

U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

**RATIONALE AND PRELIMINARY OPERATIONAL PLAN
FOR A HIGH-ALTITUDE MAGNETIC SURVEY
OVER THE UNITED STATES**

by

**Thomas G. Hildenbrand¹, Richard J. Blakely¹, Robert E. Bracken², Lynn Edwards³,
Doug Hardwick⁴, William J. Hinze⁵, Vic Labson², Hal Malliot⁶, Misac Nabighian⁷,
Bruno Nilsson⁷, Jeff Phillips², John M. Quinn², and Walter Roest⁸**

Open-File Report 96-276

(This report is preliminary and has not been reviewed in conformity with U.S. Geological standards. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. government.)

¹U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025

²U.S. Geological Survey, Federal Center, P.O. Box 25046, Denver, Colorado 80225

³Geometrics, 395 Java Drive, Sunnyvale CA

⁴National Research Council, Montreal Road, Ottawa, Ontario K0A2N0 Canada

⁵Purdue University, Dept. of Earth and Atmospheric Sciences, 1397 Civil Engineering Bldg., West Lafayette, IN 47907

⁶Lockheed Martin, ORG 9200, 3251 Hanover Street, Palo Alto, California 94304

⁷Newmont Exploration, 1700 Lincoln Street, Denver, Colorado 80203

⁸Geological Survey of Canada, 1 Observatory Crescent, Ontario U1A0Y3, Canada

CONTENTS

Abstract.....	1
Introduction.....	1
Digital Terrain Elevation Mapping System (DTEMS).....	4
Rationale for the ER-2 Magnetic Survey.....	11
Scientific Rationale for a High-Altitude Aeromagnetic Survey.....	11
High-Altitude Aeromagnetic Data: The Canadian Perspective.....	15
Needed Resources.....	17
Test Flight Results and Mission Flight Procedures.....	19
Compensation and Calibration of Aeromagnetic Data.....	19
Test Flight Maneuvers.....	20
Test Flight Results and General Recommendations for Aircraft Compensation.....	22
Guidelines for Compensation.....	33
Quality Control Proposal for Calibration Maintenance and Aircraft Compensation.....	35
Are Tie Lines Necessary for the ER-2 Mission?.....	37
Important Mission Questions Answered with Educated Guesses.....	41
Diurnal and Reference Field.....	45
Instrumentation.....	47
ER-2: A Suitable Platform for Magnetic Measurements.....	47
Cesium Magnetometer.....	47
Potassium Magnetometer.....	49
Summary.....	50
Acknowledgments.....	51
References Cited.....	52
Appendix A: Workshop Participants.....	53
Appendix B: Workshop Agenda.....	55

Figures

1. NASA's high-altitude aircraft, the ER-2.....	2
2. DTEMS incorporates SAR interferometry, differential GPS, GPS interferometry, and satellite data transmission.....	7
3. DTEMS will maximize area coverage rate by collecting SAR images in 28 kilometer swaths, simultaneously, on both sides of the aircraft.....	7
4. The on-board DTEMS data processing and handling system.....	9
5. The data processing system uses an array processor to reduce the recorded raw data to produce DTM and SAR images which will be stored in an archive...	9
6. In two passes, DTEMS will fill in the uncovered swaths and cover a total width of 94 kilometers.	10
7. After recursive SAR IGB tilt correction, the terrain elevation error distribution ranges from 0.21 to 0.52 m and has a mean of 0.3 m.....	10
8. Amplitude spectra of magnetic surveys flown at two altitudes.....	12
9. Amplitude spectra of magnetic surveys flown at three altitudes.....	12

10. Cloverleaf flight maneuver over the Fresno magnetic observatory.....	21
11. Comparison of the uncompensated total magnetic field measurements from test flight 5 and aircraft roll.....	23
12. Comparison of uncompensated total magnetic field data (from test flight 5) and the same data compensated for maneuvers.....	24
13. Enlarged section of figure 12, revealing small variations due to noise in the compensated magnetic field in comparison to those in the uncompensated field	25
14. Comparison of uncompensated total magnetic field data along 3 flight lines (from test flight 5) showing DC offsets.....	27
15. Comparison of the same data shown in figure 14, but the data have been compensated for maneuvers.	28
16. Comparison of the same data shown in figure 15, but the data have corrected further by compensating for diurnal variations.	29
17. Test flight 5 total field magnetic data showing a large step in the field, unrelated to maneuvers or diurnal variations.....	30
18. Enlarged section of the data shown in figure 17, showing the 33 nT step in more detail.....	31

ABSTRACT

A proposed high-altitude survey of the U.S. with an ER-2 to collect radar data offers an exciting and cost-effective opportunity to collect magnetic anomaly data. At this workshop, a group of magnetic specialists addressed this opportunity by discussing the need for high-altitude magnetic data and by formulating a preliminary operational plan to acquire such data. The high-altitude aeromagnetic survey would provide critical data needed to expand our knowledge of the geomagnetic field, with applications to a variety of earth science issues including geology, tectonics, core-processes, and rock-magnetism. Test flights with a cesium magnetometer indicate that the ER-2 has the potential to measure the magnetic field at an accuracy of 2 nT or better along flight lines. If the national ER-2 survey is carried out, the successful collection of high-altitude magnetic data hinges on establishing a consortium of federal and state agencies, private industry, and academic institutions to provide the identified resources.

INTRODUCTION

by Tom Hildenbrand (U.S. Geological Survey) and
Bill Hinze (Purdue University)

On December 13, 1995, a group of 23 scientists from the federal, private and academic sectors met at a workshop at the Ames Research Center, California, to discuss the feasibility of collecting magnetic anomaly data from an ER-2 aircraft¹ (fig. 1). The need for this 1-day workshop arose because of a possible exciting and cost-effective opportunity to collect invaluable magnetic anomaly data during an ER-2 mission over the U.S. next year. Lockheed Martin Missile and Space Co. is currently considering funding a reimbursable ER-2 aircraft mission to collect synthetic aperture radar (SAR) imagery at an altitude of about 21 km over the conterminous U.S. and Alaska. The additional collection of total and vector magnetic field data would represent a secondary mission objective (i.e., a "piggy-back" magnetometer system). Because Lockheed Martin would fund the main flight costs of the mission, the geomagnetic community would inherit invaluable magnetic data at a nominal cost. These new data would provide new insights on fundamental tectonic and thermal processes and give a new view of the structural and lithologic framework of the crust and possibly upper mantle.

Background

Opening remarks at the workshop included the history that led up to the convening of the workshop. In 1992 U.S. scientists at the National Geomagnetic Initiative Workshop pressed for more accurate and consistent magnetic anomaly data. In a

¹ The ER-2 is the NASA remote sensing version of the U.S. Air Force Lockheed U2-R, which replaced the older U.S. Air Force U2.

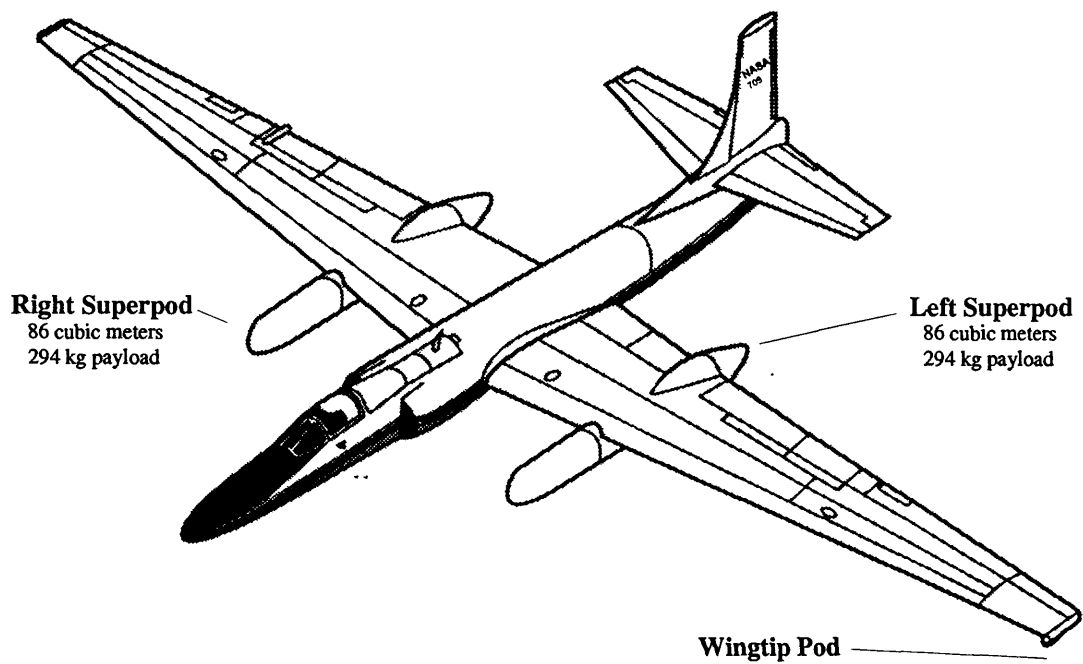


Figure 1. NASA's high-altitude aircraft, the ER-2. The superpods and wingtip pods are the proposed locations of the magnetometers.

workshop report [National Research Council, 1993 (see p. 67)] 90 attendees from academe, state and federal government, and private industry voiced the need to improve the U.S. aeromagnetic database. To address the problem, the U.S. Geodynamics Committee, National Research Council, charged a task group (the U.S. Magnetic-Anomaly Data Task Group, chaired by Thomas G. Hildenbrand) to develop the rationale and operational plan to upgrade the database. In 1994 the group issued a report [U.S. Magnetic-Anomaly Data Task Group, 1994 (see p. 17 and 24)] that offers a plan. Both these earlier reports include a recommendation to acquire consistent magnetic anomaly data at a high-altitude over the U.S. (see above noted pages in each report).

During February 1995 Lockheed Martin's intention to conduct a national SAR survey became known. The cost reimbursable ER-2 mission is proposed to be initiated in calendar year 1997, contingent upon current campaigns planned for NASA's ongoing Research and Analysis program, and changes in airborne program implementation brought about by NASA-wide aircraft consolidation. The mission objective will be the acquisition of interferometric SAR imagery and differential GPS that will serve as the basis for deriving digital terrain elevations at an absolute (1 sigma) accuracy of about 0.6 m (discussed below). The planned flight pattern of the survey consists of pairs of 22-km-spaced flight lines with a 66 km gap between each pair.

An ad-hoc executive committee was formed to determine the feasibility that the mission also includes the acquisition of high-quality magnetic anomaly data. Committee members are Thomas G. Hildenbrand (chair), William J. Hinze, and Robert A. Langel. The ensuing 8 months leading to the December workshop included 3 main objectives: (1) obtain authorization to include magnetometers on the proposed ER-2 national SAR survey, (2) establish a funding base to begin to develop a rationale and operational plan to collect the magnetic data, and (3) attempt to acquire magnetic data from test flights using the ER-2. All 3 objectives were met. During December 1995, George R. Keller was asked to be a fourth member of the executive committee.

Workshop attendees and agenda

Workshop attendees spanned a variety of organizations (see also Appendix A):

Mario Acuna, Goddard Space Flight Center, NASA
John Arvesen, Ames Research Center, NASA
Rick Blakely, Geologic Division, U.S. Geological Survey
Rob Bracken, Geologic Division, U.S. Geological Survey
Lynn Edwards, Geometrics
Arthur W. Green, Geologic Division, U.S. Geological Survey
Tom Hildenbrand, Geologic Division, U.S. Geological Survey
Bill Hinze, Purdue University

David Howell, Geologic Division, U.S. Geological Survey
John La Brecque, NASA Headquarters
Vic Labson, Geologic Division, U.S. Geological Survey
George Lee, National Mapping Division, U.S. Geological Survey
Jack Lynch, National Mapping Division, U.S. Geological Survey
Art McGarr, Geologic Division, U.S. Geological Survey
Hal Malliot, Lockheed Martin Missile and Space Co.
Alan Mikuni, National Mapping Division, U.S. Geological Survey
Misac Nabighian, Newmont Exploration
Bruno Nilsson, Newmont Exploration
Earnest Paylor, NASA Headquarters
Jeff Phillips, Geologic Division, U.S. Geological Survey
John Quinn, Geologic Division, U.S. Geological Survey
Walter Roest, Geological Survey of Canada
Dick Wold, Geometrics

In preparation for the workshop, several individuals were appointed to chair working groups on major workshop topics. These working groups met prior to the workshop and attempted to resolve some of the major problems in collecting magnetic data from an ER-2. Topics and assigned group leaders were:

- Compensation/Calibration/Tie Lines—John Quinn
- Diurnal Variations/Reference Field—Jeff Phillips
- Instrumentation—Vic Labson
- Rational Plan—Rick Blakely.

These group meetings helped to focus workshop discussions on the remaining critical issues.

The following sections of this report describe important technical and political issues surrounding the proposed ER-2 magnetic survey of the U.S. The order of these sections follows the sequence of presentations at the workshop (see Appendix B). Some of the included information evolved after the workshop on topics raised at the workshop and is provided here for completeness.

DIGITAL TERRAIN ELEVATION MAPPING SYSTEM (DTEMS)

by Harold A. Malliot (Lockheed Martin Missiles & Space)

A digital terrain matrix (DTM) with sub-meter precision and at least three meter posting is needed to support a variety of environmental, geophysical, economic and resource management tasks. Repeated measurements of DTM changes with five centimeters to one meter vertical resolutions and at least ten meter posting are needed for detection and measurement of a variety of geophysical processes. The Lockheed Martin Missiles & Space Digital Terrain

Elevation Mapping System (DTEMS) will be capable of providing data to satisfy these needs. DTEMS will use a NASA's Lockheed ER-2 aircraft with an X-band interferometric synthetic aperture radar (IFSAR) for collection, processing and archive of DTM with thirty centimeter average precision and one to three meter posting. DTEMS is expected to become operational by the summer of 1997.

Introduction

Lockheed Martin Missiles & Space is planning an airborne sensor campaign that will use an interferometric synthetic aperture radar (IFSAR) in an ER-2 aircraft to develop a comprehensive, high precision, high resolution digital terrain matrix (DTM) of the USA and other countries (Malliot, 1996a, 1996b). The initial DTM collection campaign will be followed by a DTM change detection and measurement campaign. The data will be available to the public and research personnel from a digital archive at a cost substantially less than the present cost to obtain equivalent data by stereo photogrammetry. The system will also provide cartographic, terrain perspective viewing, GIS, and topographic engineering products. The system will have an area coverage rate exceeding $700 \text{ km}^2/\text{minute}$ and, for terrain with 45° slope, it will deliver a DTM with average relative one σ elevation precision of 0.3 meter and average absolute one σ elevation accuracy less than 0.6 meter. The DTM will satisfy National Map Accuracy Standards (NMAS) contour intervals of 0.7 to 1.7 meters

DTEMS

An analysis of alternative techniques for DTM collection found that a wide swath interferometric synthetic aperture radar (IFSAR) carried in a NASA's Lockheed ER-2 aircraft would provide highest data quality at the lowest cost (Malliot, 1996a). The ER-2 offers a number of advantages over other aircraft:

1. low operational cost (\$6500 per flight hour as compared to \$10,000 or more for other jet aircraft);
2. operations between 18 and 21 km (60,000 and 70,000 ft) provide the capability for large area coverage rate, avoids the impacts of weather and air traffic control on flight operations, and subjects operations to minimal turbulence and jet stream encounters;
3. the 8.5 meter center to center separation of the wing pods provides an 8.5 meter SAR interferometer geometric baseline (SIB) and the rigid attachment of the wing pods to the wing eliminates excessive pod movement;
4. payload capacity of 4000 pounds and 25 kilowatts of power availability; and
5. mission duration up to eight hours with more than six hours of data collection time.

The major disadvantages of the ER-2 are special ground handling operations and use of an unusual fuel type. These eliminate ER-2 operations from most commercial airports. Also the single engine limits the off shore range of ER-2 operations to a few hundred kilometers.

Alternative techniques for sensing the terrain elevation include IFSAR (Malliot, 1996a), stereo photogrammetry, and laser ranging. IFSAR was selected for DTEMS for the following reasons:

1. IFSAR can provide a DTM with the desired data accuracy and posting;
2. IFSAR provides the maximum achievable area coverage consistent with the desired data quality;
3. data can be collected through cloud cover and day or night;
4. the data can be processed at relatively low cost on digital computers with minimum manual intervention;
5. topographic maps derived from IFSAR data are superior in many respects to topographic maps derived from stereo photographs (Ledner, 1994); and
6. production of marketable products and services that are presently not available (e.g., high resolution digital polarimetric SAR imagery, periodic measurements of terrain elevation changes, and detection of human activities).

The DTEMS system configuration, illustrated in figure 2, will use SAR receivers placed in the ER-2 wing pods to collect simultaneous images of the swath illuminated by the transmitter. At these locations, with zero roll, the horizontal baseline distance between the receivers will be 8.5 meters and the vertical baseline distance will be zero.

The radar transmitter will be located in an instrument bay in the fuselage behind the pilot. Four GPS antennas and receivers will be used, in the differential GPS (DGPS) mode, to collect aircraft position and velocity data which will be used for SAR image forming and DTM extraction. A GPS aided inertial navigation system will also be used to collect motion data that will be needed for motion compensation during SAR image formation. GPS interferometry (GPSI) will be used to measure the SAR interferometer geometric baseline attitude at one second intervals. An on-board clock, synchronized to the GPS 1 pulse per second time signals, will provide system time.

To realize the maximum area coverage per flight, DTEMS will collect data in swaths on both sides of the aircraft. The coverage, illustrated in figure 3, will

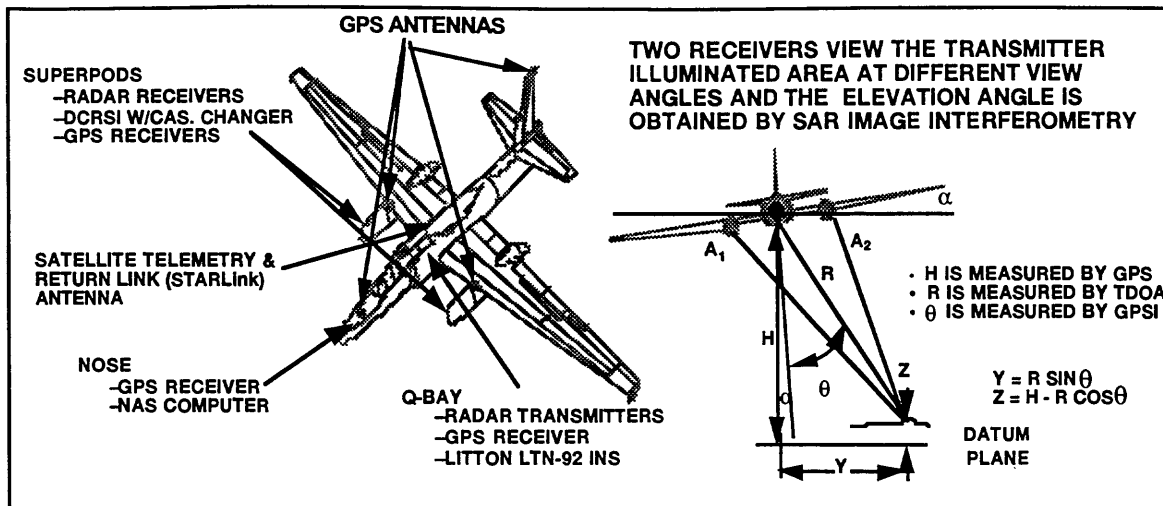


Figure 2. DTEMS incorporates SAR interferometry, differential GPS, GPS interferometry, and satellite data transmission.

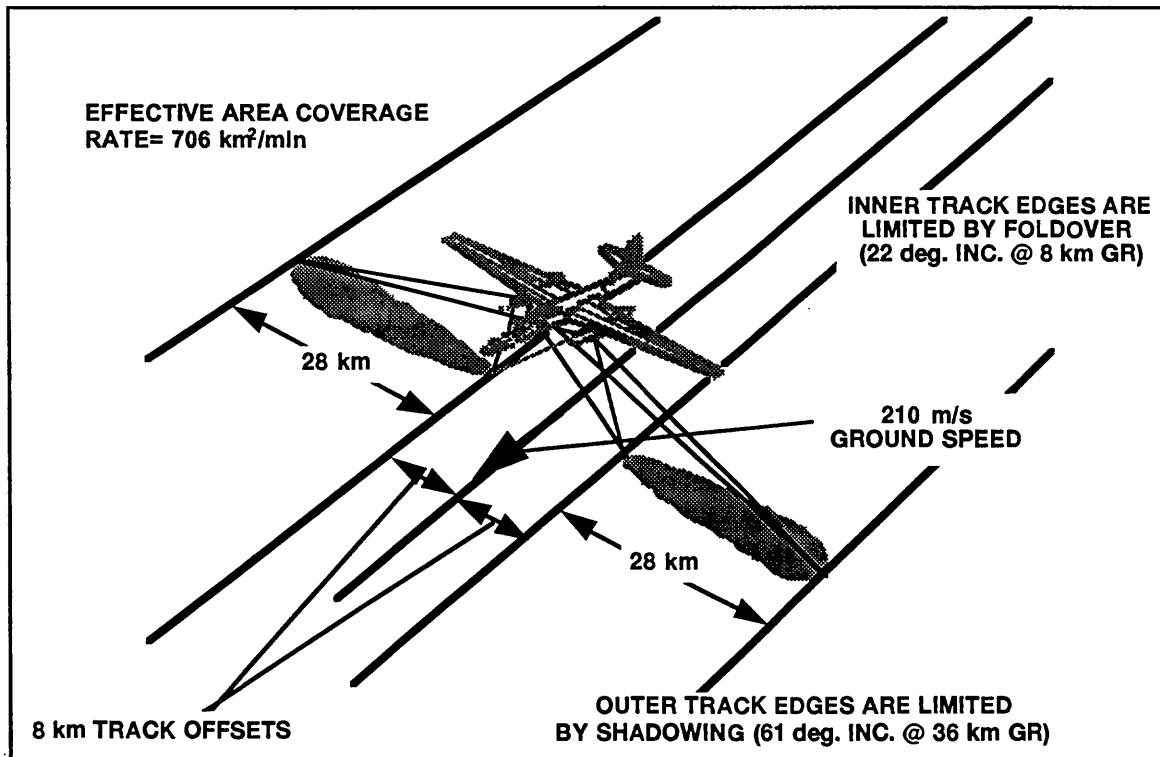


Figure 3. DTEMS will maximize area coverage rate by collecting SAR images in 28 kilometer swaths, simultaneously, on both sides of the aircraft.

extend from swath inner edges at eight kilometers ground range to swath outer edges at 36 kilometers ground range. (Ground range is measured from the aircraft ground track.) The distance to the inner edges of swaths was selected to limit the smallest angle of incidence to 22° to avoid excessive fold-over in the SAR images. The distance to the outer edges was selected to limit the largest angle of incidence to 61° to limit shadowing in the SAR images. This geometry will produce 28 kilometers of coverage in each swath and, at an effective ground speed of 210 m/s, the area coverage rate will be $706 \text{ km}^2/\text{minute}$.

The 16 km gap in coverage (between the inner edges of the two 28 km swaths) will be covered by two-pass operations as illustrated in figure 4. Typical 6.5 hour mission will have 5.1 hours of cruise time during which radar operation is conducted. Radar operations will begin after ascent to 19.8 km and will continue for about 153 minutes for 1937 km of flight distance. The pilot will then make a U turn and fly a reverse pass parallel to and 22 kilometers offset from the first pass. On the reverse pass, the swath on one side will cover the 16 km gap left on the first pass and the gap on the reverse pass will be over one of the first pass swaths. There will be six kilometers of adjacent track overlap. The total coverage is 1937 km by 94 km ($182,078 \text{ km}^2$).

Mission data includes in phase and quadrature samples of the received radar signals, mission time, and samples of the aircraft position, velocity, and attitude. These data will be combined and transmitted via the Satellite Transmission and Relay Link (STARLink) through a NASA TDRSS satellite to the TDRS ground station at White Sands Missile Range, New Mexico. In the event that STARLink or TDRS is not available, on-board data recording will be used. Data will be transmitted or data tapes will be transported to the DTEMS data processing facility.

As illustrated in figure 5, the GPS receiver, GPS aided by the internal navigational system (INS), and time clock outputs are input to the navigation and attitude sensing computer (NASC). The inputs are time tagged and processed to obtain the aircraft position, velocity, and attitude vectors at each time interval. The NASC output is combined in a multiplexer with radar data for either on-board recording or transmission via STARLink.

The data processing system, shown figure 6, will use an array processing architecture. The mission data will be input to the array processor via a workstation or PC. The resulting DTM and SAR images will be added to the DTM and image archives. Processing will include SAR image formation with motion compensation, SAR interferometry, extraction of the DTM, and

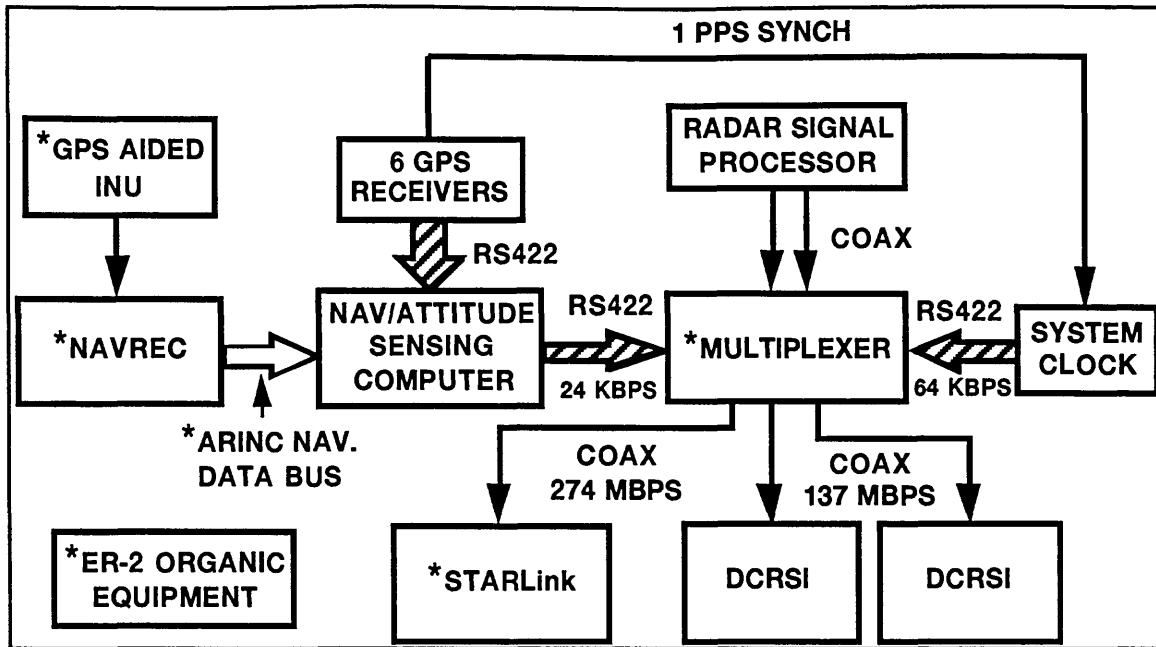


Figure 4. The on-board data processing and handling system.

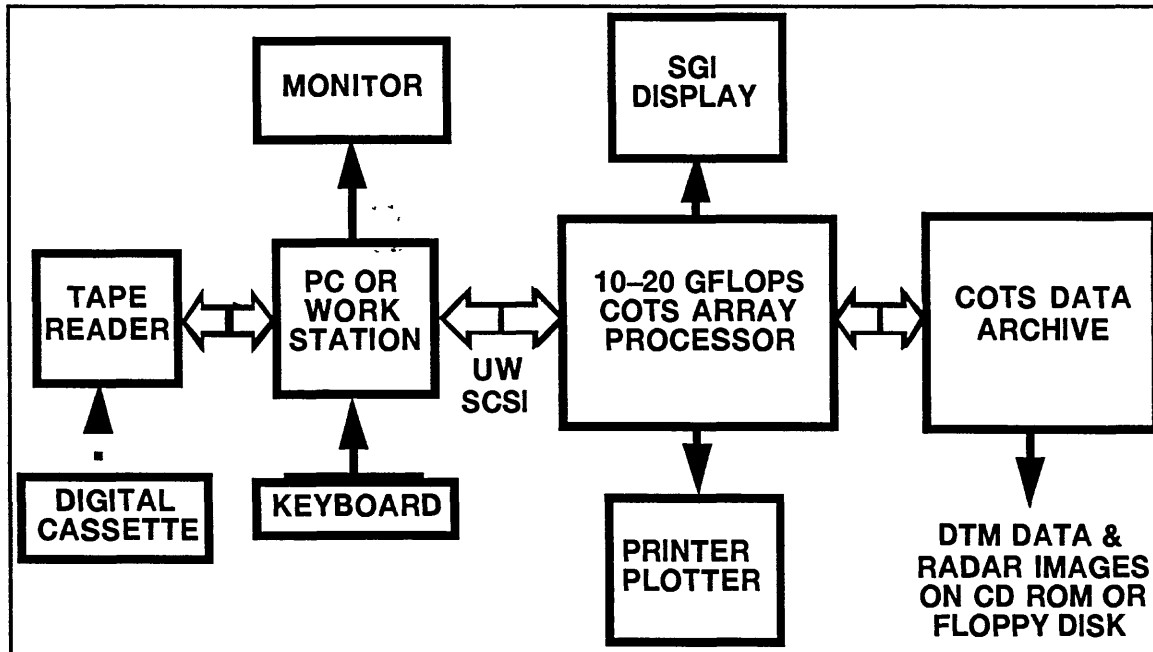


Figure 5. The data processing system will use an array processor to reduce the recorded raw data to produce DTM and SAR images which will be stored in an archive.

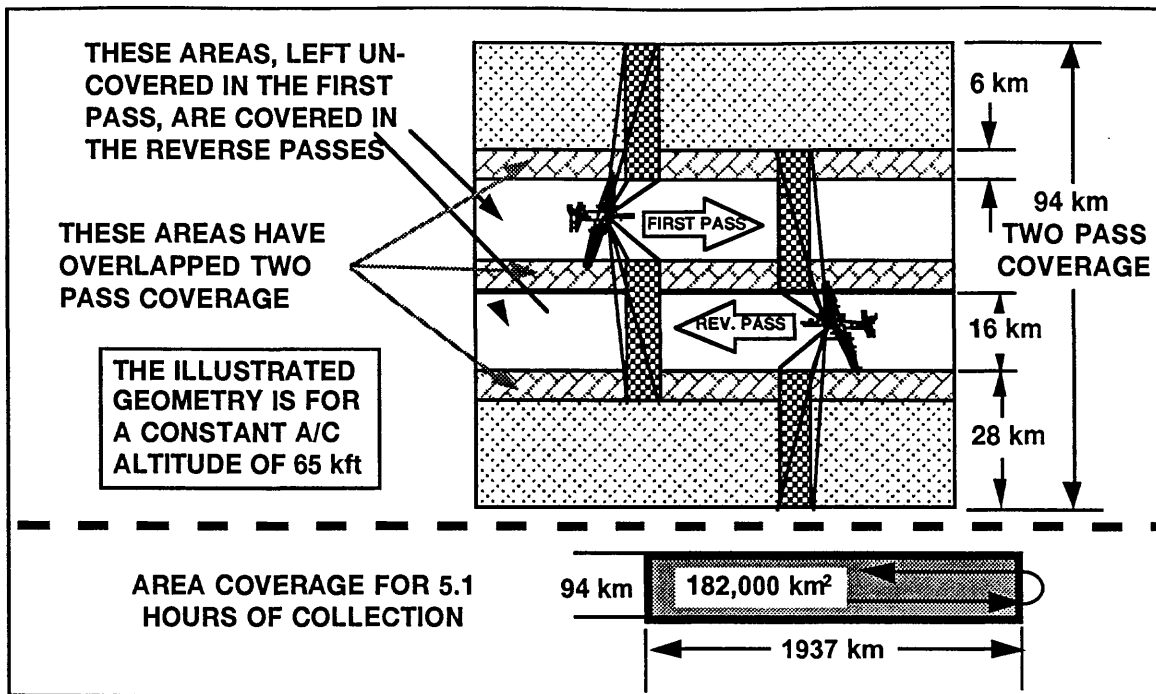


Figure 6. In two passes, DTEMs will fill in the uncovered swaths and cover a total width of 94 kilometers.

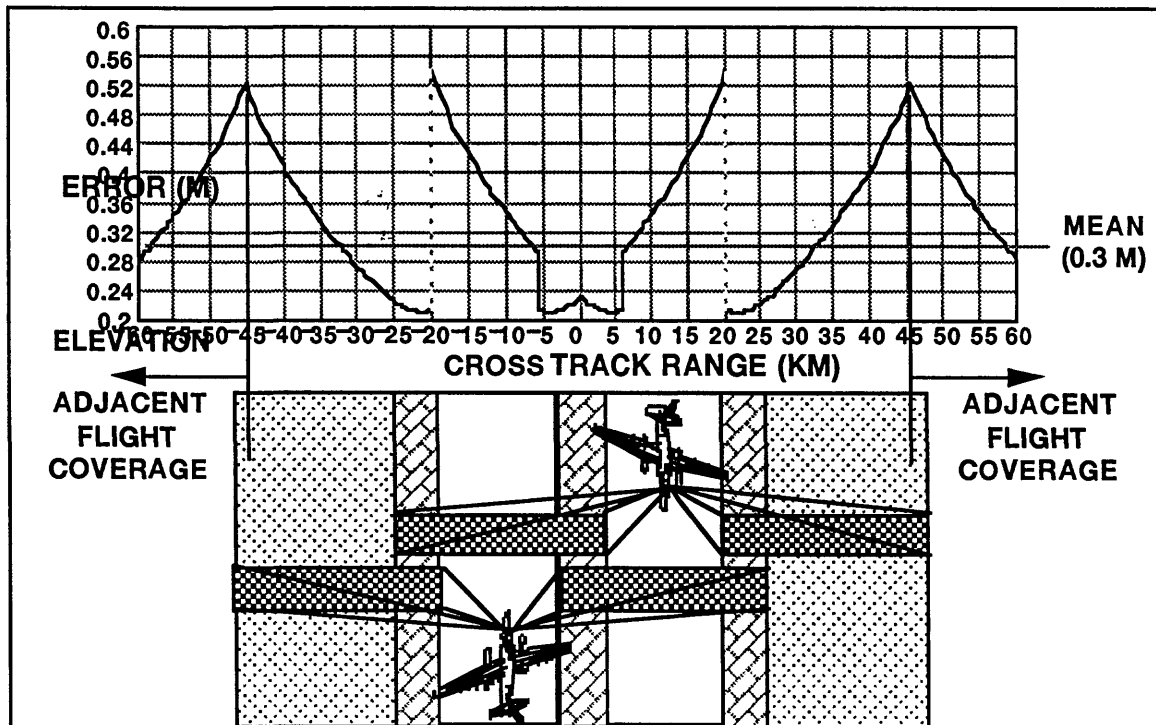


Figure 7. After recursive SAR IGB tilt correction, the terrain elevation error distribution ranges from 0.21 to 0.52 m and has a mean of 0.3 m.

coordinate transformations. The DTM will be used to geometrically correct and orthorectify the SAR images.

Terrain Elevation Accuracy

The major source of terrain elevation error is the indeterminate error in the SAR interferometer geometric baseline (SIGB) tilt (Malliot, 1996a). The total phase error, from a combination of sources, is the second largest contribution to terrain elevation error. Approximately 230 micro-radian indeterminate SIGB tilt knowledge will be obtained by GPSI. A recursive processing technique that will reduce the indeterminate SIGB tilt error to ten micro-radians is described in (Malliot, 1996b). The predicted rms terrain elevation error distribution over the 94 kilometer two-pass swath is presented in figure 7. Average terrain elevation error is 0.3 meter. This error distribution will be repeated for adjacent flight coverage on each side. On repeated coverage of same areas, changes in the DTM will be measurable with an elevation resolution of five to ten centimeters.

Conclusions

The Digital Terrain Elevation Mapping System (DTEMS) will provide orthorectified digital polarimetric SAR images with three meter resolution and a DTM of the covered area with three meter posting and, for areas with 45° or less slope, 0.21 to 0.53 one sigma elevation precision at each post. The horizontal precision at each post will be 0.5 meter and will support production of topographic maps with (NMAS) contour intervals of 0.7 to 1.7 meter. In 1997 DTEMS will create radar image and DTM archives of the USA. Data archives for other countries will follow. DTEMS will also conduct periodic operations for measurement of DTM changes with three meter horizontal and five to ten centimeter elevation resolution.

RATIONALE FOR THE ER-2 MAGNETIC SURVEY

Scientific Rationale for a High-Altitude Aeromagnetic Survey

by Richard J. Blakely (U.S. Geological Survey)

Rationale

The information contained in a magnetic survey is largely restricted to a specific band of the wavenumber spectrum, with the position of this band and the ability to resolve it being primarily a function of the survey's altitude and size. Although the 20-22 km altitude of the ER mission was established independent of the requirements of geologic or geomagnetic studies, it will be nearly optimal for bridging the gap between low-altitude aeromagnetic data and satellite magnetic data. This is illustrated by figure 8, which shows the amplitude spectra of magnetic

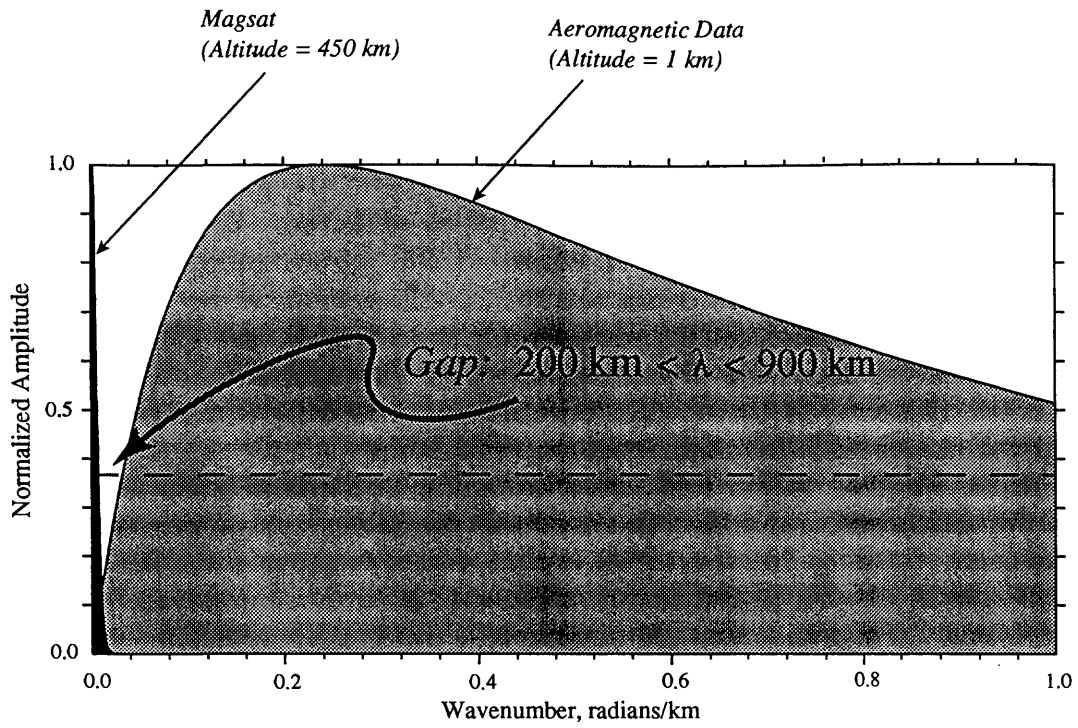


Figure 8. Amplitude spectra of magnetic surveys flown at two altitudes. Black-filled spectrum is that expected from a survey flown at 450 km, the nominal altitude of the 1979-80 Magsat mission. Gray-filled spectrum is that expected at 1 km, the altitude of a typical aeromagnetic survey. The dashed line is at amplitude $1/e$. Magnetic layer assumed to be 10 km thick.

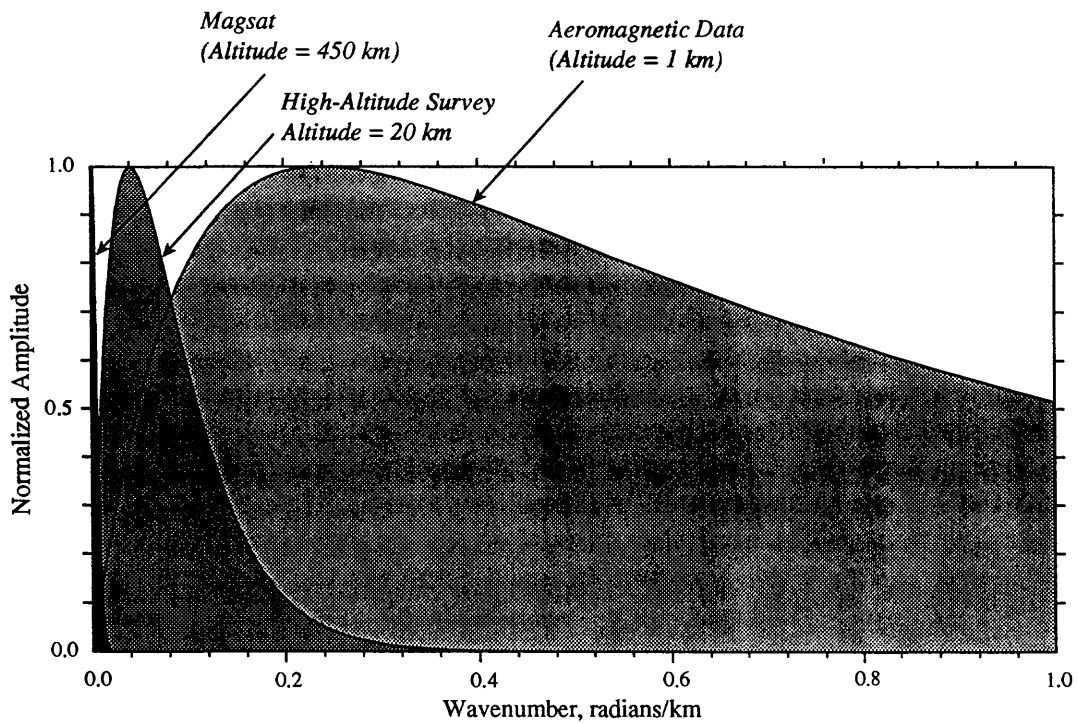


Figure 9. Amplitude spectra of magnetic surveys flown at three altitudes. Black-filled and light-gray-filled spectra are the same as shown in Figure 2. Dark-gray-filled spectrum is that expected from the high-altitude aeromagnetic survey. Magnetic layer assumed to be 10 km thick.

anomalies that would be measured at two altitudes: at 450 km, the nominal altitude of the NASA 1979-80 Magsat mission, and at 1 km, a typical altitude for aeromagnetic surveys. Assuming that the spectral information contained in crustal magnetization is "white", these curves indicate the wavenumber content of observed anomalies. Very little overlap exists between the two spectra, and indeed between wavelengths of 200 and 900 km the amplitude spectra drop below a level of $1/e$. Even if perfect knowledge of the magnetic fields was available at both Magsat and aeromagnetic altitudes (and it never will be), a significant part of the spectrum currently is poorly known. This part of the spectrum is critical to crustal studies; it is about the same length scale as major geologic structures, such as the Cascade Range, the Basin and Range province, and the Midcontinent Rift. Figure 9 shows the spectral contribution of the high-altitude aeromagnetic survey with respect to typical aeromagnetic surveys and the Magsat mission. Because of its altitude of about 22 km, the high-altitude aeromagnetic survey will eliminate the gap between wavelengths of 200 and 900 km, and, together with low-altitude aeromagnetic and satellite magnetic data, provides information across the spectrum.

Objectives/Examples

Several applications of the high-altitude magnetic data are envisioned. For example, these data will significantly improve the U.S. compilation of low-altitude aeromagnetic surveys, which represent a national resource that is fundamental to geoscience investigations. It provides key geologic, tectonic, and thermal information. This data set is currently based on a patchwork of over 1,000 airborne and shipborne surveys, acquired over a period of 40 years to address a wide variety of objectives. Significant mismatches exist between many survey data sets, some exceeding several hundred nanoTesla (an order of magnitude greater than the amplitudes of magnetic anomalies caused by some of the sources of interest). Preliminary tests demonstrate for surveys of about the size of a $1^\circ \times 2^\circ$ quadrangle sheet (e.g., NURE magnetic surveys) that a properly conducted high-altitude aeromagnetic survey will significantly reduce data mismatches at survey boundaries and thus greatly expand the utility of the low-altitude magnetic data over a much broader range of wavelengths. A consistent datum for all aeromagnetic surveys will improve both qualitative and quantitative interpretations (e.g., for geological mapping, particularly where magnetic maps are used to extrapolate observations from outcrop to covered regions, and for quantitative comparisons of magnetic properties of rock units in different parts of the U.S.). A correctly merged aeromagnetic map of the conterminous U.S. may be the single most important legacy of the high-altitude mission.

Interpretations of the high-altitude data will provide new insights on the crust and possibly upper mantle. For example, there are few direct methods to characterize crustal temperatures. Spectral analysis of the high-altitude aeromagnetic data may lead to estimates of crustal depths where elevated temperatures (above about 580°C) cause rocks to lose their magnetic properties. This depth is commonly referred to as the depth of the Curie-point isotherm. A national map of the Curie-point isotherm

depths could be used to study crustal temperatures and to improve the national heat flow map (e.g., in interpolating between areas of known crustal heat flow). The advancement in our understanding of crustal temperatures through the interpretation of the high-altitude magnetic data will benefit many socioeconomic studies. This knowledge could be used to assess geothermal resources and to provide new insights on crustal stability related to volcanoes and fault systems (since the mechanical behavior of the crust is highly temperature dependent).

The large lateral dimensions of the high-altitude aeromagnetic survey will also provide important information concerning the separation of magnetic fields of crustal and core origin. When the geomagnetic field is expressed as a spherical harmonic expansion, the core and crustal components overlap between harmonic degrees of 12 and 15. It is in this wavelength region where core fields merge with crustal fields. The dimensions of the high-altitude aeromagnetic survey will be several times larger than these wavelengths and thus will be useful in analyzing the overlap between core and crustal fields. A consistent, high-quality survey could lead to a better understanding of the statistical aspects of the crustal field over the U.S., which should lead to improved core-crustal separations worldwide. The importance of the high-altitude magnetic data to core-crustal separation studies will probably be enhanced if the ER-2 mission occurs during the planned Oersted magnetic satellite mission (scheduled launch in June 1997). Moreover, the regional crustal field defined by the high-altitude magnetic survey can be added to the improved core field to provide magnetic models needed in higher precision positioning, such as directional drilling by oil and gas exploration companies or testing missile guidance systems in U.S. firing ranges.

Offshore studies may also benefit from the high-altitude magnetic survey. For example, due to the characteristic wavelengths of these data, our knowledge of the source of the east-coast magnetic anomaly may increase. Dr. Manik Talwani, states that "the vector magnetic data from the proposed ER-2 survey may be immensely helpful in distinguishing between the proposed models for the ubiquitous, east-coast magnetic anomaly" (oral communication, 1996).

There are many other geologic and geomagnetic applications of a high-altitude aeromagnetic survey, including but not limited to:

Geology and tectonics

- A better understanding of the continent/ocean transition
- New insights on regional tectonic problems such as constraints on basin evolution and regional controls on mineralization
- Mineralogical implications for the deep crust and possibly mantle
- A continent-wide tectonic perspective by merging with Canada's high-altitude (4 km) magnetic survey

Geomagnetic field

- Improved U.S. magnetic charts

Improved magnetic field in littoral areas
Quality assurance of small amplitude and short wavelength satellite magnetic data.

Recommendations

The high-altitude aeromagnetic survey provides a critical opportunity to expand our knowledge of the geomagnetic field, with applications to a variety of earth science issues including geology, tectonics, core-processes, and rock-magnetism. To be useful for these purposes, however, the survey must be conducted with all the same care given to low-altitude aeromagnetic surveys. The flightline spacing should nowhere exceed twice the altitude, although this requirement might be relaxed if horizontal gradients or vector components can be measured. The field generated by the aircraft itself must be precisely known, and external fields must be carefully monitored at ground stations located in the immediate vicinity of the aircraft. Flight altitude should be constant, or if that is not feasible, must be precisely known at every point of measurement.

High-Altitude Aeromagnetic Data: The Canadian Perspective

by Walter R. Roest (Geological Survey of Canada)

An ER-2 high altitude aeromagnetic data set over the United States and adjacent offshore regions would serve two important purposes: one, it would allow the study of long wavelength magnetic anomalies, which provide insights in the tectonic assemblages and physical properties of the lower crust and upper mantle; two, it will provide a consistent, country-wide datum that can be used to merge individual aeromagnetic surveys. This improves the continuity of magnetic signatures and, therefore, the validity of the magnetic interpretation that is vital to geological mapping. High-altitude aeromagnetic anomalies are filling, in this respect, the significant gap that exists between low-level aeromagnetic data and satellite observations.

Background

The reliability of the long-wavelength portion (>300 km) of the magnetic field over Canada, as represented by the national aeromagnetic anomaly database compiled by the Geological Survey of Canada (GSC), was recently assessed by comparison with two independent data sets: a high-altitude (~ 4 km) country-wide survey carried out by the former Earth Physics Branch (EPB) and data from the MAGSAT and POGO satellite missions (Pilkington and Roest, 1996). The different altitudes at which each data set was measured (300 m, ~4 km and ~400 km, respectively), and their different resolution and time span of observations, allow a determination of the integrity of selected wavelength bands in each data set. The (upward continued) EPB and MAGSAT/POGO fields compare well for wavelengths of 300 km to 2500 km. The

GSC data shows significant differences to the former, indicating that the leveling and merging of several hundred individual surveys has degraded the longer wavelength components of the magnetic field. A similar situation exists in the United States. Replacing the GSC wavelength components > 300 km with those from the EPB field produces a magnetic data set containing more dependable information within the largest possible waveband.

A study in the North Atlantic (Arkani-Hamed and others, 1995), showed that long wavelength magnetic anomalies can also be successfully recovered from shipborne magnetic observations. This is mainly because the data set contains many long ship tracks crossing the entire ocean. In addition, we were able to use the raw total field observations, as opposed to compiled maps. In a qualitative sense, the upward continued ship borne data compare very well with magnetic anomalies derived from the MAGSAT and POGO satellite missions. Both these studies indicate that, despite a qualitative agreement between near surface and satellite derived long wavelength anomalies, there are significant discrepancies in the anomaly amplitudes and the exact locations of maxima and minima. A quantitative analysis of these discrepancies is needed to solve the question whether these differences are related to the processing or to physical reality. When the new data over the United States are merged with existing data over Canada and the North Atlantic, such a quantitative analysis can be carried out.

Logistics

In order to ensure optimum utility of the new aeromagnetic data, a significant overlap with existing data in Canada and offshore is essential. This will enable the merging of these data sets to create an intermediate to long wavelength data set that covers a large geographic area and can be used in spectral analysis. The present data sets over Canada and the North Atlantic are too small in geographic extent to study wavelengths longer than 1000 km in a quantitative way.

Recommendations

A minimum requirement is to continue the ER-2 tie-lines into Canada for at least 100 km. The acquisition of data along several flight lines north of the US-Canada border would be preferable. To map the magnetic signature of the Ocean-Continent Transition, which is a matter of significant debate, flight lines have to extend several hundreds of km's into the true oceanic domain, or roughly 1000 km offshore in the North Atlantic. Although the Earth Physics Branch data collected over Canada are of variable quality, the fact that the data were collected in a consistent fashion, and the flight lines were over a 1000 km long makes it possible to extract long wavelength magnetic anomalies with some confidence. This type of consistency is needed to make the ER-2 mission a success.

NEEDED RESOURCES

by Tom Hildenbrand and Rob Bracken (U.S. Geological Survey)

Although most of the mission costs would be funded by Lockheed Martin, additional resources related only to the collection of the magnetic data are needed and include:

Equipment purchase and magnetometer installation...~ \$190 k

Salaries/travel costs to develop an operational plan
and to collect and process the magnetic data.....~ \$300 k

Flight time for test flights, tie lines, calibration and
compensation flight maneuvers, etc.....~ 122 flight hours

Flight time to collect offshore data (to 300 km).....~ 140 flight hours.

These needed resources are examined in more detail below.

Equipment installation

The mounting of magnetometers (with associated instruments) and the related wiring (e.g., threading wire through the wing) can only be performed by Lockheed engineers at considerable cost. It is recommended to mount a cesium magnetometer in the wing superpod and to mount a potassium magnetometer in each wingtip pod. The estimated cost is \$50 k to install the total-field magnetometers. The vector magnetometer, mounted in the other superpod, requires more engineering to become functional due to the need to know the magnetometer attitude to within 100 microradians. The estimated cost to mount the vector magnetometer rigidly in a location where the attitude is accurately known is roughly \$100 k. The additional cost to purchase and modify a cesium magnetometer is about \$40 k. The total cost to install the magnetometers is about \$190 k.

Mission procedural flight hours

We suggest that reasonable estimates for the additional mission flight hours are:

flight tests	27 hours
compensation	40 hours
tie lines	49 hours
overlapping of flight lines	6 hours
total	122 hours.

Flight tests

Several flight tests are needed to verify proper installation of the magnetometers and to design the necessary flight procedures to assure collection of quality magnetic data. We have estimated that these tests will require 24 to 30 hours of flight time during which the following will be done: check the proper functioning of equipment; confirm and compensate for certain maneuver uncorrelated magnetic effects (discussed below); develop mission specific compensation procedures; check magnetic changes in the aircraft resulting from landing, takeoff, and maintenance; and check effects of longitude and latitude on compensation.

Mission procedure flight hours

The results of these test flights will greatly affect the operational plan involving mission procedures. Although an estimate of additional flight hours during the mission without the test flights is highly speculative, we arrive at a possible range of 21 to 60 flight hours for aircraft compensation and calibration. It is assumed that the survey will be carried out over 7 survey blocks in the conterminous U.S. and a single block for Alaska. Compensation flights are needed over a magnetic observatory before initiating flights for each survey block, after adjustments to magnetometers, and after changing aircraft. During each flight, compensation maneuvers may be needed if DC shifts related to changes in the aircraft perm occur ("p12erm" is defined here as the temporary or permanent magnetic field imprinted on any metallic part of the aircraft). Tie lines will require an additional 30 or 49 hours depending if 2 or 3 tie-lines are flown within each of the survey blocks. Overlapping of flight lines between survey blocks equal to 4 minutes of flight time results in an additional 6 hours. Thus the total range of flight hours related to compensation, tie lines, and overlapping flight lines is 57 to 115 hours.

Offshore flight hours

Until an efficient flight plan can be formulated and accepted by Lockheed Martin, estimations of the additional flight hours to extend the survey to 300 km offshore is difficult to derive. For example, are land flight lines near the coasts simply extended to 300 km offshore? If so then 3 additional survey blocks are created in the central U.S. to make up for the shortened land portion of the coastal survey blocks. On the other hand if the ocean surveys are flown completely separate from the land surveys, then the flight hours will probably increase significantly because of the need for additional compensation flights and additional tie lines. We estimate a range of 120 to 160 additional flight hours to fly offshore.

Recommendations

If the ER-2 national survey is carried out, it would represent an exciting and important opportunity to the geomagnetic community. However, the successful collection of high-altitude magnetic data will clearly hinge on the identification of

contributors of the needed resources. Due to limited budgets, the ER-2 magnetic mission would require resources from a consortium of federal and state agencies, private industry, and academic institutions.

TEST FLIGHT RESULTS AND MISSION FLIGHT PROCEDURES

Compensation and Calibration of Aeromagnetic Data

by John Quinn (U.S. Geological Survey)

The compensation and calibration of aeromagnetic data collected at high altitudes (i.e., 20 km) is not a precise scientific procedure. The reason is that typical aircraft used to measure the Earth's magnetic field are of aluminum and ferrous alloy construction. Hence, these aircraft are made of conducting materials. Conducting materials, when moving through the Earth's magnetic field, have electric currents induced on their surfaces which in turn generate secondary magnetic fields, the strength and direction of which are determined by the aircraft's physical geometry, as well as its speed and direction relative to the Earth's magnetic field, and the strength of the Earth's magnetic field itself. Additionally, electronic instruments on the aircraft may generate magnetic fields, while various parts of the such as the engines may contain ferrous materials that have either a permanent or induced field associated with it. When jet engines are involved, there may be a magnetoplasma effect associated with the jet exhaust. Even temperature changes over the surface of the aircraft can produce electrical currents, which in turn will generate magnetic fields. Each individual aircraft will exhibit magnetic fields due to these and other sources in its own unique fashion. Furthermore, the aircraft's characteristics with respect to these man-made sources of magnetic field are not constant. Landings and takeoffs can cause sudden changes in these characteristics.

There are certain measures that can be taken to isolate the magnetic sensors from identified sources, within the aircraft, such as the use of magnetic shielding materials. Secondly, mapping the aircraft's intrinsic magnetic field on a non-magnetic section of an airfield known as the Compass Rose can be done. The problem with these ground based approaches is that these characteristics tend to change once the aircraft is airborne. The Compass Rose may be considered a ground level calibration range. There is no equivalent calibration range in the air at operational altitudes. The only viable substitute is to perform a set of specially designed flights over one of the approximately two hundred geomagnetic observatories that are scattered around the world, or to establish temporary magnetic observatories for making these special calibration flights. The higher the flights are above the observatory, the more difficult it becomes to use the observatory data for calibration purposes. Complications outside of the experimenters control for calibration purposes include the anomalous crustal magnetic fields beneath these observatories and the anomalous conductivity

distributions (which, when coupled to ionospheric magnetic field fluctuations, cause crust induced magnetic fields).

Because of all the variables involved, no exact means of calibration exists. The procedures are thus not based entirely on exact physical theory, but are to a large extent phenomenological. That is, one develops a "magnetic compensation" model that has a minimal set of parameters that can account for the maximum amount of the man-made magnetic signature of the aircraft. These parameters are then determined via the special calibration flights over regions where the field is presumed known, such as at geomagnetic observatories. These special calibration flights are costly. So, some intimate knowledge of the aircraft is necessary to determine the necessary frequency of such flights. The key theme is to have "ground truthing" to provide an absolute reference from which to determine these compensation coefficients. However, due to the inexactness of the compensation model itself, other procedures are required, such as using tie lines, and overlapping edges of contiguous sections of the survey so that consistency of measurements over the same region can be determined.

Test Flight Maneuvers

by Tom Hildenbrand (U.S. Geological Survey)

During October and November 1995, six test flights were carried out with the ER-2 with a cesium magnetometer mounted in the wing superpod (fig. 1). The flight instructions for four flights were to fly loops such as the one shown in figure 10 and:

- Fly over the Fresno Magnetic Observatory (latitude 37.09°; longitude 240.28°E).
- Fly one maneuver pattern keeping the plane as level as possible. Fly the pattern 2 additional times by randomly varying the plane about its 3 axes (i.e. pitch, roll and yaw), only along the straight portions of the clover leaf.
- In flying the patterns alter the turns from all left turns then all right turns.
- When banking, do not exceed a roll of 15°. Attempt to keep a constant bank (i.e., stop random maneuvers).
- Fluctuations about the axes should be: yaw = $\pm 5^\circ$ or less, pitch = $\pm 10^\circ$ or less, and roll = $\pm 15^\circ$ or less (never exceed 17°). Unless safety is a factor, attempt some maneuvers at these maximum angles. It is important in performing these maneuvers that no mechanical part of the aircraft (e.g., flaps) moves that would not do so during a true mission.
- These random maneuvers should be performed with variable periods, such as a quick maneuver at 1-5 sec and a slow maneuver at 5-10 sec when going from the neutral-to-extreme-to-neutral position. Consequently, rotation angles will vary greatly depending on the period.

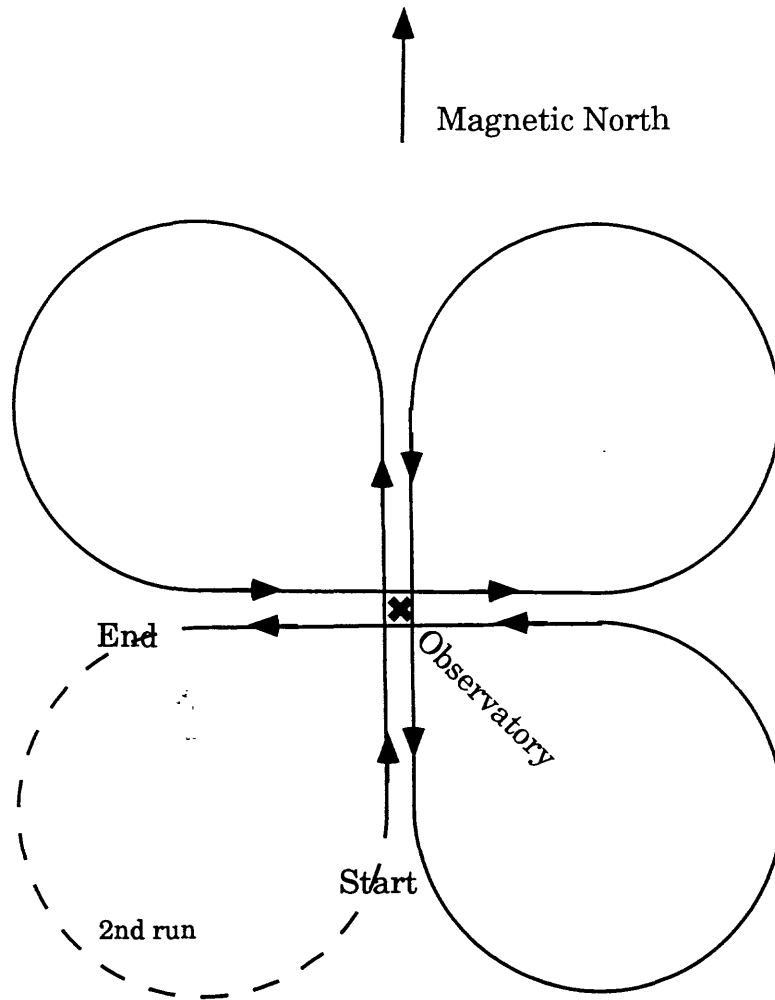


Figure 10. Clover-leaf flight maneuver over the Fresno magnetic observatory.

- The distance of the straight portion of the maneuvers should be equal to a time of at least 75 seconds before and after the observatory (i.e., minimum distance = about 32 km (20 mi) at 410 knots over 150 seconds).

The goals of these test flights were:

- Perform a magnetic compensation of the ER-2
- Determine the magnetic effects at the superpod location
- Determine the magnetic noise associated with a level flight
- Evaluate the diurnal effects at the 20 km altitude using the Fresno Magnetic Observatory magnetic data.

The remaining two test flights were a "piggy-back" flight to Santa Barbara and a small survey with E/W flight lines. The latter flight was over the Fresno Magnetic Observatory. The following discussions on mission procedures are largely based on the results of these test flights.

Test Flight Results and General Recommendations for Aircraft Compensation

by Rob Bracken (U.S. Geological Survey)

Doug Hardwick performed standard compensation computations on cesium magnetometer data obtained during a series of ER-2 test flights in October and November 1995. Some of his results were presented together with comments by Rob Bracken.

Summary

Two general types of data reduction problems exist in aeromagnetic surveys: (1) problems associated with "offsets and DC shifts" and "long wavelength variations" and (2) problems associated with "gross noise and drop-outs" and "short wavelength variations." The former effects are of great concern because they possess wavelengths comparable to those of interest in the geomagnetic field, mainly the medium to long spatial wavelengths. The latter effects are routinely compensated in small area surveys, and therefore, existing methodologies give a high degree of confidence for affecting their removal.

The compensation done by Doug Hardwick is designed to remove maneuver correlated variations of both long and short wavelength and DC shifts occurring between flights. Figures 11-13 indicate a great degree of success in removing maneuver-correlated short-wavelength variations. Variations of 20 nT peak to peak are reduced to less than 2 nT.

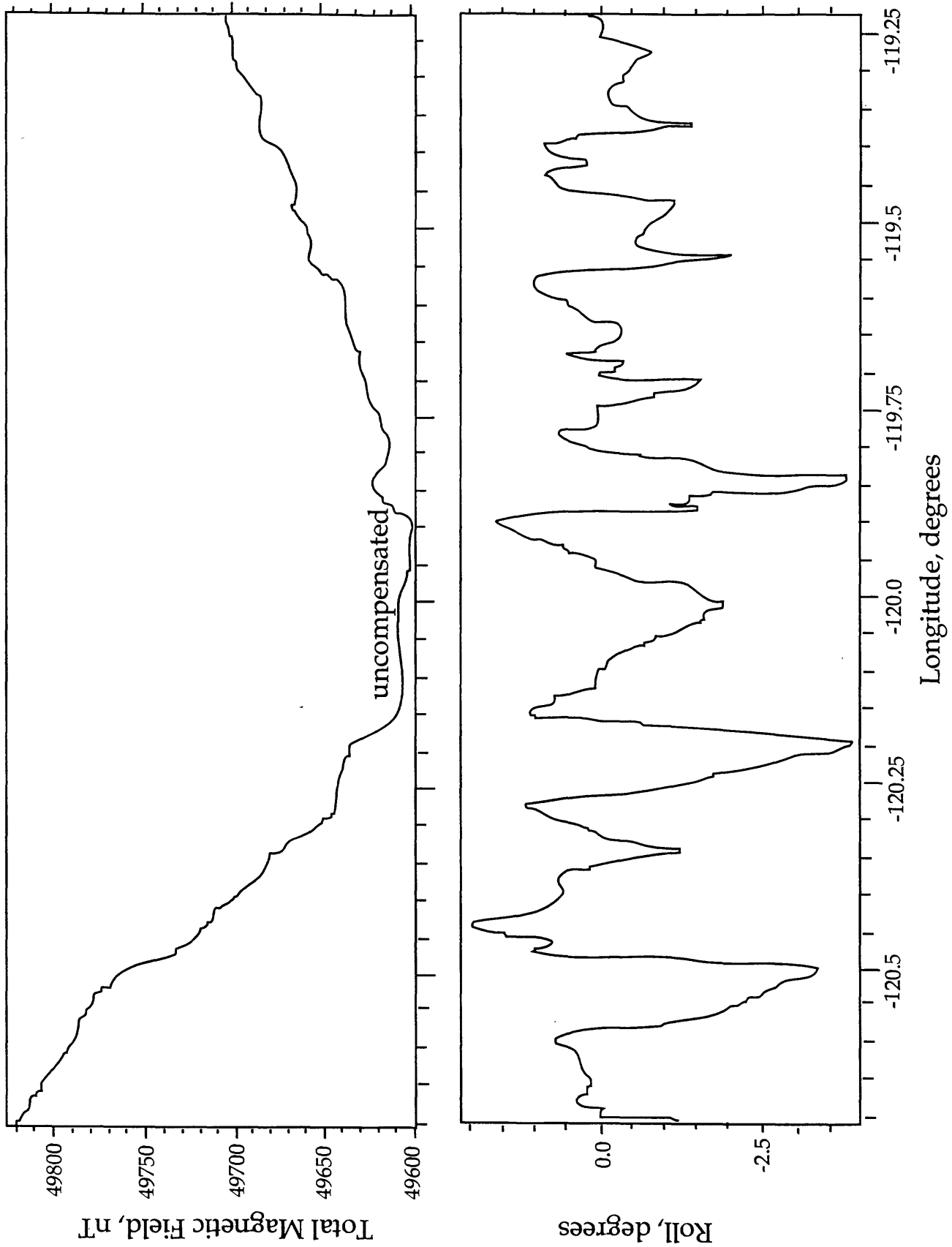


Figure 11. Comparison of the uncompensated total magnetic field measurements (top) from test flight 5 and aircraft roll (bottom).

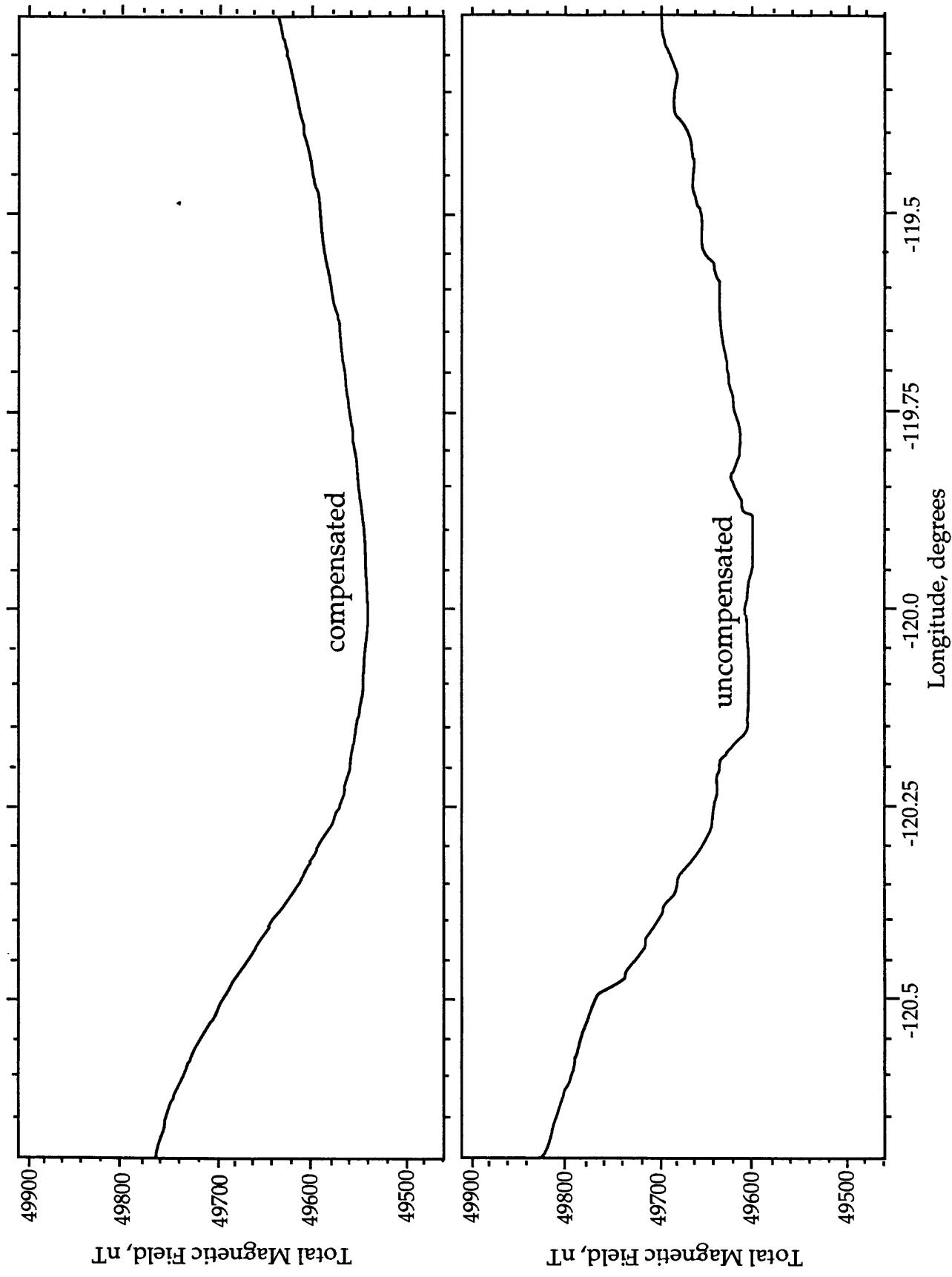


Figure 12. Comparison of uncompensated total magnetic field data (from test flight 5) and the same data compensated for maneuvers. Compensation coefficients derived from Doug Hardwick's routine using data from test flight 3.

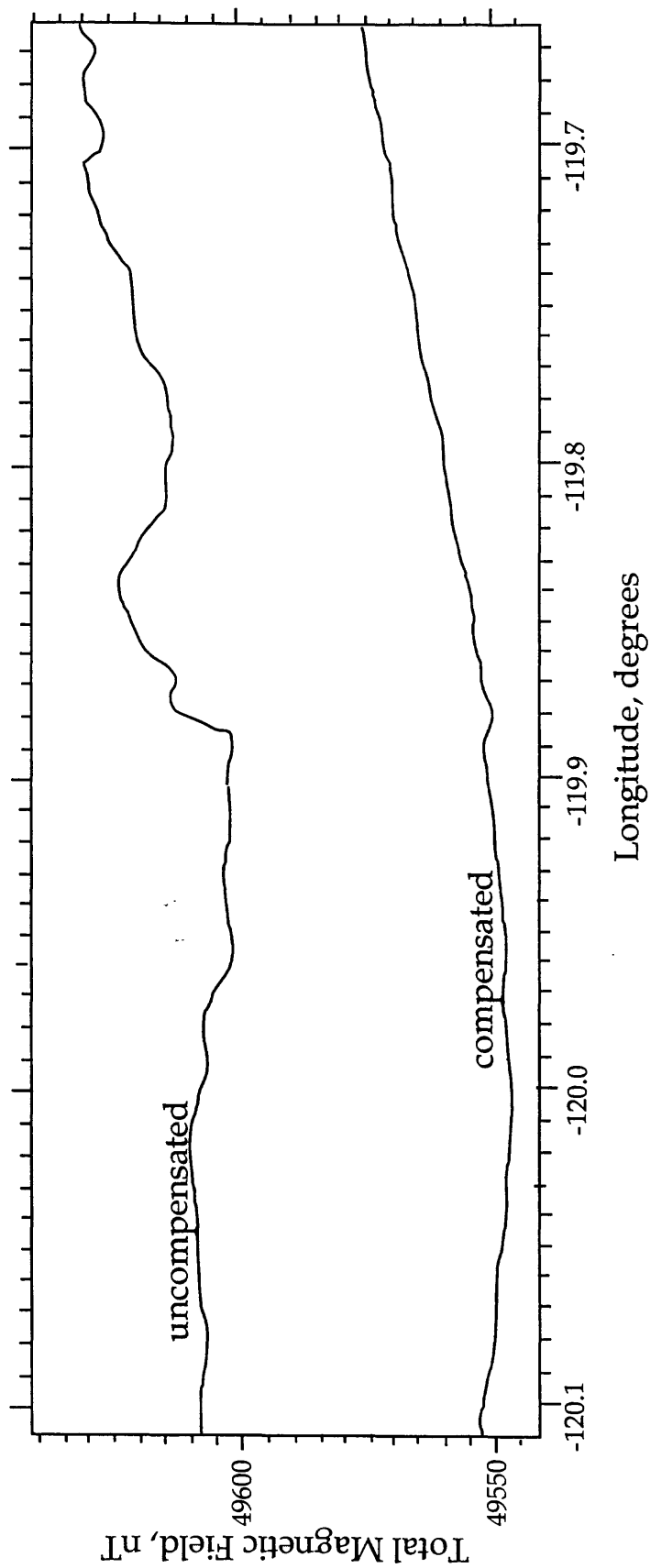


Figure 13. Enlarged section of figure 12, revealing small variations due to noise in the compensated field in comparison to those in the uncompensated field.

Figures 14-16 are magnetic profiles of three test lines flown over the same ground track. They indicate the presence of DC shifts about 50 nT in amplitude that have not been removed by the compensation method nor are they altitude correlated. The largest portion of the shifts occurs during turns but there also seems to be a long-wavelength component that varies slowly along the profiles. (A suggestion that the magnetometer was undergoing large temperature swings was later refuted by Lynn Edwards who found that even large temperature variations would cause much smaller magnetometer error.)

Figures 17 and 18 show a step of 32.8 nT in amplitude that is uncorrelated with any maneuver. Steps of this size and character could easily result from on-board electrical systems and, if occurring primarily during turns, could account for a large portion of the DC shifts mentioned above.

The first cut at compensating the ER-2 for magnetic effects has given better results than were at first anticipated. If the DC shifts can be eliminated, it appears that the compensation procedure will yield consistent and accurate data.

Logistics

The goal of these compensation tests was to determine the degree to which aircraft generated noise could be removed from total-field magnetometer data using standard techniques. These tests may also have given insight regarding uncompensated noise and additional tests to perform. The mission goal is to remove all flight related noise larger than a few nanoTeslas. Noise not related to flight (e.g., daily variation, magnetic disturbances, etc.) must also be removed; however, they are discussed below in a different section.

Doug Hardwick's compensation procedures removed maneuver correlated noise to within mission acceptable limits. However, in addition to maneuver correlated noise, there were large DC shifts varying randomly in amplitude up to 90 nT. These shifts seemed to occur during banking maneuvers but it is unclear whether they are stepped or gradual. A gradual change in DC level of up to 30 nT amplitude also would occur while in straight and level flight. It could be part of the DC shift phenomenon.

These shifts are of great concern in accomplishing the mission goal because they will compromise the long-wavelength data, the collection of which is a primary mission justification. The shifts cannot be compensated by any standard procedures because they occur while in flight and are uncorrelated to maneuver. Therefore, an understanding of their origin (see below) must be gained before devising a removal method.

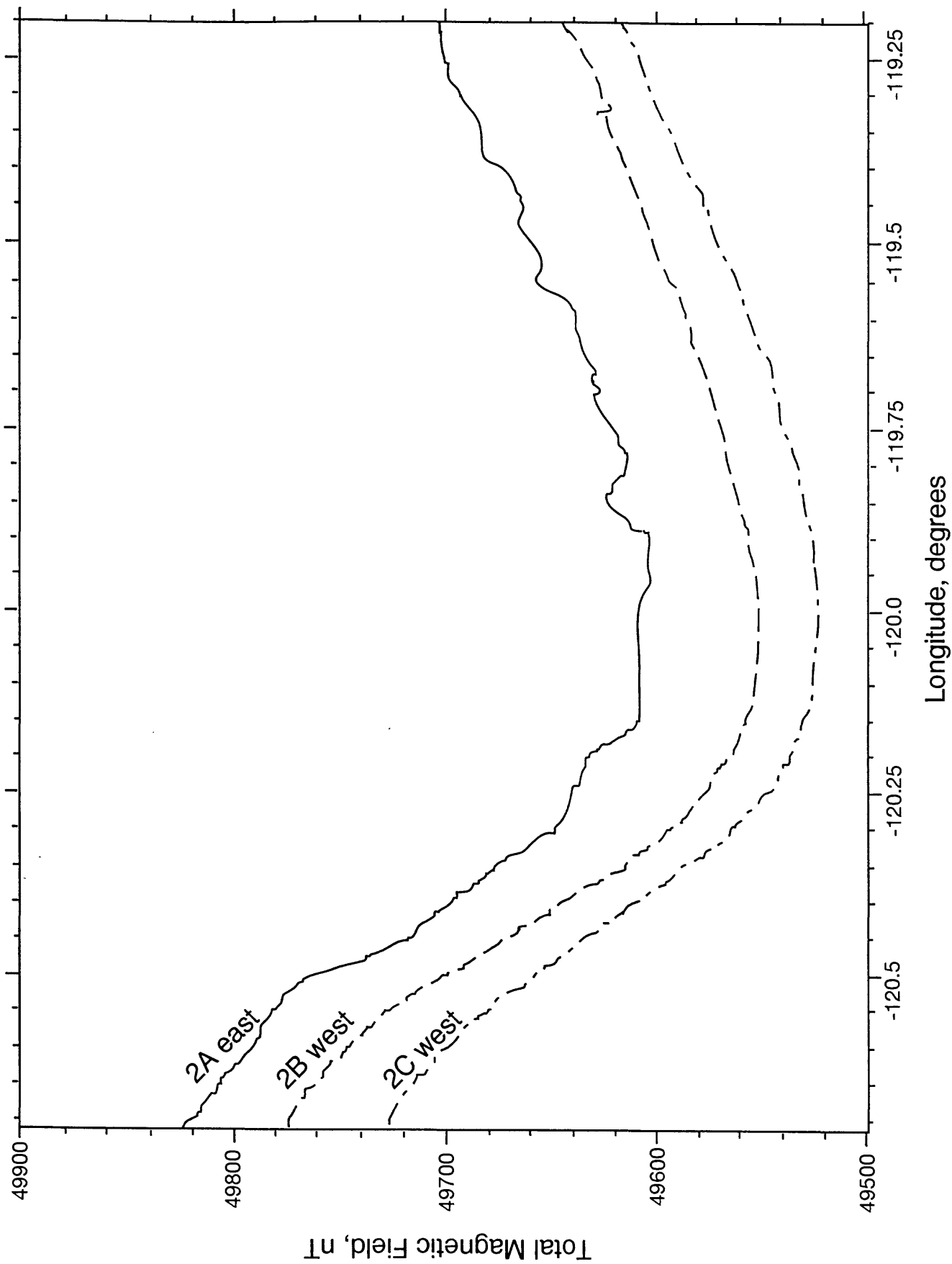


Figure 14. Comparison of uncompensated total magnetic field data along 3 flight lines (from test flight 5) showing DC offsets. After compensation (see figures 15 and 16), the lines should overlap with the exception of a roughly 2 nT noise level.

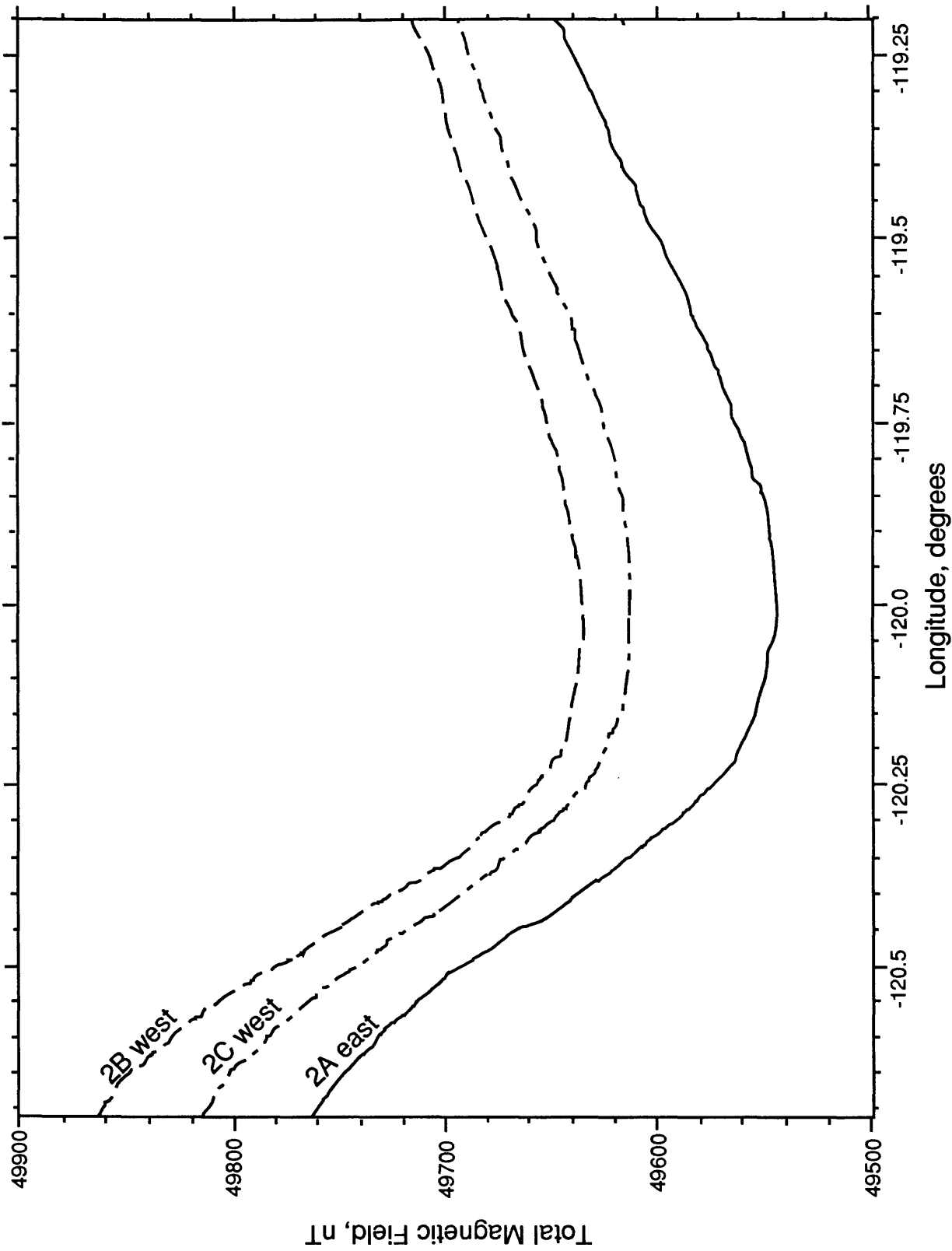


Figure 15. Comparison of the same data shown in figure 14, but the data have been compensated for maneuvers. The maximum difference in data values between lines is roughly 100 nT. Note that although compensation considerably changed the DC value along each flight line, the differences in data values between flight lines remains high.

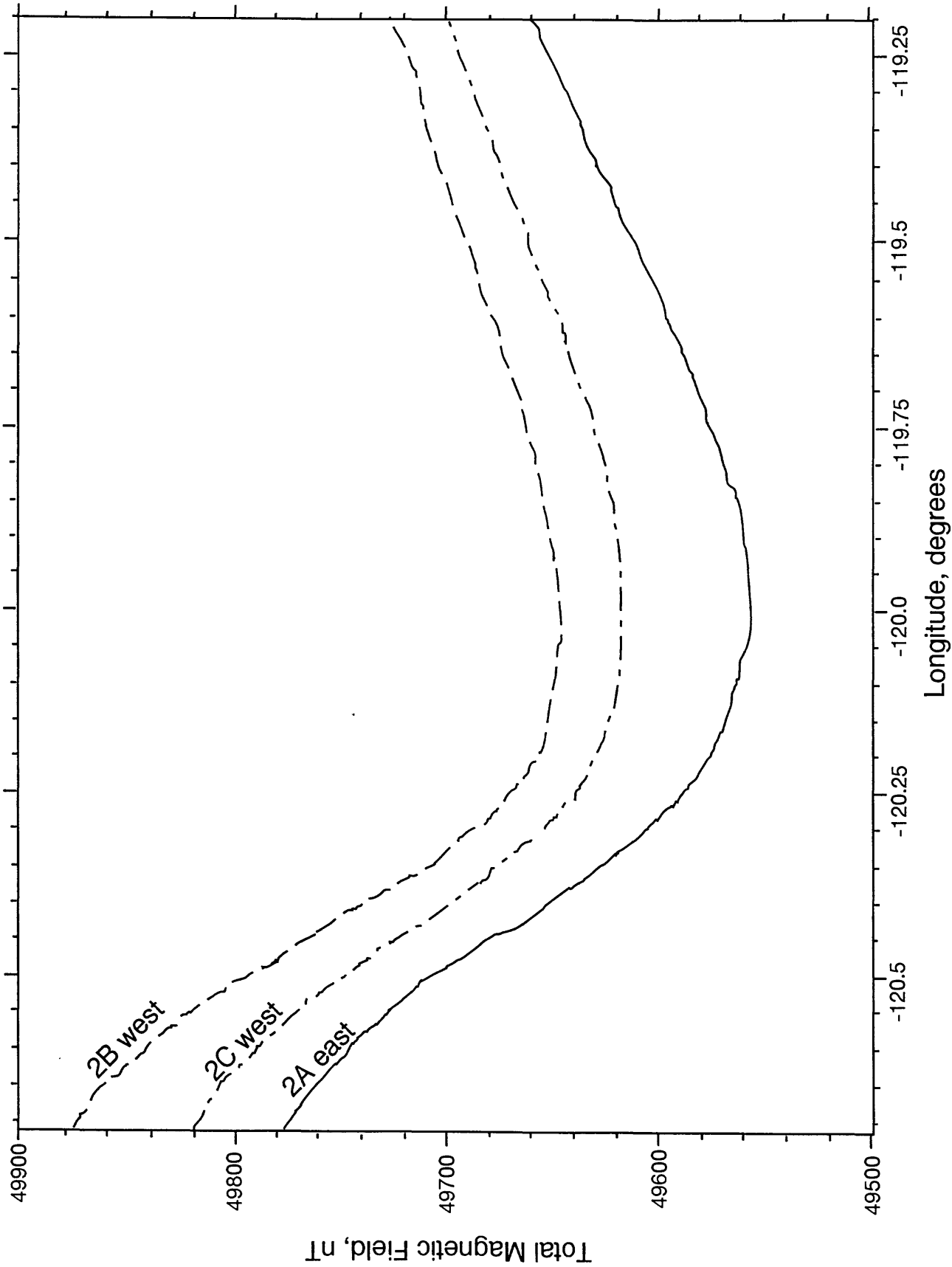


Figure 16. Comparison of the same data shown in figure 15, but the data have been corrected further by compensating for diurnal variations. Significant DC offsets remain between these flight line data.

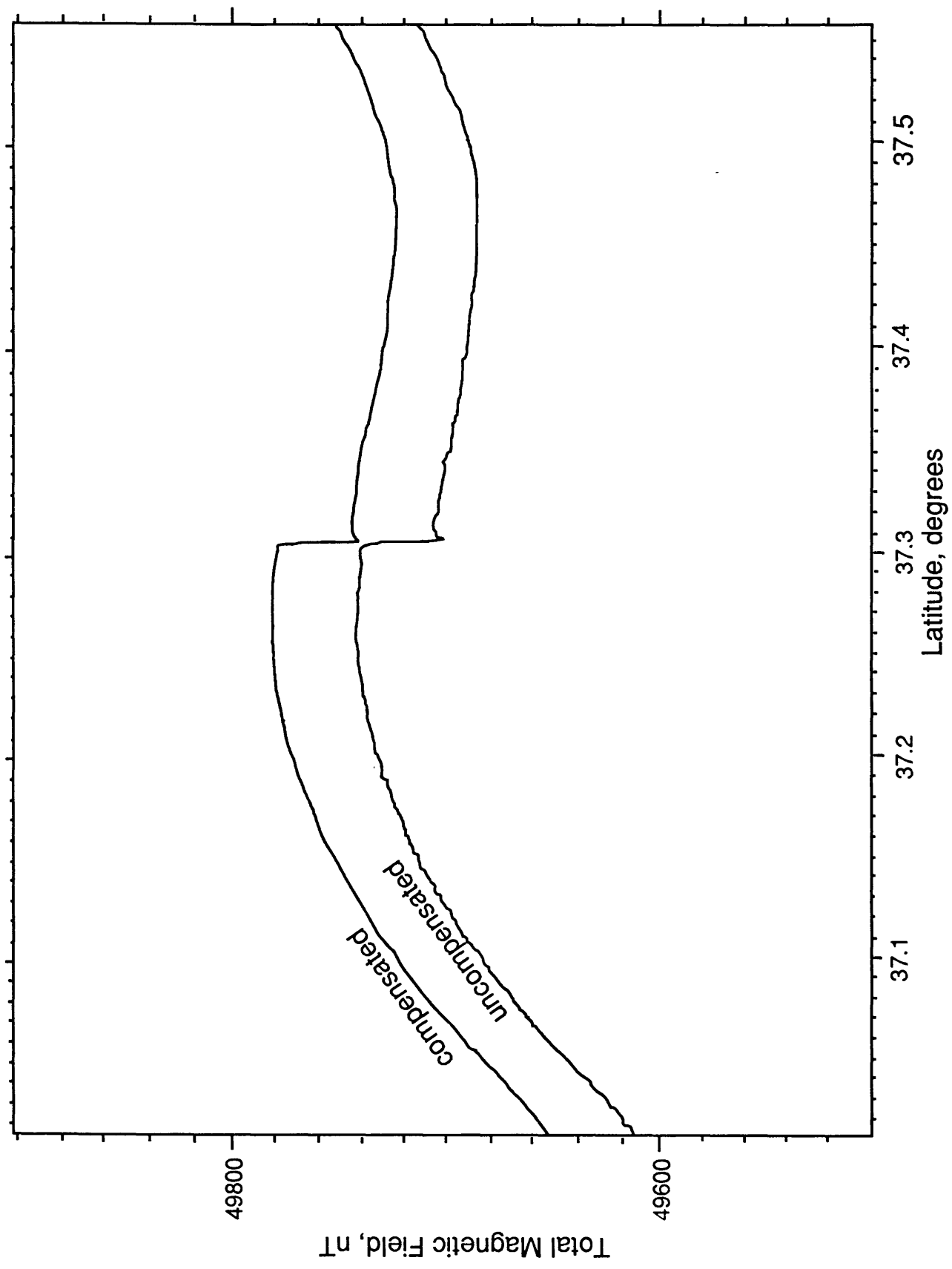


Figure 17. Test flight 5 total magnetic field data showing a large step in the field, unrelated to maneuvers or diurnal variations.

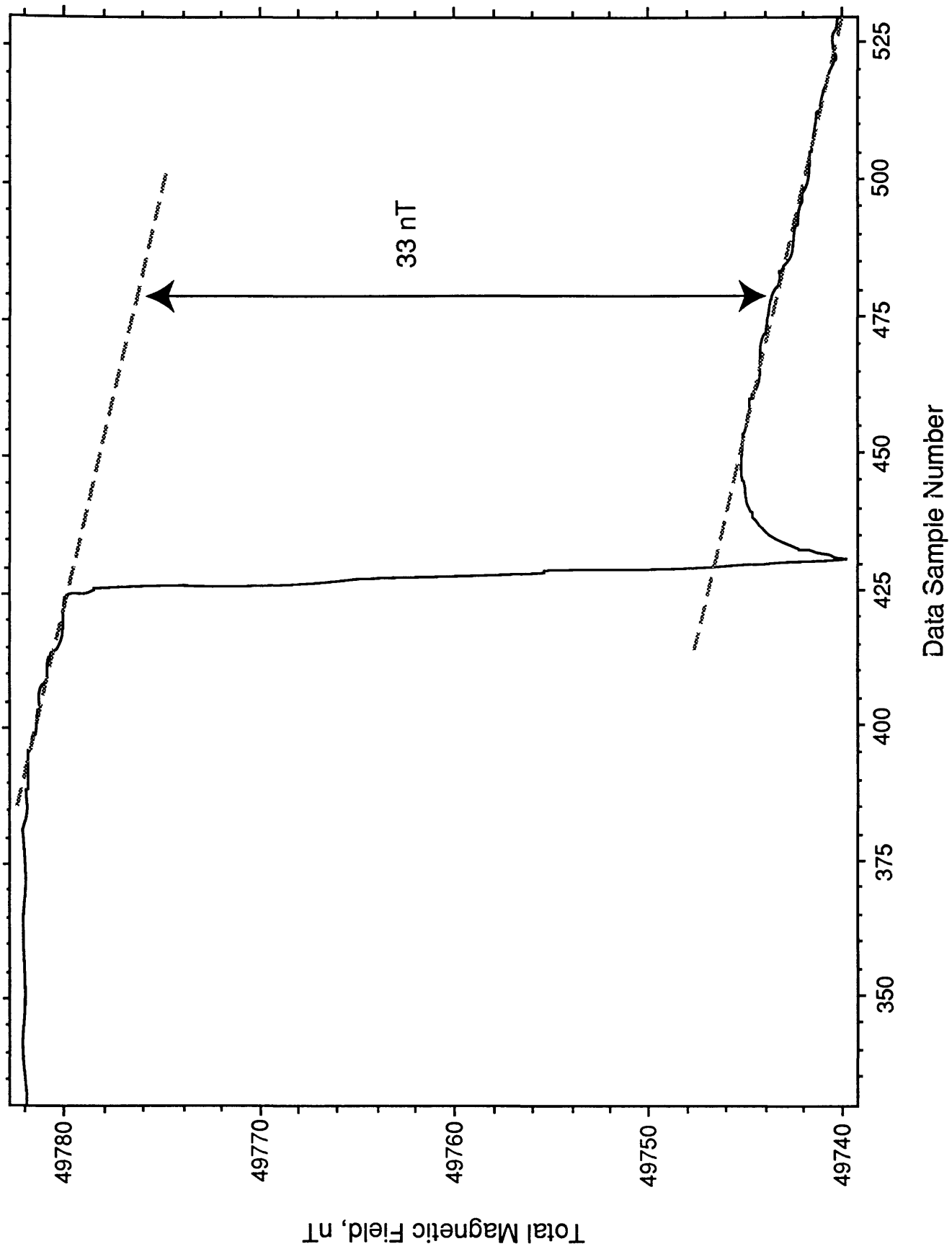


Figure 18. Enlarged section of the data shown in figure 17, showing the 33 nT step in more detail.

Recommendations

The following recommendations are based on the data we have received from the six test flights:

1) The origin of the DC shifts must be determined and confirmed through flight testing. The current hypotheses are: a) on-board systems are generating extraneous fields and b) Thompson-effect currents are being generated by extreme thermal gradients near the magnetometer sensor. Other hypotheses (see below) are possible, but the two mentioned above should be tested first. The on-board systems probably can be tested on the ground. It may also be possible to test the Thompson-effect currents on the ground.

2) A series of test flights should be arranged to determine whether or not landing/maintenance/takeoff will cause significant perm changes. The results of these tests will have direct impact on the short compensations described below.

3) Three compensation procedures are recommended: a) a "long" procedure would require about an hour to complete. It would consist of a square figure of merit pattern and two or three four-heading checks; b) a "short" procedure consisting of one four-heading check would take about 10 to 20 minutes depending on the altitude at which it can be flown. The times for a) and b) do not include transit time; and c) an online "check" (taking no extra flight time) would consist of a few rolls and pitches while online. These compensation procedures should be performed according to the following guidelines:

- A long compensation over an observatory immediately BEFORE and AFTER any significant change to the aircraft or magnetometer. Among other things, these changes would include altering the attitude of the magnetometer sensor or changing aircraft.
- A long compensation (not necessarily over an observatory) near the mid-point magnetic latitude of each 3-degree-wide band of flight lines. According to the current flight plan, that would translate into a long compensation for each 10 flight lines. These data should also be applicable to the tie lines as long as the aircraft and magnetometer configuration have not changed and there is no evidence that the compensation has changed. If it has changed, the current tie-line block should have a long compensation for every 3° of magnetic latitude. It is expected that data gathered from long compensations will apply for much more than $\pm 1.5^\circ$ of magnetic latitude. However, the mission should be planned to include them at that frequency; if it becomes obvious after a few tests or mission flights that they are not needed as often, their frequency can be reduced.
- A long compensation if more than 2 weeks has elapsed since the previous one, or if an along-line compensation check reveals that a serious compensation error has developed.

- A short compensation at the beginning of each flight. This procedure is only necessary to characterize any perm changes that might have occurred during landing and take-off. Although unlikely, if test or mission flights indicate that perm changes are not significant or that they can be characterized by some other means, then the short compensation may be eliminated. This compensation becomes more important if tie lines are not used.
- An online compensation check once or twice during each flight. The location or duration of this check may be constrained by SAR data collection requirements.

Guidelines for Compensation

by Doug Hardwick (National Research Council of Canada)
 [Following text presented at the workshop]

My objectives have been to assure that robust compensation of the system is possible under all conditions and in particular, that consistent measurement of the absolute value of total field can be obtained throughout the project. My analysis, as presented at the workshop, shows that good compensation can be obtained with the system as flown in the test flights and the recommendations that follow address the stability of total field measurement. In addition, I am interested in techniques for reducing or eliminating tie lines. A lateral gradiometer configuration can achieve this goal, but such a system would require more airframe work for two wingtip gradiometers, and the front-end magnetometer processing would have to be upgraded.

Recommendations

For consistent absolute value measurement of total field, the following issues need to be addressed:

1. Absolute value of total field measurement after (or before) compensation can only be tested by flying over a point of known field value at a specific height, with that point tied to a permanently maintained reference magnetometer.
2. Experience flying a number of aircraft over the established reference point at Ottawa has shown that the compensation solution can be fine tuned to give reasonably high assurance of correct absolute field measurement after compensation.
3. If an established reference point is not available, the next best approach is to establish a point at survey altitude near home base, in a low gradient area, preferably on the transit path to and from the survey area. The point should be as close as possible to a continuously operating ground magnetometer. The point should be overflown on the four headings corresponding to the axes of the survey, to form a

four-heading check. Guidance should be done using the highest possible accuracy, real-time differential global positioning system (DGPS), with waypoints defined for tracks sufficiently long to allow stable flight over the point.

4. On a four-heading check, a scatter of less than 2 nT assures reasonable low frequency compensation. Any departure in the four-heading mean value, when calculated with respect to the base station reference magnetometer, should be used as a correction to the current total field measurements. The four-heading check should be done at the beginning of each survey flight.

5. In the compensation procedure, robust coefficients that allow evaluation against a standard, can best be obtained by flying a square pattern, either on cardinal magnetic headings or on the principal axes of the survey, in a low gradient area. This procedure is sometimes referred to as a figure of merit (FOM). On each heading, there should be four pitches and four rolls, starting with slow, large amplitude inputs and ending with a small cycle at the natural maneuver frequency of the aircraft. The small, fast maneuvers must not excite wing flexing or any other structural bending. Turns between headings should be at the maximum bank angle allowed by the magnetometer. (It should be noted that a discontinuity in the magnetometer signal will void the compensation sequence.) The legs should be flown on DGPS such that they are of equal length, so that the average local horizontal gradient will be close to zero and will not be absorbed into the compensation solution. A small departure in heading to maintain track is less important than maintaining the balanced pattern. The whole procedure should not take more than 12 minutes in areas where the magnetometer allows reasonably large bank angles.

6. It is not uncommon for the magnetic signature of an aircraft to change from one flight to the next. Some causes are obvious, such as the addition of magnetic parts or components to the airframe, or flying with a different electrical configuration from that of the pilot's magnetic check list. A more subtle cause of signature shift is the high currents drawn by the engine starters. The fields from these currents can drive a steel component to saturation and because of hysteresis, when the field disappears, the component remembers the ambient magnetization from the earth's field, which may be different from the magnetization that it had at the time of compensation. It is for these reasons that four-heading checks are recommended throughout the project.

7. A final quality control item is recommended that does not add to flying time. Two or three times on a line, two pitches and two rolls of about 1 to 3° should be executed. This gives assurance that the compensation is correct; if it is, the maneuvers will not be evident in the data. If the compensation is not correct at these points, there is in the compensation algorithm a "trim-up" procedure that corrects the compensation without changing the DC value of the total field measurement.

8. A hardware recommendation is that the pilot should be provided with some form of visual indication of when the magnetometer ceases to operate due to exceeding the bank angle for a particular magnetic latitude. This will be particularly useful at the lower field inclinations where the bank angle limit is expected to be around 10°.

Quality Control Proposal for Calibration Maintenance and Aircraft Compensation

by Doug Hardwick (National Research Council of Canada)

This is a proposal for maintaining the integrity of total field measurement throughout the project. It is an amplification of my presentation at the workshop, which is given in the previous section entitled "Guidelines for Compensation."

Basic Compensation

The model that I have used on the ER-2 has the following characteristics:

- It is insensitive to changes in total field and declination angle (dip); the calculated coefficients are robust with respect to these two parameters. In other words, the model is insensitive to changes in magnetic latitude.
- The compensation model is insensitive to small-to-moderate diurnal variations (DV) that occur during the compensation process.
- A robust compensation data set can be collected in approximately 12 minutes at ER-2 flying speeds.
- The compensation model produces the correct DC value (i.e., steady-state) of total field to within 1 or 2 nT. This has been demonstrated by a number of survey aircraft flying this model over a calibrated, diurnal-corrected test point in Ottawa, maintained by the GSC as a national standard. Aircraft flying GSC-sponsored surveys are required by contract to do this calibration at this test site or at a similar one in western Canada.
- The compensation model cannot compensate for non-maneuver related changes in an aircraft's magnetic field or for non-linear effects such as magnetic hysteresis, magnetic effects of control surface movement or magnetic effects of structural deformation.

From the first test flights, it can be seen that the model is effective in compensating the ER-2. Although the compensation maneuvers were not particularly suited for the model, it was possible to use the first cloverleaf from Flight 3 to compensate

adequately the remainder of that flight, as well as Flights 4 and 5. The Flight 3 coefficients were surprisingly robust (see figures 12 and 13).

Maintaining Total Field DC Integrity

Although the compensation procedure can produce a nearly correct DC total field value, for continental-scale tie lines such as were flown for the North American Magnetic Anomaly Map, this feature was not relied upon. Furthermore, I can state with confidence that in virtually every survey aircraft, there are flight-to-flight changes that occur as the result of landing, engine starting and other ground operations. It would be wasteful of flying hours to have to carry out a compensation for each flight. A better alternative is the procedure I proposed based on the four-heading check. Basically, this consists of defining a point in space as accurately as possible using high quality DGPS, as close as practical to a ground reference magnetometer, that can be conveniently flown within the operation envelope of the ER-2.

After the last compensation before the start of the first survey flight, this point would be flown on the four headings corresponding to the axes of the survey. The mean value of the four total field measurements, along with the reading of the ground magnetometer, would be taken as reference values for the survey. On every subsequent flight, this procedure should be carried out and any change from the four-heading reference value, taking into account the corresponding value of the ground magnetometer, should be used as an adjustment to the measured value of the total field.

In moving to a new survey block, the current reference point would be flown and at the end of the transit flight, a new (pre-determined) reference point would be flown, thus effectively transferring the original reference value to the new point.

Several practical aspects of the four heading check have to be considered, in particular the flight time required to fly the procedure. I have suggested that once the reference has been established using the four headings, an acceptable compromise would be to fly just the two headings corresponding to the survey lines. The procedure can be shortened by flying steeper turns than allowed by the magnetometer operating envelope, just so long as the magnetometer is operating at the time the reference point is overflown. Another possibility would be to establish the reference point at a lower altitude than the 19.8 km (65,000 ft) survey altitude, where the aircraft can fly slower; if the point were established approximately on the transit leg to and from the base, flying time would be saved and it would have the added advantage of being closer to the ground reference magnetometer, assuring better spatial coherence. The success of the procedure is dependent on this spatial coherence, which is discussed extensively elsewhere in this document.

In summary, this DC reference procedure ensures integrity of total field measurement throughout the project. With this confidence, one big variable will be eliminated from the critical task of tracking the DV during the survey flights.

Further Quality Control Measures

The above DC reference procedure does not mean that the basic compensation can be neglected throughout the project. Magnetic changes can occur in the aircraft that can affect the quality of long wavelength measurements. Fortunately, such changes can be detected without additional flying time. I have strongly recommended that on every line, at least twice, two or three small pitches and rolls be flown. If a significant change in the magnetic signature has occurred, it will show up in the data; in the compensation algorithm, there is a trim-up procedure that resets the sensitive compensation coefficients based on these maneuvers without changing the DC value of the total field measurement. If maneuver noise does not show up during these trim-ups, there is good assurance that the compensation is correct down to the lowest frequency values, excluding, of course, DC, which is being controlled as outlined above.

If the trim-ups showed substantial maneuver noise, a new compensation would be called for (this requires 12 minutes, excluding transit time). After the compensation, a four-heading check would have to be carried out to readjust the DC value to the reference.

Conclusion

In the vast majority of aeromagnetic surveys, little attention is paid to the absolute value of the total field measurement; the regional field is usually removed, leaving the anomaly field. An exception was in the flying of long tie lines in support of the North American magnetic anomaly map, where the National Research Council of Canada's Convair 580 flew tie lines over the eastern part of the continent from the north pole to the Caribbean. The methods I am proposing for the ER-2 project are those used in the previous project and which were effective. I believe that starting with proven techniques is a more reliable approach than developing new ones on the fly that might require considerable flight time to validate.

The material that was presented on my behalf at the workshop, can be read as background in support of the methods outlined above.

Are Tie-Lines Necessary for the ER-2 Mission?

by Misac Nabighian (Newmont Exploration)

I would like to submit for discussion the proposition that tie-lines are not only unnecessary for the ER-2 mission but will lead to a degradation of the final product.

To determine the compensation coefficients for a given area we carry out a figure of merit (FOM) flight. The roll, pitch and yaw data collected are combined with the known parameters of the earth's magnetic field (i.e., field intensity, inclination and declination) to produce the compensation coefficients. Normally we assume that the magnetic field parameters do not vary significantly over the survey area: a reasonable assumption for small exploration type surveys.

For the ER-2 mission we will be flying E-W lines. The proposed tie-lines will be flown N-S and be quite long. We will have enough problems trying to compensate the magnetic data flown E-W, given the changing values for the magnetic field parameters over long distances. It will definitely require some thought on how this can be accomplished with one or two FOM flights.

For tie-lines this problem becomes even more critical, since the magnetic field parameters (especially field intensity and inclination) vary much more rapidly in the N-S direction than in the E-W direction. The compensation of the tie-lines will be highly questionable, resulting in a final product with gross errors.

Since the position in space of ER-2 will be known with better than 0.5 meters in X, Y and Z coordinates I propose to do the best compensation we can on E-W lines, using multiple FOM flights, and then use any of the available techniques (e.g., equivalent source, etc.) to reduce the magnetic data to a plane of constant elevation. I submit this is a more accurate procedure than using improperly compensated tie-lines. In addition, such a procedure has an inherent "smoothing" included in the process.

For those who feel uncomfortable with such an approach, we can include at most four tie-lines connecting only the ends of each survey region (i.e., one tie-line each on the East and West coast, and one tie-line each 1/3 of the way inland).

Since we will be probably flying multiple magnetometers, including hopefully two Potassium magnetometers at each wingtip, such an approach can also take into account any DC shifts observed while compensating the data.

The amount of time and especially money saved by this approach can be more profitably used elsewhere.

Comments by Rob Bracken:

In response to Misac Nabighian's proposition, "Are tie-lines necessary for the ER-2 mission?", following are some of my thoughts:

My feeling is that we will need the tie-line data. If we do remove them, it should only be after a thorough study of the all the implications.

Discussion of the proposition elements

Flying the tie lines by itself cannot degrade the product. However, as Nabighian clearly states, the resources to fly them may be better spent elsewhere. This consideration of funds is the strength of the no-tie-line argument. If it appears that by flying tie lines we will have to reduce the number or quality of the compensation flights to stay within a time or money budget, then the discussion becomes a comparison between the benefits of tie lines and the benefits of compensation flights (or other tie-line substitute activities). If, however, the budget permits both, we should fly the tie lines to be safe. Traditionally, we have always flown tie lines because they are cheap (relatively) insurance. In this case however, the insurance is not so cheap; and the budget may be of great concern.

Scientifically, the primary argument against tie lines is that the limited scope of compensation coefficients will create a potentiality for systematic errors that depends upon magnetic latitude. I agree that this potentiality exists (Rob Bracken, personal communication, 1995).

However, the argument goes on to imply that the systematic error can neither be characterized nor removed; the end result being "a final product with gross errors." This idea must be examined carefully, and I would disagree as follows. The notion that we can do without tie lines implies that there is a substitute method available that can aptly perform the tie-line function. However, the substitute method would have to be able to characterize the same systematic errors that were used to argue against tie lines. In other words, if we have the ability to do without tie lines, then we also have the ability to fix whatever may be wrong with them.

I believe that we can compensate the tie lines. In fact, the very existence of the tie lines will probably yield valuable information indicating how compensation errors propagate as a function of latitude. This understanding may become a critical factor in characterizing subtle but destructive latitude dependent errors along flight lines.

However, I do agree with Nabighian in that there may be other ways to compensate without tie lines. Traditionally, I have not collected tie line data for small area surveys. I have always felt that a better absolute accuracy is available without all the assumptions of a tie-line program. (Of course, in the small area survey, the transfer function between the base magnetometer and the aircraft is practically one, a matter for further discussion.) Also, heading dependent compensation errors are easily removed visually as well as by numerical methods (such as mentioned by Nabighian). Therefore, I agree that we likely will be able to find a compensation method that will effectively remove latitude dependent compensation errors.

Daily variation correction

In addition to providing corrections for poor compensation, tie lines also provide corrections for errors due to daily variation (DV) of the magnetic field. In a small area survey, the variations at the base magnetometer are very nearly the same as those at the aircraft. Therefore, the variation at the aircraft can essentially be measured directly. This procedure will not work in a survey of continental scale. We are currently looking for ways to characterize the DV at great distances from base stations; everything that has been proposed involves fairly complicated models and many assumptions, none of which has been field tested at this scale. My experience has shown that employing untested processes is a formula for failure and when collecting data, the use of elaborate models can be risky. If it can be done, a measurement is always best.

Usually when tie lines are flown, the position of the aircraft is not well known, especially the altitude. In this case, the position in time and space will be accurately known. Therefore, a large portion of the ambiguity normally associated with tie lines will not exist. Thus they will more accurately produce corrections to DV as well as compensation.

The errors I have seen in the DV model can be 10 or 20 nT during the mid-day peak in middle latitudes (50 nT in Alaska), which is much larger than the roughly 5 nT or targeted for this survey. With the additional error introduced from upward continuing 19.8 km, there is reason to believe that the diurnal model may not perform well enough to fly without tie lines. My previous recommendation (a minimum of 3 tie-line crossings per flight line) gives about one crossing every 45 minutes, enough to help quantify amplitude errors in the DV model.

I would recommend planning to fly the survey with tie lines. Later, if we discover that the crossings are consistently within a few nanoTeslas abandon the tie lines. However, I would predict that the crossings will have much larger errors and the tie-line correction will need to be applied.

Comments by Doug Hardwick:

This note is in response to the concerns expressed by Misac Nabighian with regard to compensation for tie lines being affected by changing magnetic field intensity, declination and inclination. At the outset, I must state that I understand Misac Nabighian's compensation methods only in general terms and I am certainly not up to date with his latest techniques. On the other hand, I do know that my compensation model is insensitive to magnetic field parameters and we have demonstrated this while flying out of Resolute Bay, which is very close to the North magnetic pole. Therefore, I do not see any problem on tie lines if my algorithm is used.

The above declaration does not mean that I am making a case for tie lines. As I stated in an earlier note, I would be enthusiastic about flying a lateral gradiometer, in that if it is sufficiently accurate, good leveling can be achieved without tie lines. The down side is that a gradiometer is many times more complicated than a total field system and requires more sophisticated hardware.

Comments by Bill Hinze:

Misac Nabighian has come up with original and useful thoughts. They deserve careful consideration, most particularly from those who are versed in compensation problems. The problem of changing compensation coefficients especially along north-south lines is difficult to evaluate without some real numbers (estimates?). What is the magnitude of the problem in terms of both precision and accuracy? If the errors will exceed a reasonable error envelope, is it possible to put a latitude/longitude term into the error coefficients based on empirical evidence? Further, if the errors do exceed the envelope will they at the tie points be the same? If so, can they be used for estimating temporal variations even if they cannot be used to tie the survey together?

I am very concerned that without tie lines, the survey cannot be adjusted for temporal variations. How else can we approach the problem (permanent and temporary base observations)? Will the lack of tie-lines lead to a perception about the survey that is undesirable?

Important Mission Questions Answered with Educated Guesses

by Rob Bracken (U.S. Geological Survey)

The first 6 test flights have given us a feel for the mission viability including the ER-2's magnetic environment, instrument installation requirements, flight characteristics, data acquisition procedures, and communications with pilot and support personnel. The next set of tests should be designed to answer specific fundamental questions that have arisen; the answers to which are necessary for defining mission procedures. I will answer each question with an educated guess that will form the foundation for both the testing and mission procedure recommendations.

1) What is causing the 90-nT shifts and what must be done to minimize them?

Data from the 3 repeat lines flown in the simulated survey during test flight 5 (11/2/95) revealed a large-amplitude, long-wavelength magnetic phenomenon. The source of this variation either must be close to the magnetometer or it must be very large. Because the ER-2's turbo-jet engine is a high-energy device, it has the potential to be a large magnetic source. Engine-caused magnetic fields (turbo-magnetics) may

be of sufficient amplitude and character to produce the DC shift phenomenon. Some possible mechanisms are as follows:

- The rotating turbine likely has some accumulations of charge at a finite radius from the centerline. The turbine's tremendous rotation rates could easily convert these charges into substantial annular currents, with variable amplitudes dependent upon revolutions/minutes and other engine parameters.
- Mario Acuna pointed out that Thompson-effect currents flow through electrically conductive materials along the direction of thermal gradients. The engine has the potential to set up large thermal gradients within metallic cowlings, causing electrical currents with unpredictable orientations.
- If charge imbalances or ionized particles exist within the combustion chamber, they would be accelerated to high velocities producing a net longitudinal current or an associated electromagnetic phenomenon assuming a mechanism exists to produce sufficient charge separation.
- Certain metallic parts in the engine may be near the Curie temperature; and small variations in their temperatures could cause perming and de-perming.

Because the engine runs at a nearly constant power output, there is probably a DC turbo-magnetic level associated with its operation. However, there may also be long-wavelength variations riding on top of the DC level resulting from variations in flight condition and power output. Some of these variations may even be low-pass filtered by heat capacities and insulation.

The back of the superpod is only 4.3 m (14 feet) radially away from the engine's axis and longitudinally centered; it is not unreasonable, therefore, to assume that the turbo-magnetics are large enough accumulatively to produce 90 nT variations at the sensor's location. If this hypothesis is true, then a calculation can be made indicating the turbo-magnetics' potential effect at the wingtip. The superpod is 4.33 m (14.21 ft) from the engine axis and the wingtip 15.75 m (51.67 ft) giving a 0.275 ratio. Estimated variations at the wingtip are:

$$\begin{aligned}90 \text{ nT} * 0.275^3 &= 1.9 \text{ nT (dipolar point source)} \\90 \text{ nT} * 0.275^{2.5} &= 3.6 \text{ nT (short line of dipoles)} \\90 \text{ nT} * 0.275^2 &= 6.8 \text{ nT (infinite line of dipoles)}.\end{aligned}$$

Although these values are marginally within mission acceptable limits, it may be possible to reduce them further by putting a primary sensor in the wingtip and a secondary, engine sensor in the superpod. These two sensors working together would act as a gradiometer that could be calibrated through test flights to characterize engine noise. I estimate that engine effects could then be reduced by an order of magnitude to better than 0.4 nT in the total field. Because there is only one

engine and it is equidistant from the wingtips, the turbo-magnetics should have a reduced effect on a wingtip lateral gradiometer. However, it may still cause difficulties.

It will probably be necessary to design a compensation procedure to minimize the turbo-magnetic effect (using both superpod and wingtip magnetometers). However, the nature and complexity of this compensation is unknown until a better understanding of the source is gained through tests. For example, measurements could be made on the ground with a portable magnetometer for "engine on" and "engine off" conditions to establish the reality of a turbo-magnetic effect and its characteristics.

2) Where are the best locations for mounting primary sensors?

The best locations for mounting primary sensors are most likely the wingtips. Although we do not yet have knowledge of all compensation related problems at the wingtips, I am fairly certain that the close-in locations (superpods, tail, and Q-bay) are too close to the engine for reliable compensation. The mid-range areas (the system20 pod and nose, fig. 1) would improve turbo-magnetics responses and should be examined from that perspective. However, the wingtips hold the most promise from the turbo-magnetics standpoint. A trade-off is that the wingtips are most susceptible to wing flexure. However, it may be possible to characterize wing flexure by placing accelerometers in each wingtip and the fuselage. Although compensating for the wing flexure may be difficult, it will probably be easier than characterizing the turbo-magnetic effect.

3) How large an effect will the landing/maintenance/takeoff sequence have?

The landing/maintenance/takeoff sequence is usually significant in larger aircraft. How this particular aircraft responds can only be known from flight testing and experience. Therefore, until more data are available, we should expect the existence of DC shifts significant enough to require a four-heading check on every flight.

4) Over how many degrees of magnetic latitude will a given compensation yield a datum that is constant to within a few nanoTeslas?

The effect of magnetic latitude is difficult to evaluate. However, Misac Nabighian has expressed serious concerns about stability with respect to magnetic latitude and therefore it is a subject worth consideration. The purpose of this question is to develop a basis for estimating how far (in magnetic latitude) we can go between compensations. One basis may be to use the attitude envelope of the aircraft during a compensation flight and then disallow magnetic latitudes that must be extrapolated. During an ER-2 compensation flight, the maximum pitch is about $\pm 1.5^\circ$. Therefore, I believe that a given compensation will yield a datum that is constant to within a few nanoTeslas over a $\pm 1.5^\circ$ range. Because this basis is probably

the most restrictive case, it constitutes a MINIMUM latitude change between compensations.

5) Can compensation procedures performed in differing uncalibrated airspaces produce the same datum to within a few nanoTeslas?

Doug Hardwick states guardedly that when the compensation minimizes differences between the cardinal headings, the average crossing value is calibrated. However, when making procedural recommendations, he does not rely on this relation. Therefore, we should attempt always to find (over observatories) or to make (over a base magnetometer) calibrated airspaces for compensation and four-heading checks.

6) Will compensation coefficients need to be changed over time?

It is likely that small changes in aircraft magnetic fields may sum over time to produce a measurable effect that may become visible over a period of days or weeks.

7) How can geomagnetic temporal variations be removed from a compensation flight?

Geomagnetic temporal variations can be removed from a compensation flight by two basic approaches. The first would be to model the field at the aircraft by establishing a transfer function between a nearby observatory and the compensation flight location. The second would be to use the compensation data set itself and separate or cancel a temporal component. Either or both of these methods would probably be acceptable for these compensations.

8) How can geomagnetic spatial variations be removed from a compensation flight?

Geomagnetic spatial variations can be removed from a compensation flight by two basic approaches. The first would be to model the field at the aircraft by upward continuing existing data to the flight level. The second would be to use the compensation data set itself and separate a spatial component. Misac Nabighian's compensation routine does this function by fitting the spatial component to a 3rd order surface. Doug Hardwick's routine does it by requiring a square compensation pattern to cancel gradients.

9) Will compensation coefficients need to be changed during a flight?

If compensation coefficients need to be changed during a flight, the necessity could be indicated by making an online compensation check once or twice during the flight. Doug Hardwick's compensation routine has a built-in function for adjusting compensation parameters.

10) What is the attainable level of repeatability?

The attainable level of repeatability should be measured during the test-flights; I believe that ± 2.5 nT is not unreasonable within the DC to low frequency range.

DIURNAL AND REFERENCE FIELD

by J. D. Phillips (U.S. Geological Survey)

The purpose of the diurnal/reference field group² is to assure that the geomagnetic reference field and diurnal variations are correctly removed from the ER-2 high-altitude magnetic survey.

Summary

The relative importance of diurnal field effects in the high-altitude magnetic survey data will depend on the level to which the data can be compensated for the magnetic field of the aircraft. If, as the initial test flights indicate, the data can be compensated to within 1 nT, then diurnal effects will be important.

During the October/November test flights, observed diurnal effects at the Fresno magnetic observatory consisted of 10 nT/hour long-term changes produced by the solar quiet daily (or Sq) variations, and 1-3 nT short period excursions produced by micropulsations. Geomagnetic conditions during the test flights were characterized by a substorm K index of 3, which corresponds to the maximum level of disturbance normally allowed for flying a regional aeromagnetic survey.

Observatory one minute values are the result of passing a 120 second gaussian filter over 5 second samples; there is virtually no aliasing. Digitization noise at the observatory is less than 0.1 nT.

Diurnal effects at 22 km altitude are expected to be the same as at ground level, but possibly with higher amplitudes due to closer proximity to the sources.

The largest source of survey error will be neither the aircraft noise (~ 1 nT rms) nor the diurnal field (1-50 nT during the day, 1-5 nT at night). The largest source of error will be the missing flight lines, which will produce errors of 35 to 100 nT in a crustal anomaly field with a total range of 1000 nT.

One way to reduce the error due to missing flight lines requires using the existing low-altitude magnetic anomaly data grid. This data grid can be upward continued to the ER-2 survey altitude, and resampled along the widely-spaced ER-2 flight lines. A grid constructed from the resampled data can be subtracted from the upward continued grid to produce a grid of the short-wavelength error due to the wide flight

² Members of working group on the diurnal and reference fields include J. Phillips, R. Langel, M. Nabighian, J. Quinn, A.W. Green, R. Bracken

line spacing. This error grid can be added to a grid of the actual high-altitude magnetic anomaly data to correct for the missing flight lines. This approach assumes that the low-altitude data is reliable at wavelengths of 44 to 132 km, which it may not be (Grauch, 1993).

A second way to reduce the error due to missing flight lines would be to improve the prediction capabilities of our gridding algorithms using cross-line gradients or known anomaly trends. Using a combination of improved gridding algorithms and short wavelength information from low altitude magnetic anomaly data may provide the best approach.

Two possible ways to apply diurnal corrections to the high-altitude data are (1) treat Sq as time terms in the aircraft compensation, or (2) incorporate Sq in the global geomagnetic field model. The effects of Sq will be greatly reduced if the survey is flown at night.

The geomagnetic reference field over the U.S. for the period of the ER-2 mission must be accurately calculated following the mission so that it can be removed from the magnetic field measurements. It is possible that a geomagnetic reference field model can be designed that incorporates measured diurnal variations (Sq) during the mission. To ensure the best possible field model, the ER-2 mission should be flown during the Oersted satellite mission (scheduled launch in June 1997). The magnetic measurements from the ER-2 aircraft should be used in building the field model. North American ground-based measurements from both magnetic observatories and from portable stations incorporating vector fluxgate and total field sensors should be used in building the model. Universities should be invited to participate in the collection of ground-based data. The geomagnetic field model can be based on the North American and satellite data, as well as any available worldwide observatory data; data gaps outside North America can be ignored for the purposes of this mission.

Recommendations

- Fly at night.
- Interrupt flights during substorms (k4 and above).
- Use the best compensation possible.
- Fill in flight line gaps if at all possible, otherwise experiment with alternate gridding and data integration techniques.
- Fly during the Oersted mission (3/97 - 5/98).
- Use the aircraft data in building the global field model.
- Correct for Sq by using time terms in the compensation, or by incorporating Sq in the global field model.
- Consider using portable stations and University participation to fill holes in the observatory coverage.
- North-south tie-line data, if it can be accurately compensated for the effects of an aircraft passing through a wide range of geomagnetic latitudes, should be useful

for identifying and removing (or at least characterizing the error due to) long-wavelength diurnal effects

INSTRUMENTATION

ER-2: A Suitable Platform for Magnetic Measurements

by Thomas G. Hildenbrand and Vic Labson (U.S. Geological Survey)

The test flights demonstrate that it is possible to measure the magnetic field from an ER-2. We believe that the magnetic field can be measured at an accuracy of 2 nT or better along flight lines. The only major problem that may prevent obtaining this accuracy is possible effect of the engines (referred to above as the "turbo-magnetic" effect). Measurements are needed on the ground with a portable magnetometer for "engine on" and "engine off" conditions to establish the reality of a turbo-magnetic effect and its characteristics. If this problem exists, a viable solution may involve mounting total field magnetometers in one superpod and in both wingtip pods. The resulting multiple samples of the magnetic field should provide a means to compensate for an engine effect. Moreover, the possible "turbo-magnetic" effect may be sufficiently reduced at the distant wingtip pods to provide acceptable data.

The planned instrument package includes:

- 2 potassium magnetometers mounted in the wingtip pods
- cesium magnetometer mounted in a superpod
- inexpensive fluxgate (needed for compensation) mounted in the superpod with the cesium magnetometer
- NASA vector magnetometer in the other superpod.

All magnetic data measurements will be synchronized with the ER-2's navigational system. Several test flights are needed to assure the proper installation and functioning of the equipment. Roughly 27 flight hours or 9 short test flights are anticipated.

Cesium Magnetometer

by Lynn Edwards (Geometrics)

Geometrics is a manufacturer of a variety of magnetometers. The magnetometer used for the six test flights in October and November was Geometric's G858 portable cesium vapor total field magnetometer. This magnetometer was modified with a special sensor/console cable to allow penetration of the pressure bulkhead in the

ER-2. Data for each flight was stored internally in RAM and was dumped to a PC at the end of the flight.

Logistics/Concerns

There were several issues that were not resolved during the test flights. There were other issues that surfaced during the workshop that may impact magnetometer performance. Each of these will have to be addressed:

- 1) Short-wavelength magnetic noise appears in the data up to several nanoTeslas in amplitude. Most likely these are caused by electrical current in the aircraft skin, probably in the fuselage.
- 2) A 20 nT drift or greater of unknown origin was observed.
- 3) Magnetic interference caused by electric currents in the aircraft was the biggest problem during the test flights, and likely will increase as more equipment is installed. I believe that there will be 4 recorders for the radar system in the superpods along with GPS receivers, which can generate additional currents and magnetic field. Also interference from the bias fields of the fluxgate magnetometer to the total field magnetometer may result.
- 4) Radio frequency interference to the magnetometer may occur. The effects of this on the magnetometer (and other equipment) is unknown.
- 5) Radio frequency from the magnetometer (the G858 uses a two watt radio-frequency oscillator to light a lamp inside the sensor) is approximately 90 Mhz. The lamp and the driver circuitry are shielded to reduce stray radio-frequency radiation, but may still radiate enough to cause problems with aircraft communication. This never became an issue during the test flights but the requirements were less stringent because of the temporary nature of the installation. I believe that the fluxgate is sensitive to radio-frequency in the FM band.
- 6) The magnetometer used in the test flights had a longer cable made from special materials to conform to aircraft safety requirements. The coax cable used has very stringent requirements from a magnetometer standpoint, and also from a temperature range and flammability standpoint. Electrically the coax must have a fast velocity of propagation, low loss, 75 ohm impedance, 0.1 inch diameter, and must be non-magnetic (steel center conductors are very common in small coaxes).

The coax used for the test flights used a proprietary center conductor insulation called RayFoam (made by RayChem) which technically is not a NASA approved material (but was designed specifically for aircraft environments). It was allowed for the test flights, but may not be allowed for a permanent installation. Teflon foam cable may be needed to replace the present cable, but costs about \$2.00 per foot in a 2000 foot minimum order that requires roughly 20 weeks to deliver.

7) A "No Larmor Signal" fail light indicator is needed. Doug Hardwick properly suggests that the fail light should come on whenever the sensor enters a dead zone to alert the pilot that the bank angle limit has been exceeded.

Recommendations

Most of the above concerns deal with possible compatibility issues between different units and/or the aircraft. Since simulating the possible interactions may be difficult, tests are needed to sort out the problems while the instruments are operated together in the aircraft. We need to allocate time for these tests. The amount of time is difficult to assess, especially since we are not sure if some of the above issues are problems. Because purchasing teflon cable will take time, it is important to minimize the time from getting the "go signal" to getting the cable ordered. Problems with currents in the aircraft skin (if they are a problem) are going to require some help from the Ames engineering group.

Potassium Magnetometer

by Bruno Nilsson (Newmont Exploration)

Newmont Mining Corporation, Denver, Colorado, is willing to support the high-altitude magnetic survey covering the US. It will make its potassium magnetometer technology and its expertise in magnetic compensation available to the program.

The potassium magnetometer is, in our opinion, the most capable magnetic field sensor for airborne survey applications. Newmont has refined the original Russian design extensively and is routinely operating this type of magnetometer in its global exploration program. The potassium magnetometer has a sensitivity of 0.1 pT and a heading error that is less than 1 pT over a $\pm 35^\circ$ cone, both specifications significantly better than those for a typical Cesium sensor.

Logistics

Newmont would provide two sensors, one for each wingtip. Each sensor will be provided with its own independent data acquisition system, which will be mounted in the super-pods. This arrangement would offer following benefits:

- Redundant measurements. The mean of the two measurements will offer an improvement in the signal-to-noise ratio
- An estimate of the horizontal gradient of the total field will be available, providing additional useful information to the final magnetic map.
- In the event that one sensor fails, we would still have information about the magnetic field, although with somewhat reduced accuracy.

Recommendations

Newmont has a flexible schedule when it comes to the installation of the equipment in the ER-2. We should be able to carry out the installation at any time the aircraft is available. Once the equipment is installed we need to carry out a test program on the ground. This will require the aircraft to be moved to a magnetic relatively quiet location on the airfield on a couple of occasions. Final testing needs to be carried out in flight. We estimate that two flights, with a duration of at least 3 hours at altitude, will be required. Preferably these tests will be combined with the final testing of the DTEMS (radar data system) to determine possible interference. The main procedure required, as part of the mission, is to dump the collected data from the two data acquisition systems after each flight to a portable computer.

SUMMARY

by Tom Hildenbrand (U.S. Geological Survey) and
Bill Hinze (Purdue University)

Of the many workshop issues addressed, probably the most critical one dealt with the quality magnetic data collected from the ER-2. Magnetic data collected last November during six test flights with a cesium total field magnetometer indicate that the ER-2 is an appropriate platform for magnetic measurements. We conclude that (1) the instrument package (fig. 1) should include 2 potassium magnetometers (one in each wingpod), a cesium magnetometer in a wing superpod, and a high-precision vector magnetometer in the other wing superpod; (2) although the proposed ER-2 magnetic survey is an appropriate platform to collect total-field magnetic data, further tests are needed to establish the anticipated quality of the vector magnetic data; and (3) additional studies and test flights are needed to evaluate methods to overcome diurnal variations, to isolate observed DC shifts, and to design optimum compensation/calibration flight maneuvers.

We also addressed the resources needed to install the magnetometers and to collect, process, and distribute the magnetic anomaly data. Although most of the mission costs would be funded by Lockheed Martin, additional costs related only to the collection of the magnetic data exist and include:

- Equipment purchase and magnetometer installation
- Processing and distributing the magnetic data
- Flight time for test flights, for mission tie lines and for compensation flight maneuvers (~ 122 flight hours)
- Flight time to collect offshore data (to 300 km)(~ 140 flight hours).

The U.S. Geological Survey has provided resources to carry out the November test flights and to convene the Ames workshop, and it plans to commit people to assist

in the further planning of the mission and the processing of the data. Many other scientists from the geomagnetic community have and will continue to support this effort. However, funding sources for the remaining additional costs have yet to be identified. The estimated 122 flight hours, primarily for tie lines and for compensation and calibration maneuvers, may decrease if new test flights indicate that (1) tie lines may be unnecessary or (2) the planned number of maneuvers for compensation and calibration can be reduced. The 140 flight hours to collect offshore data could also be reduced by eliminating less critical offshore coverage.

If the ER-2 national survey is carried out, it would represent an exciting and important opportunity for the geomagnetic community. However, the successful collection of high-altitude magnetic data hinges on the identification of contributors of the needed resources. Due to limited budgets, the ER-2 magnetic mission would require combining resources from a consortium of federal and state agencies, private industry, and academic institutions.

ACKNOWLEDGMENTS

The assistance of several individuals must be acknowledged, as their contributions greatly helped in the success of the workshop. John Arvesen (Chief, High-Altitude Missions Branch, Ames Research Center, NASA), who has great enthusiasm in the measurement of magnetic data from the ER-2, generously provided flight time and made available his technical staff. His support led to the successful acquisition of test flight data critical in assessing the ER-2 as a viable platform for magnetic surveys. Arvesen also hosted the workshop, arranged for engineers and an ER-2 pilot to be available for questions, and guided a tour of the hangar housing ER-2s. Doug Hardwick, (National Research Council, Canada), although unable to attend the workshop, contributed considerable time in processing test flight data and in providing valuable advice on aircraft compensation. Similarly, Misac Nabighian, Newmont Exploration, also volunteered his time to this effort by reducing test flight data and studying major issues of the mission. Dick Wold, Geometrics, kindly furnished the cesium magnetometer for the test flights and has represented this project in a Washington meeting. Lastly Hildenbrand must acknowledge the valuable assistance of all the workshop participants, many of whom devoted many hours to provide important workshop contributions. The great response from so many colleagues (with little or no compensation) is remarkable and reassuring of the mission's relevancy.

REFERENCES CITED

- Arkani-Hamed, J., J. Verhoef, W.R. Roest and R. Macnab, 1995, Intermediate wavelength magnetic anomaly maps of the north Atlantic Ocean derived from satellite and shipborne data: *Geophysical Journal International*, v. 123, p 727-743.
- Grauch, V.J.S., 1993, Limitations on digital filtering of the DNAG magnetic data set for the conterminous U.S.: *Geophysics*, v.58, no. 9, p.1281-1296.
- Ledner, R., 1994, IFSAR earns high marks in mapping applications: *Voxel Inc., Voxel Visions*, Vol. 1, n. 3.
- Malliot, H.A., 1996a, Digital terrain elevation mapping system: *Proceedings 1996 IEEE Aerospace Applications Conference (IEEE 96CH35904)*, Vol. 4, Snowmass at Aspen, CO, Feb. 3-10, p. 91-105.
- Malliot, H.A., 1996b, DTEMS Interferometric SAR design and method of baseline tilt determination: *Proceedings 1996 IEEE Aerospace Applications Conference (IEEE 96CH35904)*, Vol. 4, Snowmass at Aspen, CO, Feb. 3-10, p. 107-127.
- National Research Council, 1993, *The National Geomagnetic Initiative Report*: National Academy Press, Washington D.C., 246 pp.
- Pilkington, M. and Roest W.R., in press, 1996, An assessment of long wavelength magnetic anomalies over Canada: *Canadian Journal of Earth Sciences* v. 33, p. 12-23.
- U.S. Magnetic-Anomaly Data Set Task Group, 1994, *Rationale and operational plan to upgrade the U.S. magnetic-anomaly data base*: NASA, Washington, DC, 25 pp.

APPENDIX A: WORKSHOP PARTICIPANTS

John C. Arvesen
NASA-Ames Research Center
Mail Stop: 240-6
Moffett Field, CA 94035-1000
Phone: (415)604-5376
FAX: (415)604-4987
email: John_Arvesen@qmgate.arc.nasa.gov

Mario Acuna
NASA-Goddard Space Flight Center
Mail Code: 695
Greenbelt, MD 20771
Phone: (301)286-7258
FAX: (301)286-1683
email: Mario.acuna@gsfc.nasa.gov

Walter Roest
Geological Survey of Canada
1 Observatory Crescent
Ottawa Ont U1A0Y3, Canada
Phone: (613)992-1546
FAX: (613)952-8987
email: Roest@agg.emr.ca

Jeff Phillips
USGS/Denver Federal Center
Box 25046, MS 964
Denver, CO 80225
Phone: (303)236-1206
FAX: (303)236-1425
email: jeff@musette.cr.usgs.gov

Rick Blakely
U.S.G.S
MS 989 - 345 Middlefield Road
Menlo Park, CA 94025
Phone: (415)329-5316
FAX: (415)329-5133
email: blakely@gauss.wr.usgs.gov

David Howell
USGS
MS 919 - 345 Middlefield Road
Menlo Park, CA 94025
Phone: (415)329-5151
email: dhowell@octopus.wr.usgs.gov

Lynn Edwards
Geometrics
395 Java Drive
Sunnyvale, CA
Phone: (408)734-4616
FAX: (408)745-6131
email: Lynn@GEOM.GEOM

John M. Quinn
USGS/NCIC
MS 968/Denver Federal Center
Denver, CO. 80228
Phone: (303)273-8475
FAX: (303)273-8450
email: quinn@gldfc.cr.usgs.gov

Art McGarr
USGS
MS 977 - 345 Middlefield Road
Menlo Park, CA 94025
Phone: (415)329-5645
FAX: (415)329-5163
email: mcgarr@isdmal.wr.usgs.gov

Misac Nabighian
Newmont Exploration
1700 Lincoln Street
Denver, CO 80203
Phone: (303)837-5823
FAX: (303)837-5851
email: mnn@nel.newmont.com

Arthur (Bill) Green
U.S. G.S/Denver Federal Center
Box 25046/MS 968
Denver, CO. 80225
Phone: (303)273-8482
FAX: (303)273-8450
awgreen@gldfs.cr.usgs.gov

William (Bill) J. Hinze
Purdue Univ,
Dept. of Earth & Atmos. Sc.
West Lafayette, IN. 47907
Phone: (317)494-5982 or 583-2530
FAX: (317)496-1210 or 583-2530
email: hinze@geo.purdue.edu

Rob Bracken
USGS/Denver Federal Center
Box 25046, MS 964
Denver, CO. 80225
Phone: (303)236-1207
FAX: (303)236-1425
email: rbracken@musette.cr.usgs.gov

Bruno Nilsson
Newmont Exploration
1700 Lincoln Street
Denver, CO.80203
Phone: (303)837-6162
FAX: (303)837-5851
email: byn@nel.newmont.com

John La Brecque
NASA Headquarters
Mail Code: YSG
Washington, DC 20546-001
Phone: (202)358-1373
email: jlabrecq@mtpe.hq.nasa.gov

George Lee
USGS/NMD
345 Middlefield Road
Menlo Park, CA. 94025
Phone: (415)329-4255
email: gylee@usgs.gov

Jack Lynch
USGS/NMD/WMC
345 Middlefield Road
Menlo Park, CA 94025
Phone: (415)329-4386

Alan Mikuni
USGS
345 Middlefield Road
Menlo Park, CA 94025
Phone: (415)329-4254
FAX:
email: amikuni@usgs.gov

Hal Malliot
Lockheed Martin
ORG 9200 - Bldg 254 -
3251 Hanover Street
Palo Alto, CA 94304-1191
Phone: (415)424-2619
FAX: (415)424-2662

Vic Labson
USGS
Box 25046
Denver CO 80225
Phone: (303)236-1312
email: vlabson@musette.cr.usgs.gov

Richard Wold
Geometrics
395 Java Drive
Sunnyvale, CA
Phone: (408)734-4616
email: rwold@geom.geometrics.com

Earnest Paylor
NASA Headquarters
Mail Code: YS
Washington, DC 20546-0001
Phone: (202)358-0851
email: epaylor@mtpe.hq.nasa.gov

Tom Hildenbrand
USGS
345 Middlefield Road
Menlo Park, CA 94025
Phone: (415)329-5303
FAX: (415)-329-5133
email: tom@laplace.wr.usgs.gov

Doug Hardwick
National Research Council of Canada, Bldg. U-6
Montreal Road
Ottawa Ontario K0A2N0 Canada
Phone: (613)998-3525
FAX: (613)952-1704
email: doug.hardwick@nrc.ca

APPENDIX B

WORKSHOP AGENDA: THE RATIONALE AND OPERATIONAL PLAN FOR THE HIGH-ALTITUDE MAGNETIC SURVEY OVER THE U.S.

8:30–8:50 a.m.: Welcoming Remarks and Introductions—Tom Hildenbrand, USGS; John Arvesen, Chief, High Altitude Missions, Ames Research Center

8:50–9:25 a.m.: Digital Terrain Elevation Mapping System—Hal Malliot, Lockheed Martin Missiles and Space Co. Inc.

9:25–10:15 a.m.: Mission Rationale/ Costs

Rationale for High-altitude Magnetic Survey—Rick Blakely, USGS (20 min.)

Canadian Interest in ER-2 Mission—Walter Roest, GSC (15 min.)

Required Resources to Carry Out Mission—Tom Hildenbrand (15 min.)

10:15–10:30 a.m.: Coffee Break

10:30 a.m.–11:10 a.m.: Test Flights

Rationale —Tom Hildenbrand; Lynn Edwards, Geometrics (5 min.)

Plane Magnetic Effects/Compensation—Rob Bracken, USGS; Misac Nabighian, Newmont Exploration Limited (30 min.)

Preliminary Survey—Tom Hildenbrand (5 min.)

11:10 a.m.–Noon: Operational Plan

Compensation/Tie Lines—John Quinn, USGS; Rob Bracken (30 min.)

Diurnal/Reference Field—Jeff Phillips, USGS (20 min.)

Noon–1:30 p.m.: Lunch & ER-2 Inspection

1:30–2:45 p.m.: Operational Plan (Cont.)

Proposed Instrument Package and Their Optimum Locations—Vic Labson, USGS (15 min.)

Total Field Magnetometers—Bruno Nilsson, Newmont Exploration Limited; Dick Wold/Lynn Edwards, Geometrics; Bill Green, USGS (20 min.)

Vector Magnetometer—Mario Acuna, NASA (20 min.)

Data Collection/Reduction/Distribution—Group discussion (20 min.)

2:45–3:00 Break

3:00: Closing Discussion/What's Next?