movement of the intersection within the accuracy of the flight path should be made if such movements will reduce corrections to within the required limits. The altimeter record should also be consulted to identify misties due to differences in altitude. Heading errors as determined during calibration checks may be applied, however these are usually small compared to diurnal corrections.

8.5.2 Gradiometer

Although not sensitive to diurnal variation, heading errors and instrument drift do contribute to a low frequency level shifts which must be removed.

Several techniques have been used successfully for levelling gradiometer data

(1) High pass filters. Such filters should be designed to remove only wavelengths greater than approximately 20 km. although this will not affect the high frequency, near

surface components which are of prime interest, low frequency components which may be due to deeper sources will be removed or distorted. In particular, operations such as the calculation of the total field from the vertical gradient cannot be carried out with data that has been processed in this fashion. Special preprocessing must be used to reduce the effect of large anomalies so that the compensation will not follow the anomalies. This is usually done by 'clipping' anomalies whose magnitude exceeds a multiple of the variance from the mean before applying the low pass filter to calculate the baseline. Filtering is a last resort process and should only be used after consultation, and then fully described in the report.

(2) Linear Interpolation between control lines. In the approach compensations are assigned at critical points, usually intersections, and applied linearly to points between the critical points. The corrections applied are selected to minimize 'flight-line' effects in the contours. The change in slope between two successive segments must be less than the minimum contour interval.

(3) Decorrugation Filters. This approach can be used when herring-bone effects are present due to level shifts which cannot be removed by ordinary levelling techniques and should be used only as a last resort and with approval of the client. Every effort should be made to ensure that there is no contribution to the problem from positional errors. Essentially the technique consists in stripping off the high frequency component from each line, then gridding and applying a directional filter in the transverse direction to the residual with a bandpass designed to eliminate wavelengths less than twice the line spacing. Finally the low frequency component of each line is reinterpolated from the filtered grid and added to the original high frequency component. With this technique the high frequency components along the line which are of most interest are not affected.

8.6 Gridding

The gridding algorithm should normally honour both the line and control-line data although the latter might not be possible for some draped surveys in rugged terrain, and should provide a smooth interpolation between data points. Extrema can be generated between lines, but must be justified by the surrounding data. Anomalies caused by overshoot or undershoot of the interpolating algorithm at points of rapid change are not permissable. For contours the grid interval should normally be approximately 0.25 cm at the map scale, whereas for colour interval maps the required interval is less than 1 mm to avoid the grid being conspicuous on the map. (Some plotting algorithms will carry out the necessary sub-interpolation to produce a plot of the required quality). In no case should the grid be interpolated from the line data at an interval less than the average distance between recorded values. Finer grids can be produced by sub-interpolation of the grid.

Special consideration is required when portions of the flight lines are closer together than 0.25 of the line spacing. In such cases, minor differences between the two line sequences will be amplified in the gridding process. It is necessary, therefore, for the algorithm to either reject one line segment or to average the two line segments. The first option is normally preferable and should be done in such a way that the differences between the remaining intervals are minimized.

A standard grid projection (i.e. UTM) should be used. However it might be desirable to extend a UTM zone in order to generate a continuous grid for the survey area.

Trend reinforcement procedures wherein interpolation is forced in a particular direction should only be used when trends are clearly oriented in the wrong direction usually at right angles to the flight line direction (normally due to inadequate line spacing). When these procedures are used they should be clearly documented in the report.

8.7 Regional Subtraction

Regional subtraction is normally carried out to reduce the proportion of the earth's core field in the data. This is particularly advantageous when data from adjoining areas are to be combined to form a composite map. The resultant map is then relatively free of temporal changes and trends due to the core field. For coloured pixel maps this permits a smaller colour interval to be used. It should be noted that current Geomagnetic Field References Fields are expressed in 10th order spherical harmonics. Thus anomalies in the range of hundreds of kilometres will remain in the data, such that in any local area, there could still be a significant contribution from the core field. The accepted International Geomagnetic Reference Field updated to the time of survey should be used in order to ensure that the total field can be recovered by adding back in the reference field if reprocessing is required at a later date. Preferably the original data, before IGRF removal, should be retained for later use.

8.8 Contour Maps

The minimum contour to be shown should not be less than twice the required noise level. a minimum of four line types should be used (i.e. dotted, dashed, solid, heavy) and be assigned to contour intervals such that the resulting contour levels are easily determined (e.g. 5, 20, 100, 500). Contour labelling should also be of an adequate frequency such that all levels can be easily identified and labelling orientated to indicate gradient direction.

Contours should be feathered, starting at the minimum interval, whenever they are closer together than one grid interval to improve legibility, as is done with the federal regional aeromagnetic surveys. Latitude and Longitude should be printed for sheet corners and intermediate points along the sheet edges (GSC regional maps). Information to be included on sheet.

(1) Area identification including NTS

(2) Scale (printed) and scale bar

(3) Projection

(4) Date of publication

(5) Regional field subtracted (if any)

(6) Legend

(7) Descriptive notes including:

  (1) Contractor, and period of flying

  (2) Magnetometer(s), configuration and sensitivity

  (3) Navigation system(s) and accuracy obtained

  (4) Elevation and line spacing

  (5) Grid interval

  (6) Filtering used

8.9 Colour Interval Maps

The same information should be included on colour interval maps as for contour maps. The colour scheme to be used is usually a matter of personal choice. However the most common colour scheme that is presently utilized conforms to the spectrum of white light with red at the high positive end. Thirty-nine colour intervals are normal. The selection of colour intervals is usually made after compilation to maximize the information presented, for example, by using an equal colour area algorithm. In any case the minimum interval should be approximately twice the required sensitivity, and should be positioned to provide maximum detail. For gradiometry, the minimum interval should correspond to the zero level at the central (yellow) portion of the spectrum. This results in positive values being in the warm colour range and negative values in the cool range. With this system geological contacts at high magnetic latitudes are delineated by the central yellow zone.

9. PRODUCTS, FORMATS AND REPORTS

Map Products

There are a number of ways in which data can be presented. Each of these can have limitless variations in terms of scales, parameters, colour schemes, etc. The final decision on the details of presentation should often be made after the data is examined, but the major products should be identified beforehand. In this section the more common presentations, namely contour maps, colour interval maps and stacked profiles will be discussed. Procedures such as shaded relief can now be routinely run on gridded data but are normally considered to be enhancements rather than fundamental survey products.

9.1 Contour Maps

9.1.1 General

Contour maps are usually presented using different colours for contours, flight lines and base map information with the most distinctive information being for magnetic information and base map information subdued.

9.1.2 General Program Features

The contour program should be capable of 'feathering' data, that is dropping contours where the density is too great for legibility. Contour values should be clearly numbered on selected contours and with adequate frequency so that the value of any contour can be easily determined. Different contour weights such as dotted, dashed, normal, thick and ultra-thick lines should be used for the basic contour interval and selected multiples (e.g. 10, 50, 500, 1000, 5000) thereof to facilitate easy identification. Lows should be clearly marked so that it is easy to distinguish lows from highs. Examples of GSC format total field and vertical gradient contour maps are included as Figs. 10a and 10b as a guide. The contractor should present examples of previous contour work on the same type of survey to ensure that he has the required capability.

9.1.3 Scales

The basic map scale should correspond to approximately one to two cm between flight lines on the map. Even scales such as 5000, 10000, 25000, 50000, 100000, 250000 should be used.

9.1.4 Base Maps

Choice of base maps can vary depending on what is available. In Canada, controlled aerial photography as well as accurate topographical maps are available for most of the country. For detailed work, mosaics constructed from controlled aerial photographs are often preferred as base maps, however, the user should make his choice based on examples of existing maps and source material available. In some areas of the world the best base maps are now available from satellite data.

9.1.5 Composite Maps

Composite maps at a smaller scale (often 1:250,000) can be produced either by replotting or by photographic reduction. The advantage of the latter technique is that more detail can be presented. The disadvantage is that contour notation cannot be easily read. Normally the flight lines are omitted from composite maps in order not to obscure the magnetic patterns.

9.2 Colour Interval Maps

Several choices for selecting intervals are available - expanding scales as used by the GSC and most other users or equal area intervals. The latter can often display more data efficiently but will not give uniform scales from map sheet to map sheet. As stated in Chapter 9, the choice of colours and colour intervals to give the optimum display is data dependent and is also very subjective. Many users prefer gray scales to multi-colour maps. Contour lines can also be plotted on the map, but may detract from the readability of the basemap information.

9.3 Profile Maps

Profile maps can be used to allow fine detail to be effectively presented in a map format. The normal technique is to plot the flight path at the desired scale and then plot the required data field as an offset, perpendicular to the mean direction of the flight line. This sometimes necessitates the subtraction of an appropriate constant or regional and the selection of an appropriate data scale to prevent overlap for maximum readability. Band-pass filtering and colouring of highs and or lows at the amplitude of interest can also aid in tracing fine detail across flight lines. This technique is particularly effective for checking data, even when not required as a final product, as errors are readily apparent.

9.4 Digital Data

Digital profile data should be delivered in ASCII code and should include time, corrected latitude and longitude, corrected raw magnetic values final compensated magnetic values, raw gradient, levelled-gradient, radar altimeter, barometric altimeter, and ground station(s).

Each line of data should be preceded by a header containing flight number, date, line no., part, direction code, line or control line code, starting and ending time and number of points.

Gridded data should correspond to the fundamental map scale. The grid origin should be an integral grid multiple for the projection origin (e.g. Lat 0° and Long of central meridian for UTM). Different grids with overlap will be required for surveys that extend significantly into different UTM zones. (However, it is normal to extend one zone if the area is small, or extends only a small distance into the second zone). Each grid should be preceded by a header containing the projection and standard latitudes and longitudes, latitude and longitude and northing and easting of the origin and grid corners, grid interval and angle of rotation of the grid with respect to the projection.

The levelling network should include compensation to line and tie-line, X and Y movements, line and tie-line altitude, time (or fiducial on line and tie-line, latitude and longitude and northing and easting.

9.5 Reports

- Contractor - project manager
  subcontractors
- area with diagram
- period of Survey
- base of operations
- flight specifications
- instrumentation, make and models
- navigation system(s) - accuracy obtained
- aircraft
- full discussion of compilation process, including filtering, levelling, flight path processing.
- flight logs
- tape labels and contents (e.g. line nos., grids) with appropriate index

9.6 Formats

Formats for delivered digital data should be similar to that required by the GSC for contract surveys (example enclosed in appendix A). Formats will have to be adjusted to correspond to the parameters of the particular survey (ie VLF channels may be replaced by additional flight path channels on line archive). If format is not similar to that required by the GSC, documentation should be provided, together with source code to enable the user to read the tape.

9.7 Additional Processing Products

Although the purpose of this document is to describe the basic products of aeromagnetic surveys, an overview of the many processing options that are available will underline the importance of obtaining a high quality digital data set, and thus the need for having and adhering to high standards of positioning, noise levels, diurnal control, levelling and gridding in order that the maximum benefit may be obtained. Many of these, such as artificial draping of constant elevation surveys have been alluded to elsewhere in the text. No description of advanced processes can hope to be complete, thus here we will mention only the more common techniques.

9.7.1 Shaded Relief

This is a process in which an artificial light source can be positioned to produce a shading effect on the magnetic surface, treated as topography. The technique can be useful for delineating detail that is not readily apparent on the normal contour or colour interval maps. The direction of shading can be varied to enhance or suppress features with a particular strike direction. It is also a powerful tool for detecting errors in levelling when the light source is placed in a direction perpendicular to the flight lines.

9.7.2 Continuation

Upward continuation applied to gridded data can be used to suppress high frequency anomalies due to near surface features, thus emphasizing deeper sources and as such is a form of filtering that does not alter the basic relationship between the sources and the field other than the separation. Downward continuation has the opposite effect. Although these processes are usually applied to constant elevation gridded data, techniques do exist for variable downward continuation as in 'draping' or continuation between surfaces which are not necessarily planes. The user should request to see examples of these procedures applied to the type of survey which is being planned if they are to be included as a product. For example the decision on whether to fly a well controlled constant elevation survey or a more expensive draped survey in rugged terrain could depend on whether the data can be adequately post-processed to bring out the high frequency detail. It should be remembered however that all such processes require some assumptions such as known magnetization direction, and are subject to errors due to position, levelling and gridding.

Vertical Gradients

A calculated first or second derivative map can be very useful for emphasizing near surface features and particularly for outlining contacts and are standard products for many surveys. The last statement of the previous paragraph applies here as well.

10. CONTRACTUAL CONSIDERATIONS

Evaluation of the Contractor

Often the main criterion for selecting an airborne geophysical contractor appears to be the price offered to perform the survey. This should be only one factor. A contractor, familiar to the contracting body may be selected, without competitive bids, provided that the persons making the decision are knowledgeable and recognize that the price offered is one from which the contractor can make a reasonable profit.

Government agencies and large companies usually require competitive bids. When this is the case the contracting body should establish all the parameters of the survey and send these to the contractors asking for a technical proposal in addition to a cost proposal. Experience, ability to meet the deadlines and adherence to contract specifications on previous contracts should weigh the highest in the selection of the contract, provided that the contracting company has not changed ownership or had several personnel and equipment changes. References and past experience should be checked thoroughly. A visit to the contractors premises should be made and the key personnel mentioned in the proposal should be met. Sample maps and representative data profiles should be viewed to ascertain that the contractor can deliver the maps required and acquire the data within specifications. If possible, a visit to a flight crew could be made. If after all this and the prices are close the contractor can be selected on the basis of comfort level and general industry acceptance. **Do not select a contractor simply on price.** This is not healthy for the industry and if the contractor can make a profit it is in his best interest to improve his instrumentation or perform R&D. If the contractor does not make a profit, the industry will stagnate.

Once a contractor has been selected a contract should be prepared with the following considerations included. This is not intended to be complete and it is recommended that a lawyer review the contract.

10.1 Technical Specifications and Survey Parameters

All technical specifications, survey parameters, area to be flown and anything else mentioned in the technical proposal, including final products should be specified in the contract. This can be included as an appendix to the contract.

10.2 Period of the Contract

After discussion with the contractor a start up time and delivery date of final products should be established. This should be a realistic time frame considering the geographical location of the survey, time of year and the length of time to compile all the data and produce the required maps.

10.3 Survey Kilometres

An approximate total number of line kilometre including control lines should be established and written into the contract. The contractor will be paid for line kilometres flown and accepted. Payment for more than the estimated number of line kilometre stated must be approved in writing by both parties prior to the execution of the additional kilometres and at a mutually agreed price.

10.4 Payment Fees

It is recommended that the price be broken down into a mobilization/demobilization flat fee plus an all inclusive rate per line kilometre.

10.5 Method of Payment

The following is recommended. In actual cases financing may be determined by policy of the contracting organizations.

(i) Fifty percent of the mobilization/demobilization fee when the aircraft reaches the base of operations and has demonstrated operability by successfully flying a pre-determined number of line km.

(ii) Depending on the size of the contract interim payments will be made at certain points in the contract (usually completion of blocks). These interim payments can be made on the basis of 60% of the per line kilometre rate multiplied by the number of kilometres flown.

(iii) At the completion of the flying portion 60% of the per line kilometre rate multiplied by the total line kilometres should have been paid in addition to 50% of the mobilization/demobilization fee.

(iv) Following delivery and acceptance of preliminary maps and reports 30% of the all inclusive rate multiplied by the number of acceptable line kilometres flown will be paid.

(v) Following delivery and acceptance of the final products the remaining 10% of the firm all inclusive rate multiplied by the number of acceptable line kilometres will be paid.

(vi) All payments should be made within thirty days of receipt of the invoice.

Note: This method of payment is recommended so that the contractor does not have to finance the purchase of large amounts of fuel and support costs for a long period of time. If the contractor has to wait until the delivery of final products to be paid for the majority of the contract then finance charges may be reflected in the price of the contract.

10.6 Pilots Discretion

The flying is to be carried out in the best interests of the survey but the decision of the pilot not to fly specific flight lines or parts therefore for reasons of safety should be conclusive and binding and the line kilometres not flown as a result of such decision shall be deducted from the kilometres to be flown as set out in the contract.

10.7 Force Majeure

The contractor will not be responsible for delays or non-performance in the execution of the survey and the delivery of the results which are occasioned, in whole or in part, by force majeure including without limitation, labour and civil disobedience acts of God, or any other cause which is beyond the contractor's reasonable control.

10.8 Confidentiality

All reports, maps and information obtained and furnished by the contractor shall be for the exclusive use of the contracting body. The contractor shall keep confidential all information, reports, maps, and anything else pertinent to the survey including the survey area.

10.9 Assignment

Neither party will have the right to assign all or part of their obligation without the written consent of the other party.

10.10 Insurance

Proof of insurance showing public and personal liability should be included. If the insurance is not adequate it should be increased.

10.11 Government Requirements

The contractor should adhere to workmans compensation rules, by-laws, rules, regulations orders and statutes of governmental authorities whether federal, provincial or municipal or otherwise, relating to the survey.

10.12 Termination

If the contract is terminated for reasons such as (i) breach of any terms of the agreement (ii) bankruptcy, or for any other reason the contractor will be paid for any and all work completed and accepted to the date of termination.

10.13 Arbitration

If any dispute arises, technical or otherwise which cannot be resolved by the two parties, then the dispute will be settled by arbitration. Three arbitrators are recommended, one appointed from each party and the third selected by the two arbitrators thus appointed. The decision of the arbitrators should be final and binding. The powers and duties of this tribunal should be conducted in accordance with an appropriate governmental arbitrations act.

10.14 Jurisdiction

A statement should be included stating what legal jurisdiction by which the agreement is governed.

SELECTED REFERENCES

The following references have been selected because of their review nature. Numerous further references are contained in the bibliographies of these papers for the reader who requires further information.

1. **Bullock, S.J.; Barritt, S.D.**
1989: Real-time navigation and flight path recovery of aerial geophysical surveys: A review in Proceedings of Exploration '87: Third Decennial International Conference on Geophysical and Geochemical Exploration for Minerals and Groundwater, edited by G.D. Garland, Ontario Geological Survey, Special Volume 3, pp. 153-169.

2. **Hogg, R.L.S.**
1989: Recent advances in high sensitivity and high resolution aeromagnetics in Proceedings of Exploration '87: Third Decennial International Conference on Geophysical and Geochemical Exploration for Minerals and Groundwater, edited by G.D. Garland, Ontario Geological Survey, Special Volume 3, pp. 153-169.

3. **Hood, P.J.**
1965: Gradient measurements in aeromagnetic surveying; Geophysics, v. 30, p. 891-902.

4. 1967: Magnetic surveying instrumentation - A review of recent advances; Mining and Groundwater Geophysics, Dept. of Energy, Mines and Resources, Ottawa, Canada.

5. **Hood, P.J.; Holroyd, M.T.; McGrath, P.H.**
1979: Magnetic methods applied to base metal exploration; pp. 77-104 in Geophysics and Geochemistry in the Search for Metallic Ores, edited by P.J. Hood, Geological Survey of Canada, Economic Geology Report 31.

6. **Paterson, N.R; Reeves, C.V.**
1985: Applications of gravity and magnetic surveys: The state-of-the-art in 1985; Geophysics, v. 50, pp. 2258-2594.

7. **Reford, M.S.**
1980: Magnetic method; Geophysics, v. 45, pp. 1640-1658.

APPENDIX A

The following document contains typical specifications for a detailed gradiometry survey with VLF. Essentially the same format would be used for regional surveys with appropriate changes to the specifications and delivery items as discussed in the text. All parameters are, of course, subject to modifications for a particular survey depending on fields measured and relative importance.

APPENDIX A

TECHNICAL SPECIFICATIONS

HIGH SENSITIVITY (GRADIOMETER) SURVEY

1. GENERAL REQUIREMENTS

The principal method of recording and compiling the aeromagnetic survey data including that of the necessary ancillary equipment will be by digital techniques. A copy of the Technical Specifications must be readily available to or in the possession of each of the pertinent Contractors personnel who have a responsibility in the execution of the contract. The Contractor must obtain and have available in the field and office all relevant charts, maps, etc. pertaining to navigation.

2. AIRBORNE AND GROUND INSTRUMENTATION

The instrument operator shall maintain and update an equipment log book noting all equipment replacement and repairs throughout the survey and the results of calibration tests carried out on the equipment. This will be checked by the Technical Inspector during the inspection visit.

2.1 Airborne Magnetometers

The magnetic sensors utilized will either be self-orienting or be otherwise independent of orientation effects with regard to the ambient direction of the earth's total magnetic field. The magnetic sensors and processors used must be essentially identical.

The vertical gradiometer system will consist of a twin, fixed, rigidly mounted boom or towed bird system containing identical magnetometers separated by a maximum vertical distance of three (3) metres. All structural members and electrical components of the systems must be non-magnetic and not produce a measurable magnetic field at the sensors.

The recording of the magnetic field values shall be essentially without filtering except that imposed by the sampling interval itself. The vertical gradient of the total magnetic field will be measured directly in flight. Noise levels will be determined by fourth difference calculations on unfiltered data, in straight and level flight at 150 m altitude. Under turbulent survey conditions, a higher noise level will be permitted. However in instances of noise levels beyond those specified, flights will have to be terminated or that portion of the survey line re-flown between control lines.

The following define what is minimally acceptable.

	Total Field	Vertical Gradients
Sensitivity	0.01 nT	0.005 nT/M
Absolute accuracy	±10 nT	
Noise envelope	0.10 nT	0.025 nT/m
Noise envelope in turbulence	0.15 nT	
Ambient range	20,000 to 100,000 nT	±100 nT/m
Sampling interval	25 m	25 m

N.B. - The following section included if VLF to be recorded.

2.2 Airborne VLF EM

A two frequency VLF EM receiver, similar to a Herz Totem 2A, will be used to record the VLF transmissions from both a line and an ortho transmitter.*

*(The terms line and ortho refer respectively to the orientation of the flight lines with respect to the transmitted field of the remote VLF transmitter. The "line" transmitter will be that for which the magnetic field (H) is approximately parallel to the line direction i.e. perpendicular to the dominant geological strike.)

Line transmitter: NSS Annapolis, MD 21.4 KHz
Ortho transmitter: NAA Cutler, Maine 17.8 KHz

**It is required that 100% VLF data acquisition be obtained for the line transmitter so that on the maintenance day, no survey flying should be attempted. In the case of the ortho transmitter, the recording of the VLF data will be accepted on a best effort basis so that survey flying will be permitted when the ortho transmitter is not operating. Reflights will be required if non-acquisition of the line VLF data is due to a malfunction of the VLF receiver and/or associated equipment in the survey aircraft.

2.3 Altimeters

A highly reliable radar/radio altimeter and barometric altimeter will form part of the ancillary equipment for the survey aircraft.

Radar altimeter:
Minimum range: 0 - 2500 feet
Accuracy 5%

2.4 Electronic navigation

The use of an electronic navigation system will be required for the accurate navigation of the survey aircraft and the subsequent flight path recovery. GPS, INS, Syledis Mini-Ranger or any other system proven to the satisfaction of the client representative will be acceptable. Doppler is inadequate as a sole system where there are survey lines over more than 3 km of water. The positional outputs must be digitally recorded to a resolution of 25 m.

2.5 Flight Path Camera

A vertically-mounted 35 mm or 16 mm continuous strip film, interval or video camera must be used for flight path recovery purposes. For the interval camera there must be a minimum of 10% overlap between consecutive frames. The combined navigation system (electronic and photographic) must be capable of providing the required accuracy over the entire survey area to the satisfaction of the Scientific Authority.

2.6 Ground Monitoring Station

A digitally-recording total field magnetometer and VLF EM (if applicable) ground station shall be operated continuously throughout the survey operation. It shall be set up at the base of operations, at a magnetic 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. For each new installation of the ground magnetometer, the Contractor shall make simultaneous records with the airborne and ground station magnetometers while the aircraft is motionless on the ground and in the vicinity of the ground station. These records must be annotated for comparison and submitted to the client representative.

**This will depend on importance placed on VLF data by the client.

A quartz crystal clock mechanism shall be used to record the time of the ground magnetometer readings. It will be synchronized with a similar clock on board the aircraft. The ground monitoring magnetometer shall be approved by the Scientific Authority.

	Ground Magnetometer
Sensitivity	0.25 nT
Recording interval	1 second

N.B. - direct subtraction of ground magnetometer values from the airborne record is not permissible.

2.7 Field Data Verification System

The digital data tapes must be verified in the field to prevent unnecessary reflights if faulty recording has taken place. Continued in-flight verification by employing a read-after-write system plus a ground based verification system are required.

The ground based verification system should consist of a programmable microcomputer and printer, plotter or video display system. It must be capable of plotting the recorded values back at scales suitable for detecting any problems, to ensure all data are within specifications.

3. SURVEY SPECIFICATIONS

3.1 Flying

3.1.1 **Height:** 150 m ±15 m mean terrain clearance

Some deviation from this specification will be permitted in areas of particularly steep topography for safety reasons.

3.1.2 **Traverse lines:** N65W at a spacing of 300 m

All traverse lines must extend at least one and a half (1.5) km beyond the survey boundaries at survey altitude. Two (2) traverse lines must be flown outside of the survey area to provide valid contour information beyond the map boundaries. (See Index Map Appendix "B".)

A special effort must be made to ensure that all adjacent traverses are flown at a comparable speed and mean terrain clearance regardless of the direction of flight.

3.1.3 **Tolerances (traverse lines):** 525 m is maximum separation
75 m is minimum separation

Gaps in coverage must be no greater than 450 m over a distance of 5 km. Parts of lines reflown to complete a flight line must cross control lines at either end and cross the original survey line at a low angle at a point where the data is acceptable.

NOTE: No gaps will be accepted on the final maps.

3.1.4 **Control lines:** N25E at a spacing of 3 km

Control lines should be positioned to avoid, as much as possible, possible zones of steep magnetic gradient, rugged topography and 1:20 000 map boundaries. A special effort must be made to ensure that all control lines are flown at the same mean terrain clearance as the traverse lines, particularly at the point where the two cross. These flights must be carried out during optimum diurnal conditions.

3.1.5 **Diurnal Variation:** 2 nT deviation from a long chord equivalent to the average tie line spacing.

must also be performed in the survey area by flying over a known point in orthogonal directions to determine any lag in the digitally recorded navigational data.

3.2.4 Radar altimeter:

Calibration records taken monthly must be submitted for the radar altimeter, as determined from flights at altitudes of 250', 500' and 750' above the base air strip. The radar altimeter will be used to maintain the required Mean Terrain Clearance.

3.2.5 Electronic navigation:

A calibration check on the accuracy of the electronic navigation system must be carried out prior to the commencement of survey operations.

3.2.6 Daily calibration:

All recording and time synchronization systems will be calibrated daily during each flight. The data recorded during these calibrations are considered to be part of the raw data to be properly labelled and given to the client representative at the end of the survey. The altimeter recorder pen will be set up daily, prior to production, by flying at 150 m above the airstrip.

The Contractor will fly a defined gradiometer test line as designated in Appendix "B". This test line will be flown at survey altitude at least once during each survey flight showing all survey parameters to ensure the repeatability and quality of the data acquisition system. These results will be evaluated by the field project manager and submitted in analog form to the client representative with the monthly progress report.

3.3 Data Records

3.3.1 Digital:

Isolated errors or spikes and short non-sequential gaps consisting of a few points which can be corrected by interpolation are acceptable up to a maximum of 1% for any given flight line but no adjacent flight lines on any map sheet will be allowed missing digital data. The gaps corrected or replaced will be identified.

3.3.1.1 Dynamic range

Each gate of the data record which contains one variable being recorded must have sufficient digits to cover the dynamic range of the variable. Free choice of recording scale and datum is allowed provided that:

(i) this does not conflict with any stated specifications;
(ii) no change of scale or datum occurs in any variable unless the change is immediately preceded by a header record containing the new scale and/or datum.

The only exception to the above provision are those data (i.e. time) which are always positively increasing quantities. For those data, a "cycling" gate is allowable. In this case the number of digits within the gate must be sufficient to cover the range of variations over at least ten (10) physical records but need not be greater.

If in the case of time data, a gate is used which contains insufficient digits to cover a range of 24 hours to a 1 second accuracy, then every discontinuity in

This specification can be adjusted at the discretion of the Technical Inspector. The Contractor will re-fly lines or portions of lines flown during periods of greater diurnal activity. These reflights will begin and end by crossing control lines.

3.2 Calibration Flights

3.2.1 Magnetometer:

Calibration of the aircraft magnetometer system must be carried out using the calibration range at Bourget *established by the Geological Survey of Canada in the Ottawa area at the start and end of survey operations. The Technical Inspector must be notified of the scheduling of these test flights prior to their execution. This calibration will include a measurement of the heading error. Two (2) passes in each of the north, south, east and west directions must be flown in order to obtain sufficient statistical data to complete the form in Appendix C3.

NOTE: The north-south test line at Bourget has been extended to include a gradient anomaly. These limits are available from the Technical Inspector on request. The results of these tests must be presented in the analog format which is to be used during survey production and the digital format that is to be used for the archive tapes. The same decimal accuracy is required and all these test data are to be submitted to the client representative. The results must be approved by the Technical Inspector before the Contractor proceeds to the survey area.

Ground station total field values covering the duration of these calibration flights, must be obtained from the Ottawa Magnetic Observatory, Geophysics Division, Geological Survey of Canada. The procedure for obtaining these total field values using a data terminal with a modem is described in Appendix C. It should be noted that the printout will consist of the previous 110 one-minute values, so the printout must be obtained immediately upon termination of the calibration flight. Calibration checks of the magnetometers will also be carried out by the Technical Inspector during survey operations.

3.2.2 Compensation test:

FOM less than 1.0 nT on each sensor
FOM less than 1.5 nT on difference of sensors

The Contractor will be required to determine the effects of aircraft roll, pitch and yaw and to submit the results of these tests to the Technical Inspector. These tests will be performed over a magnetically quiet zone, at a high altitude. They consist of flying $\pm 10°$ rolls, $\pm 5°$ pitches and $\pm 5°$ yaws peak to peak along North, South, East and West headings over periods of 4-5 seconds. A compensation Figure-of-Merit (FOM) for the aircraft will be calculated by the Contractor, by summing up the peak to peak amplitudes of the 12 magnetic signatures.

The FOM will be determined in the survey areas before commencement of production and twice per month during the flying operation. The results will be included in the monthly progress reports. A FOM in excess of that specified will require approval of the client representative, or corrective action before survey operations can continue.

3.2.3 Lag tests:

Prior to the commencement of survey production and when any major survey equipment alteration or replacement is carried out on the aircraft or the survey system, the Contractor will be required to perform lag tests to ascertain the time difference between the magnetometer and VLF EM (if applicable) readings and the operation of the positioning devices. The results of these test flights, which should be flown in two (2) directions at 150 m MTC across a distinct anomaly, must be submitted to the Technical Inspector along with the next monthly report. Lag tests

*A calibration range has also been established at Meanook, Alberta in 1990.

recording must be preceded by a header record containing the full 24 hr-min-sec time (GMT or local) of the instant at which recording commenced.

3.3.1.2 Airborne

Header records

Information such as aircraft registration, date, line number, line segment number, direction, flight number, start time of line and any relevant scale factors or datum levels should be included in a header which precedes the relevant data. Such pertinent information should also be included on the analog records and on the flight log to be maintained by the Instrument Operator.

Recording specifications

Airborne (Digital)	Minimum Interval or Sensitivity	Sampling Interval
1. Magnetic total field upper sensor	0.01 nT	25 metres
2. Magnetic total field lower sensor	0.01 nT	25 metres
3. Vertical gradient (lower sensor minus upper sensor)	0.005 nT/ metre	25 metres
4. VLF EM line total field	At least 1% measuring range	50 metres
5. VLF EM line quadrature		50 metres
6. VLF EM ortho total field		50 metres
7. VLF EM ortho quadrature		50 metres
8. Radar altitude	10 feet	25 metres
9. Pressure altitude	20 feet	25 metres
10. Time and fiducials	½ sec.	25 metres
11. Navigation Output	25 metres	50 metres

3.3.1.3 Ground

Recording specifications

Ground (Digital)	Minimum Interval or Sensitivity	Sampling Interval
1. Total Field	0.25 nT	1 sec
2. Time	1 sec	1 sec

3.3.1.4 Digital tape log

A digital tape log book must be maintained in the field to record the following information:

(i) external tape label code;
(ii) tape content (start and finish date/time of recording and flight numbers);
(iii) dates of verification and copying;
(iv) results of verification (i.e. any read errors, or re-reads required);
(v) date original tapes shipped to compilation laboratory. Action taken if lost or damaged in transit.

3.3.2 Charts:

All analog charts must be easily reproducible by photographic means and have rectilinear coordinates. Chart records will show fiducial marks synchronized with the flight path camera. Charts can be created either in real time with the airborne recording system or post-flight with the ground based verification system.

3.3.2.1 Airborne chart specifications:

Chart speed will be approximately 3 cm per 1 km of ground distance, equivalent to 15 cm/min. at an average 300 km/hour air speed. The following display format should be utilized for the chart starting from the top edge as normally viewed.

0 – 10 cm	Total field, upper sensor 2.0 nT/cm Total field, lower sensor 2.0 nT/cm (Offset of 1 cm between the 2 traces)
10 – 16 cm	Total field, upper sensor 50 nT/cm Total field, lower sensor 50 nT/cm (Offset of 1 cm between the 2 traces)
0 – 4 cm	VLF total field line
4 – 8 cm	VLF quadrature line
8 – 12 cm	VLF total field ortho
12 – 16 cm	VLF quadrature ortho
16 – 21 cm	Vertical gradient 0.1 nT/m/cm (Lower sensor minus upper sensor)
21 – 23 cm	Fourth difference of upper sensor 0.1 nT/cm (4th difference ÷ 16)
23 – 25 cm	Fourth difference of lower sensor 0.1 nT/cm (4th difference ÷ 16)
25 – 26 cm	Fourth difference of vertical gradient 0.1 nT/m/cm (4th difference ÷ 16)
26 – 28 cm	Radar altimeter 75 m/cm
28 – 30 cm	Barometric altimeter 30 m/cm

The above format will necessitate an analog recorder having a chart paper width of 30 cm such as the type manufactured by RMS Instruments Ltd. of Mississauga, Ontario.

NOTE: The primary reason for chart output is to evaluate operation of survey equipment during or immediately following flight. All chart trace values must be visually accessible per line. Some flexibility to change vertical scales in the field should be made available, as magnetic activity demands. All data must be visually examined, annotated and evaluated by qualified personnel before data leaves the job site.

3.3.2.2 Ground chart specifications:

An analog chart recorder will be operated continuously throughout the survey period.

Chart speed (during production)	50 cm/hour
Chart speed (during nonproduction)	5 cm/hour
Time: accuracy	1 second
notations	1 per 10 seconds
Magnetic total field	2 nT/cm

The sensitivity used to record the VLF EM data will be determined in consultation with the Scientific Authority. It shall be appropriate for displaying diurnal changes as well as interruptions in the transmitted field.

4. COMPILATION OF THE SURVEY DATA

Compilation Scale: 1:20,000

4.1 Flight Path

4.1.1 Base Maps

The Contractor will acquire the necessary aerial photographs, navigational charts and maps at his/her own expense.

4.1.2 Data Recovery*

Fiducial points from the positioning film must be recovered on stable copies of the mosaics, at intervals of not more than three kilometres, where possible.
Electronic positioning data must be utilized to position the flight lines over water or large areas, where visual navigation is impossible.

Where landfall has been crossed, the positions should be recovered from the film and compared to the electronic position data and the film positions over a wide area. A correction should then be incorporated into the electronic position data program to obtain more geodetically accurate positions. The electronic position data must be corrected for constant shift or drift by using the film recovered points. The coordinates of the fiducial points will then be digitized and a computer plot of the flight lines will be made to coincide with the manual plot as a checking procedure.

A speed check must be included in the verification of the flight path data; essentially, the average speed of the survey aircraft between fiducials must be calculated. The speed check results must be listed on a printout in a clearly intelligible manner to

*These specifications assume that film recovery is the best system for absolute positioning. More commonly differential GPS or range-range in which the station location are accurately located are now considered to be more accurate.

allow inspection by the Technical Inspector. The action taken to correct apparently erroneously recovered points must be noted next to the point on the speed checking listing . The speed check criteria must be accurately determined and not exceed 10%.

4.1.3 Format

Each traverse/control line must have a unique line number with the segment number incorporated as the last digit of the line number. Partial lines must be truncated at the limiting interior control lines.

4.1.4 Plotting flight path

The traverse lines and control lines together with their respective fiducial numbers and identification must be plotted on stable base material separate from the contour information. Different plotting symbols must be utilized to distinguish ground control points from evenly interpolated points along the plotted flight line. These interpolated symbols must be plotted at intervals of approximately 1 kilometre and every second symbol labelled. A sample should be submitted to Technical Inspector for approval. The first and last fiducial of each traverse line must be labelled.

Line weights and labelling of fiducials will be discussed with the Contractor at a later date but will be similar to that utilized in the sample maps. The fiducial numbers will be labelled in parallel with the traverse lines and control lines. Traverse line numbers and control line numbers will be positioned inside the west and south boundaries of each map. Final labelling of flight line data must have a unique line number for each segment presented on the flight line map as well as in the corresponding digital archive data.

4.2 Aeromagnetic Data

As the digital data is considered to be the prime product, the Technical Inspector may request a copy of portions of the survey data. This should be provided in the standard archive tape format. Positional data should be in latitudes and longitudes, but for preliminary data it may be in UTM northings and eastings. The Contractor must establish a system for providing such data expeditiously when requested.

A 'noise' filter may be used to remove non-geological random noise from the recorded signal. Such a filter must be symmetrical and must have no effect on wavelengths greater than 0.7 of the flight elevation. Note that the recorded data should be interpolated to a fixed interval roughly equal to the distance covered in one sampling interval before filtering.

4.2.1 Profile Maps

*4.2.1.1 Vertical gradient

Profile maps must be prepared for checking purposes at a scale of 1:20 000. These maps will show the measured gradient and a calculated vertical gradient for both the sensors. The vertical scales of these traces will be selected in consultation with the Technical Inspector.

NOTE: The purpose of these plots is to check the validity and quality of the measured gradiometer data before proceeding with costly processing and presentation.

*These are used by GSC for checking purposes.

4.2.1.2 VLF EM

The VLF EM data will be presented as profiles along the flight lines and printed in black at the scale of 1:20 000. The line and ortho signatures must be presented inphase.

4.2.2 Levelling

4.2.2.1 Total Field

Film intersections should be determined for all traverse sand control lines where levelling difficulties warrant this. If no film intersection is obtainable for any control line/traverse line pair, the apparent flight path intersection on the flight path base map supported by the electronic navigation data will be used. A log will be kept for inspection by the Technical Inspector listing those lines for which no film intersection could be found. After an intersection has been found and marked on the film or base map, the position may be read as a fiducial and percentage thereof.

Intersection fiducials will be transcribed to an appropriate digital form and a computer program used to extract the two total field values for each of the intersection points from the digital aeromagnetic data tapes. The differences at the intersection points will be tabulated by a printed output from the computer program in a readily comprehensible form. At intersections which are impossible to determine, some movement of the intersection will be allowed if this will result in a smoother distribution of the differences.

Movement of the intersection should not exceed 25 metres.

Differences at intersections must be carefully analyzed and distributed proportionally along the control lines and the traverse lines to yield an identical final total field value for both lines at the given intersection.

The total adjustment must not exceed one (1) nT per kilometre.

Final values will then be assigned to the traverse profiles at the appropriate intersections and used as corrections to the digitally-recorded values along the traverse lines. In areas of steep magnetic gradient and/or of rugged topographic relief, the intersection adjustments may be deleted or an appropriate adjustment assigned to the traverse line.

NOTE: The Contractor may employ a manual, computer or combined method for determining the levelling adjustments. Whatever method is used, the Contractor is required to provide a detailed description of the methodology applied to the Scientific Authority. Diurnal variation effects will be removed as part of the levelling procedure; direct diurnal subtraction using the ground monitoring station data, will not be permitted.

In order to standardize the levelling analysis procedure, the following information must be presented as shown:

STEP 1: Traverse Line Minus Control Line Printout

CL No.	TL No.	FLT No. CL	FLT No. TL	CL FID	TL FID	LONG X	LAT Y	RAD ALT CL	RAD ALT TL	RAW MAG CL	GRADIENT INDICATOR CL	RAW MAG TL	GRADIENT INDICATOR CL	TL–CL

STEP 2: Final Levelling Analysis Printout

CL No.	TL No.	LONG X	LAT Y	POSITION SHIFT ON CL	POSITION SHIFT ON TL	TL–CL	CL LEVEL ADJ.	TL LEVEL ADJ.	LEVEL DIFF.	LEVEL DIFF. NT/KM

A graphical plot of the final total field and/or vertical gradient level adjustments along the traverse lines, may be requested. The Technical Inspector may require this as an aid to levelling analysis.

4.2.2.2 Vertical gradient

Ideally no level correction should be required for the vertical gradient, however it may be necessary to apply a constant or linear correction to individual lines. If the data cannot be satisfactorily levelled in this manner, suitable filtering can be used, provided that it has no effect on anomalies in the range of interest. The filtering procedures to be used must be approved by the Scientific Authority and demonstrated to produce satisfactory results.

4.2.3 Gridding

Map Scale	Grid Size
1:20 000	= 50 (ground metres)

A computer program will be employed to interpolate a square-celled data grid from the final levelled traverse data. Isogam contour maps will be produced from this grid by a computer contouring program. However, the contours may be digitally or manually altered where complex magnetic patterns and/or angular anomaly trends incorrectly influence the contouring algorithm.

NOTE: Where changes to the contour trends have been made, the gridded data must agree with the contours on the final map. If the survey area is gridded in more than one grid, the grids must have a common origin to enable grid merging without regridding.

4.2.4 Contouring

4.2.4.1 Total field

The contour interval for total field will be 2 nT or as the gradient dictates. Absolute total field magnetic values will appear on these maps (not relative values above some arbitrary datum). Contour intervals 2, 10, 50 and 250 nT will be shown using different line weights in consultation with the Technical Inspector. Magnetic depressions will be indicated by "tick-marks" placed around the inside of the contours expressing the locally low areas in total field magnetic values. Magnetic highs will not require any special identification. The line weights and contour labelling for the final contour maps will be similar to the sample supplied. The direction of the contour labelling should face up gradient.

4.2.4.2 Vertical gradient

The vertical gradient contour interval will be 0.025 nT/m or as the gradient dictates. Contour intervals of 0.025, 0.1, 0.5 nT/m will be shown using different line weights or colour pens. Magnetic depressions will be indicated by "tick-marks" placed around the inside of the contours expressing the locally low areas in the vertical gradient value. The line weights and contour labelling for these maps will be similar to the sample supplied. The direction of the contour labelling should face up gradient.

4.3 Technical inspection of final compilation

The Contractor must submit for approval to the client representative, before preparing for final reproduction, two (2) ozalid copies of each of the following:

(i) all contour maps
(ii) profile data
(iii) flight line and base maps

Each map submitted for approval must be accompanied by all the pertinent analog records, film flight logs, computer listings, levelling information, etc. necessary to verify the compilation. Digital data tapes and a preliminary step-by-step compilation report must also be submitted at this time.

The following are some of the criteria for the acceptance of aeromagnetic and vertical gradient maps:

- flight path will be verified
- contour values and fiducial numbers labelled in a legible manner
- magnetic depressions properly identified
- consistency of line weights within each map and in relation to adjacent maps
- identification of traverses and control lines
- validity of the contours along the traverse lines with respect to position and intensity
- valid interpolation of contours between flight lines
- absence of "herringbone" effect due to levelling or flight line position
- proper density of contours in areas of steep gradient
- traverse lines must tie in between adjoining maps, where applicable
- partial tie–lines truncated at interior boundary

The Contractor may be required to submit at least one map showing final corrected total field magnetic values and vertical gradient values transcribed along the recovered flight lines and control lines at the appropriate contour intervals as an additional check on the validity of the contouring program.

On completion of the inspection by the Technical Inspector one ozalid copy of each map will be returned to the Contractor indicating corrections, if any, to be carried out. When these corrections have been completed by the Contractor, the Technical Inspector will approve the compilation by signature on the accepted copy.

Each manuscript submitted for approval must be properly identified as to survey area, map number and the proper geographic coordinates with the creation date labelled.

5. FINAL PRODUCTS

The open file and printed maps discussed below are typical prducts for government contracts, where distribution to the public is required.

**Open File:	ink plots 2 negatives 2 positives	1:20 000	– Total field contours – Vertical gradiometer contours – VLF EM line and ortho total field and quadrature profile maps

**Colour interval maps	1:50 000	– Magnetic anomaly (residual total field) maps – Vertical gradient maps
**9-track magnetic tape		– Archive of line data – Archive of grid data
**Report		– Technical report by Project Manager

5.1 Open File

After acceptance of the final digital data in the required format and the corresponding compilation at the scale of 1:20 000, ink plots of:

(i) flight path plus total field contours
(ii) flight path plus vertical gradient contours
(iii) profile maps of VLF line and ortho total field and quadrature must be produced. **PRINTING OF THESE MAPS WILL NOT BE REQUIRED.** Two negatives and two positives only are required. The surround information will be similar to the sample Open File total field/gradiometer maps supplied. This series of 1:20 000 maps will be identified by OPEN FILE numbers, not "G" numbers. If previously published total field or vertical gradient data within NTS 20O/16, 20P/13, 21A/4 and 21B/1 is to be presented with the newly acquired information, a stable copy of the total field/vertical gradient contours and traverse lines will be made available to the Contractor at the scale of 1:25 000. VLF EM data is not available.

NOTE: See sample maps for new format for surround information.

5.2 Colour Interval Maps

NOTE: The International Geomagnetic Reference Field 1985.0 must be removed in preparing the colour interval 1:50 000 magnetic anomaly maps (residual total field).

The Contractor must submit a colour proof of one map before proceeding with preparation of colour separation negatives.

A digital colour plotting device, must be used to produce colour separations on stable base materials which will be utilized in printing the final map, and will be similar to the example supplied. A suitable topographic base will be utilized on the map so that magnetic features can be related to recognizable geographic locations. A grid interval equivalent to 50 m at 1:50 000 is required, to reinterpolate to a cell size of 0.2 mm for colour plotting.

The colour scheme for the maps should be similar to the example supplied. Up to 39 colour (contour) intervals should be used. Some experimentation will be necessary to ensure that approximately equal areas of each colour (contour) interval are used in the final products.

If previously published total field or vertical gradiometer data within NTS 20O/16, 20P/13, 21A/4, and 21B/1 is to be presented with the newly acquired information to form a complete map sheet, the necessary digital data will be made available to the Contractor to prepare the colour separations prior to printing.

5.3 Magnetic Archive Tapes

5.3.1 General specifications

The digital data set is the principal end product to be delivered and it must be of the highest possible quality, essentially error-free. All archive tapes submitted should be new and certified.

All archive tapes should be:

- fully IBM compatible
- 2400' or 1200'
- no label, ASCII
- 9 track, formatted
- 800, 1600 or 6250 bpi
- block size of 5040 bytes
- record length of 80 bytes

Only the block header can contain alphanumeric data.

The data should be ordered by survey blocks or areas, including two (2) complete overlapping flight lines from adjacent blocks, with one tape per block. If any block or area requires more than one tape, do not continue the second tape in the middle of a flight line. In consultation with the Technical Inspector, you may separate the control line data by survey area rather than by block. An area sketch map must be provided to define and locate survey blocks.

Each survey block will contain the following files:

(i) Line archive

File No. 1 Block header
File No. 2 Final data for each recorded point as it exists immediately prior to gridding

(ii) Grid archive

File No. 1 Gridded data used to produce the final contour and colour interval maps.
File No. N (1 map per file)

Geographic coordinates in decimal of degrees must be used for all positional coordinates. The Universal Transverse Mercator projection must be used for creating the gridded data. The UTM zone must be the same as that used on the particular topographic maps supplied for the survey area. All longitudes west of Greenwich should be represented as negative degrees.

5.3.2 Detail specifications

5.3.2.1 Line archive

Block header (File No. 1)

Record No. 1: Survey block number, number of sheets, GSC project number, Contractor's project number (Format (A10, I10, 2A10, 40X)) (right justified)

Record No. 2: NTS Map Number
(Format (A10,70X))

Records No. 3 to 4: Contain the latitude and longitude in decimal degrees consecutively, of the four map corners. (Corner 1 is the lower left corner, increasing clockwise.)
(Format (4E20.10))

Record N + 1: End of file.

Records 2 to 4 would be repeated for each map in the survey block on records No. 5 to Nth.

Individual line segments (File No. 2)

A line header is required for each line segment. It must contain:

- flight number
- line number
- segment number
- direction code
- control line code
- start fiducial
- end fiducial

(Format (5I10, 2F10.2, 10X))

Direction Codes 1 = North
2 = East
3 = South
4 = West

Traverse Code = 0
Control Line Code = 1

Data records for each recorded point will contain the following, in the order listed:

Each field of data must be edited and error free.

NAME	CONTENTS	UNITS	FORMAT
TIME	Fiducial	seconds	F10.2
LAT	Latitude coordinate	decimal degrees	F10.5
LONG	Longitude coordinate	decimal degrees	F10.5
MAGRAW	Edited raw total field	nT	F10.2
MAGLEV	Levelled total field (before regional removed)	nT	F10.2
IGRF	IGRF	nT	F10.2
MAGRES	Residual total field	nT	F10.2
DIURNAL	Edited ground magnetics	nT	F10.2
VGRAW	Edited raw vertical gradient	nT/m	F10.4
VGLEV	Levelled vertical gradient	nT/m	F10.4
RALT	Radar altimeter	feet or metres	F10.2
BALT	Barometric altimeter	feet or metres	F10.2
VLFTFLINE	T.F. VLF line	%	F10.3
VLFTFORTHO	T.F. VLF ortho	%	F10.3
VLFQLINE	Quadrature VLF line	%	F10.3
VLFQORTHO	Quadrature VLF ortho	%	F10.3

Record No. 6 to 9: – latitude, longitude, easting, northing of four actual grid corners, with 1 corner per record

(Format (4E20.10))

Data:

The above will be followed by a string of grid values, a column at a time, that is, each column will begin a new record:

e.g. WRITE (,) (GRID (IROW,ICOL), IROW=1, NCROWS)
(Format (8F10.3))

Each map will end with an END OF FILE.

NOTE: All archives must be read by the Contractor and a computer evaluation printout submitted for each archive tape, showing validity of tapes. For each lone archive, the computer printout must show the line header, first 2 records and last 2 records of each line (not considering the zero records between lines). A block diagram showing the survey block layout must be included. A sample listing of at least the first 15 records of each grid archive must be submitted.

5.4 Project Report (5 copies)

A technical report must be prepared by the Project Manager of the Contractor which presents (i) a reasonably comprehensive account of the field operations, (ii) a compilation of the maps and (iii) an inventory of the resultant end products which will be useful to users of the data. The project reports should include the following:

(i) Description of the field operations with statistics including a list of:

- bases of operations with pertinent dates and personnel involved
- description of the survey aircraft and instrumentation used.

(ii) Technical specifications of the survey including a description of the problems encountered during the survey. A discussion of the effectiveness of the survey techniques and instrumentation utilized with suggestions to improve the effectiveness of aeromagnetic gradiometer surveys.

(iii) Lists with index maps of all the end products of the survey. In addition for every type of data tape:

- a detailed documentation of how the tape was written (including actual WRITE statements used in the programs)
- a diagram of the logical structure of the tape
- a list of all constants, datum levels, and conversion factors required for subsequent use of the data on the tape.

A draft copy of the Project Report should be submitted to the Scientific Authority for approval prior to its finalization.

The end of data for each line must be denoted by two (2) zero records in the same format as the data record and followed by an END OF FILE on the last line.

NOTE: Any values not utilized in the gridding process must be set to a unique value by adding a constant of 100,000 to the total field data. For the vertical gradient and the VLF-EM data, a value of 10,000 must be used due to the F10.3 and F10.4 formats on the archives. This will allow data to be recovered by subtracting those constants if these data are required for further processing.

5.3.2.2 Grid archive

The data must be ordered by 1:50 000 map sheets, rotated back to an east-west north-south direction if traverses are flown off 0° or 90° and sorted by columns (south to north). Example: an area with 200 rows and 100 columns. The grid archive would read 200 rows of column 1, then 200 rows of column 2, etc.

For any map sheet the numbers of grid values per row and column must be constant for that map sheet (i.e. a full rectangle of gridded data). This infers the following:

(i) As the UTM projection of a map sheet boundary is not a true rectangle, the grid boundary must be a rectangle which encloses the four map sheet corners.

(ii) If any grid point cannot be given an interpolated value, then a null value (-9999) must be assigned to that grid point.

(iii) To ensure exact matching of contoured maps the grid must extend by at least 5 grid points beyond the smallest rectangle which contains the map sheet corners. If more than one grid is required each grid must have a common origin, to ensure that all grids may be merged back together.

File contents

Each map sheet data grid must occupy a separate file. Each file must have (i) a header, and (ii) the gridded data.

Header:

Record No. 1
- NTS map sheet number
- Geophysical Series map number
- grid spacing in metres
- number of grids in X direction (columns)
- number of grids in Y direction (rows)
- Central Meridian

(Format (2A10, F10.2, 2I10, E20.10, 10X))

Record No. 2 to 5:
- latitude, longitude, easting, northing of four map sheet corners, with 1 corner per record

(Format (4E20.10))

6. OTHER DELIVERIES

6.1 Monthly Reports

These progress reports are mandatory and should be prepared according to the outline in the Request for Proposal, Section 9.5.

6.2 Chart Records

All chart records must be stamped to show the survey area, job numbers, flight line numbers corresponding to those used on the published maps, vertical and horizontal calibrations and/or scales. The data for each flight line will be enclosed in a single labelled envelope except the position film. Where the Contractor uses a film camera the film will be cut and identified with an indelible marker and outside label so that one film roll corresponds to one flight line. Video cassettes will be labelled showing date, flight number, line number, etc.

6.3 Equipment Log Book

As described under "Airborne and Ground Instrumentation".

6.4 Levelling Listings

The final levelling network and final flight path data (compilation listings only) must be submitted. All flight path recovery sheets, levelling data and flight logs must be properly labelled prior to submission for storage.

6.5 Digital Data

Copies of all data tapes and, if used, video flight path tapes (original and final) must be stored by the Contractor for four months after the safe delivery of the same data to the G.S.C. Project Leader. During this time the tapes may not be erased except by explicit written authorization of the Technical Inspector.

After delivery of all final maps, the above raw data will be delivered to the G.S.C. Project Leader in acceptable containers (1 cubic foot) which have labels identifying their contents. The Contractor must prepare a catalogue (as part of the Project Report) for all of these data and will submit it to the G.S.C. Project Leader.