Rationale and Operational Plan for a U.S. High-Altitude Magnetic Survey

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ABSTRACT

On August 8, 2002, twenty-one scientists from the federal, private and academic sectors met at a workshop in Denver, Co., to discuss the feasibility of collecting magnetic anomaly data on a Canberra aircraft (Figure 1). The need for this 1-day workshop arose because of an exciting and cost-effective opportunity to collect invaluable magnetic anomaly data during a Canberra mission over the U.S. in 2003 and 2004. High Altitude Mapping Missions (HAMM) is currently planning a mission to collect Interferometric Synthetic Aperture Radar (IFSAR) imagery at an altitude of about 15 km and with a flight-line spacing of about 18 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 HAMM would fund the main flight costs of the mission, the geomagnetic community would obtain invaluable magnetic data at a nominal cost. These unique 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 the upper mantle.

This document highlights: (1) the reasons to conduct this national survey and (2) a preliminary operational plan to collect high-altitude magnetic data of a desired quality and for the expected resources. Although some operational plan issues remain to be resolved, the important conclusions of the workshop are that the Canberra is a very suitable platform to measure the magnetic field and that the planned mission will result in quality high-altitude magnetic data to greatly expand the utility of our national magnetic database.

INTRODUCTION

Opening remarks at the workshop included the long history leading 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 workshop report [National Research Council, 1993; 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) 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; 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 IFSAR survey became known. 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 aircraft. The mission objective was to acquire IFSAR imagery and differential GPS that will serve as the basis for deriving digital terrain elevations at a 1-meter accuracy and with a 1-meter posting. Unfortunate events led to the cancellation of the ER-2 mission. In the Fall of 2001, the IFSAR mission once again became a reality but funded by High

Figure 1. Canberra owned by High Altitude Mapping Missions—capable of flying at 50,000 ft, above air traffic and bad weather. Planned tail stinger will house the magnetometers.

Altitude Mapping Missions, a private company, using a Canberra aircraft.

An ad-hoc executive committee was formed to ensure that the operational plan for the magnetic aspects of mission would lead to optimal results. Committee members are Thomas G. Hildenbrand (Chairperson), William J. Hinze, G.R. Keller, Walter Roest, and Vic Labson. A decision was made to convene the August workshop to mainly begin identifying a viable operational plan to collect magnetic data at a 15-km altitude in a Canberra.

The twenty-one workshop attendees spanned a variety of organizations:

Mario Lacuna, Goddard Space Flight Center, NASA
John Arvesen, High-Altitude Mapping Missions (HAMM)
Rob Bracken, Geologic Division, U.S. Geological Survey
Ron Buhmann, National Geophysical Data Center, NOAA
Guy Flannigan, Society of Exploration Geophysicists—Phillips Petroleum
Richard Hansen, Pearson, Ridder, and Johnson
Doug Hardwick, C.D. Hardwick Consulting (NRC, Canada, retired)
Alan Herring, Society of Exploration Geophysicists—EDCON
Tom Hildenbrand, Geologic Division, U.S. Geological Survey
Bill Hinze, Purdue University
G.R. Keller, University of Texas, El Paso
Robert Kucks, Geologic Division, U.S. Geological Survey
Vic Labson, Geologic Division, U.S. Geological Survey
John List, Mapping Division, U.S. Geological Survey
Jeffrey Love, Geologic Division, U.S. Geological Survey
Hal Malliot, High-Altitude Mapping Missions
Misac Nabighian, Colorado School of Mines
Jeff Phillips, Geologic Division, U.S. Geological Survey
Tiku Ravat, Southern Illinois University
Walter Roest, Geological Survey of Canada
Dick Wold, Blackhawk

The workshop agenda (see Appendix A) provided time to discuss the rationale for the national airborne magnetic mission but concentrated on developing a realistic operational plan to accomplish a successful mission. In preparation for the workshop, several individuals were appointed to chair focus groups on major workshop topics. These focus groups met prior to the workshop and attempted to resolve some of the major problems in collecting magnetic data from a Canberra. Topics and participants were:

- ***External and Core Magnetic Field Corrections***
  Jeff Phillips (Chairperson), Rob Bracken, Jeffrey Love, Misac Nabighian, Tiku Ravat, and Terry Sabaka (NASA)
- ***Aircraft Magnetic Effects***
  Doug Hardwick (Chairperson), Rob Bracken, Richard Hansen, and Misac Nabighian

- *Instrumentation Package*
  Rob Bracken (Chairperson), John Arvesen, Bill Davies (HAMM), Ray Hutton (USGS), Ken Smith (Geometrics), and George Tate (Geometrics)

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

Appendix B describes the resulting important technical issues surrounding the proposed Canberra magnetic survey of the U.S. in the order of presentations at the workshop (Appendix A). From the issues and recommendations listed in Appendix B, an operational plan will be developed so that results of the desired quality can be obtained for the available resources. The rationale for the mission and a summary of the evolving operational plan (Appendix B) are provided below.

RATIONALE FOR THE CANBERRA MAGNETIC SURVEY

Scientific Rationale for a High-Altitude Aeromagnetic Survey
By William Hinze

Magnetic anomaly data have found important uses in studying the crystalline rocks of the Earth's lithosphere. These data provide unique information on the lithology, structure, geochemical processes, temperature, and thermal and magnetic history of the Earth in a relatively inexpensive manner. <u>A high-altitude aeromagnetic survey is especially important to consider at this time because of the convergence of the technical and economic feasibility of the survey and the increasing interest in the questions that can be addressed by these unique data</u>.

Information contained in the data from a magnetic survey is restricted to a specific band of the wavenumber spectrum, with the position of the band largely controlled by the altitude of the survey above the magnetic sources. Although the 15-km altitude of the Canberra mission was established independent of the requirements of geologic or geomagnetic studies, it will be nearly optimal for bridging the gap in wavelengths between currently available low-altitude aeromagnetic and satellite magnetic data. The present gap in wavelengths can only be eliminated by direct measurements at high-altitudes and these are the very wavelengths in the range of several hundred kilometers that permit investigation of the magnetic structure of the lower crust and large geologic features.

Based on modeling and our understanding of the magnetic properties of the lithosphere, especially in the lower crust, we anticipate that high-altitude magnetic anomaly data will be used to aid in the solution of a broad range of scientific and applied earth science issues related to:

- Geologic, thermal and mechanical properties of the lithosphere
- Crustal accretion and evolution
- Geologic and tectonic processes
- Societal concerns, such as:

- Localization of favorable areas for mineral, energy, and thermal resources
- Mitigating earthquake and volcanic hazards
- Waste disposal

The wavelength band of magnetic anomalies that is the objective of the high-altitude survey will be particularly helpful in studying the lower crust – its composition, structure, and thermal regime – and large geologic/tectonic structures, such as basement terranes, the Cascadia subduction zone, the Midcontinent Rift, and Basin and Range structures. In addition, these results will provide significant new constraints for geological interpretation of complementary regional topographic, seismic, gravity, and heat flow data. A particularly important role of the high-altitude magnetic anomaly data will be to investigate the lower limit of magnetization caused by either the level of the Curie point isotherm within the lithosphere or the bottom of crustal lithologic units.

The basic magnetic observations of the high-altitude survey will be scalar measurements of the total intensity of the geomagnetic field, however, investigations are underway to determine the feasibility of supplementing the scalar observations with measurements of the vector components of the field. Vector field measurements, which will provide independent information, will aid in the isolation of magnetic fields originating within the ionosphere, assist in identification of remanent magnetization as a source of individual anomalies, aid in distinguishing between two- and three-dimensional sources, and increase the stability of inversion of the anomalies for their magnetic sources.

Importance in Correcting National Low-Altitude Aeromagnetic Database and in Offshore Studies
By Tom Hildenbrand

Of particular importance is that the high-altitude magnetic data will provide a reference field to properly level the long wavelengths in the U.S. low-altitude aeromagnetic database. A recent ambitious effort to upgrade the low-altitude aeromagnetic database (NAMAG, 2002) has led to a data resource that is fundamental to geoscience investigations. However, this database, representing 100's of millions of dollars, has been constructed from a patchwork of over 1,000 airborne and shipborne surveys, acquired over a period of about 50 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). 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.). <u>A correctly merged low-altitude aeromagnetic database of the U.S., using the high-altitude magnetic data as a reference field, may be the single most important legacy of the Canberra magnetic mission, as it will greatly expand the utility of our invaluable national magnetic data set</u>.

Offshore magnetic data led to the identification of magnetic stripes and to one of the most important geologic paradigms, plate tectonics. The availability of high-altitude magnetic data could lead to other important geologic breakthroughs. For example, these longer magnetic wavelengths could address the geologic framework of passive rift margins (east coast) by identifying associated tectonostratigraphic terranes (important, for example, to petroleum exploration) or active margins (west coast) advancing our knowledge of subducting plates and obducted oceanic crust (important to hazards assessment).

High-Altitude Aeromagnetic Data: The Canadian Perspective
By Walter Roest

The Geological Survey of Canada (GSC) shares many of the same arguments outlined above as to why a high-altitude mission would be beneficial. In fact, these high-altitude data are needed at this time, both in terms of its application to the current National Aeromagnetic Program and with respect to a more fundamental understanding of the Earth's magnetic field and the external components that influence magnetic observations near the Earth's surface. GSC's aeromagnetic program has collected aeromagnetic data since 1948, and although strict national standards were developed and applied, calibration was initially absent, leaving the base levels of many surveys blocks undetermined. A vector magnetometer survey, carried out by the then Earth Physics Branch (EPB) of the Department of Energy, Mines and Resources between 1969 and 1976, demonstrated what magnetic data collected along long flight lines (> 2000 km) and at higher altitude (>4 km) can contribute to the mapping of the crustal component of the magnetic field (Pilkington and Roest, 1996). Regrettably, the EPB surveys had poor navigation, as well as incomplete coverage due to instrumentation and other problems. Despite these problems, the EPB data set has been a prime contributor to the Canadian Geomagnetic Reference Field (CGRF), which improves upon the international IGRF field by providing a higher precision definition of the variation in inclination and declination across Canada, of importance to specific applications, such as navigation and directional exploration drilling.

Despite the problems of the EPB surveys, they form a cornerstone of our understanding of the magnetic field over Canada. Building upon the EPB experience, GSC understands the potential for a well-conducted high altitude survey to contribute to both the exploration aspects of aeromagnetic surveys, as well as to the more fundamental aspects of understanding the Earth's magnetic field. Hence, GSC will try to engage its partners in finding support for extension of the US survey over Canada's landmass and offshore. In order to garner such support, it is deemed essential that the aeromagnetic data are collected to the highest standards possible, given the circumstances of the survey, where, we realize, magnetic acquisition takes second place to IFSAR. At the same time, it will be essential to ensure coverage of the continental margins and ensure significant overlap across the international borders. In order to ensure that the high-altitude survey contributes to Canada's priorities in resource development and in geomagnetism, the deployment of at least one vector magnetometer is essential. Although gradiometer data would be an asset, it is understood that given the aircraft configuration and speed, it may not be feasible to collect this type of data.

GSC's funding for aeromagnetic data acquisition will depend on the ability to successfully compete for funding under the Northern Resources Geoscience Program, the Geosciences for Sustainable Development Program, and the Geohazards program. Funding for the high-altitude mission will have to be presented under the same umbrellas, as an integral component of our national program.

OPERATIONAL PLAN SUMMARY

By Tom Hildenbrand and Rob Bracken

Based on the issues and recommendations in Appendix B, a summary of the evolving operational plan is provided here to demonstrate that the mission outcome will be successful. Of the many workshop issues addressed, probably the most critical one dealt with the quality of magnetic data collected from the Canberra. Magnetic data collected from test flights and from ground tests with a cesium total field magnetometer both indicate that the Canberra is a very suitable platform for magnetic measurements.

The present operational plan includes the following instrument package: (1) based on tests of the magnetic effects of the Canberra, a 12-foot tail stinger is to be constructed to house magnetometers; (2) the instrument package in the tail stinger will include 2 total-field magnetometers, likely cesium magnetometers supplied by USGS and 2 vector magnetometers supplied by NASA; (3) 2 additional vector magnetometers will be attached to the interior of the fuselage, and the resulting data will be useful in correcting for aircraft magnetic effects during surveying; and (4) if necessary, a laser system will measure movement of the tail stinger relative to the fuselage. If the effects of the IFSAR system are determined minimal when it is installed, the magnetic noise generated by the aircraft will remain small and thus may negate some costly compensation and calibration flight maneuvers during the national survey.

Additional studies and test flights will be carried out to further evaluate methods to overcome diurnal variations, to isolate and remove aircraft effects as the IFSAR system is developed and installed, and to design optimum compensation and calibration flight maneuvers. Existing test data and intuitive reasoning by workshop participants have led to the following conclusions: (1) tie lines may not be cost effective and thus may not be flown (but data will be collected, at least, oblique to survey flight lines when the aircraft makes its way to the survey area); (2) magnetic data from existing magnetic observatories and from a fixed array of 9 base stations or less, spaced roughly 600 km apart, will be used to remove ionospheric magnetic effects; and (3) the comprehensive model developed by NASA will need to be expanded to estimate secular and diurnal magnetic effects at survey altitudes using the high-altitude magnetic survey data, data from semi-permanent and permanent magnetic observatories, and data available from the three geomagnetic satellites flying during the high-altitude mission (Oersted, Oersted2, and CHAMP).

NEEDED RESOURCES

The workshop also addressed the resources needed to install the magnetometers and to collect, process, and distribute the magnetic anomaly data. Although HAMM would fund most of the mission costs, 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 and for compensation flight maneuvers
- Flight time to collect offshore data (to 300 km).

The Canberra national survey, which is scheduled to begin during the latter part of 2003, will 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 needed resources. The U.S. Geological Survey has provided resources to carry out the tests thus far and the funding to convene the workshop. Although the USGS plans to continue to support the mission by committing nominal funds for equipment and people to assist in the further planning of the mission and the processing of the data, significant additional funds are needed. Many scientists from the geomagnetic community have and will continue to support this effort, as evidenced from the great participation at the workshop. However, roughly 2/3 of the mission costs needs to be identified to ensure a successful mission. These funding needs do not include offshore data collection costs, where the geomagnetic community would have to identify the total mission costs. In short, the Canberra magnetic mission clearly requires identifying resources from a consortium of federal and state agencies, private industry, and academic institutions.

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APPENDIX A

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

August 8, 2002

Denver CO

8:30–8:50 a.m.: ***Welcoming Remarks***—Tom Hildenbrand and Vic Labson, USGS

8:50–9:30 a.m.: ***National IFSAR Mapping Mission***

The Canberra and Survey Operational Plan—Arvesen, HAMM
IFSAR—Hal Malliot, HAMM

9:30–10:15 a.m.: ***Mission Rationale***

Mission Importance—Bill Hinze, Purdue U. (20 min.)
Importance in Correcting National Low-Altitude Aeromagnetic Database and to Offshore Studies—Tom Hildenbrand, USGS (20 min.)
Canada's Perspective—Walter Roest, GSC (15 min.)

10:15–10:30 a.m.: ***Coffee Break***

10:30 a.m.–11:30: ***Operational Plan***

Is the Canberra a suitable platform and are the IFSAR and magnetometer systems compatible?—Rob Bracken, USGS (30 min.)
Diurnal/Reference Field—Jeff Phillips, USGS (30 min.)

11:30–1:00 p.m.: ***Lunch***

1:00–2:45 p.m.: ***Operational Plan*** (Cont.)

Compensation/Tie Lines—Doug Hardwick (30 min.)
Vector Magnetometer—Mario Lacuna, NASA (30 min.)
Proposed Instrument Package—Rob Bracken (30 min.)
Data Collection/Reduction/Distribution/Web Site—Group discussion (15 min.)

2:45–3:00 p.m.: ***Break***

3:00-4:00 p.m.: ***Closing Discussions/Action Items***

APPENDIX B

OPERATIONAL PLAN

Is the Canberra a Suitable Platform and are the IFSAR and Magnetometer systems Compatible?
By Rob Bracken

Issue 1—Flight Capabilities of the Canberra: Although we believe that we have found a suitable aircraft for a high-altitude magnetic mission, it is necessary to prove that the performance of the Canberra is appropriate for such a mission before committing substantial resources. Flight capabilities involve issues of safety and over-water qualifications, range, altitude, speed, and payload.

A literature search indicated that the Canberra has a good safety record for our type of mission. A range of over 1700 nautical miles and over-water qualifications were proved by a round-trip demonstration flight from California to Japan. Two test flights confirmed that the aircraft could easily attain a pressure altitude of 48,000 feet and at this altitude sustain true airspeeds over 400 knots. Preliminary engineering studies and test flights show that the Canberra can easily carry the necessary payload in weight, volume, and placement.

Recommendation: The English Electric Canberra with tail number N40UP (and inferentially, its sister aircraft, N30UP) is quite capable of meeting all flight requirements for the proposed high-altitude magnetic mission. Therefore from the flight capability standpoint, this aircraft is recommended.

Issue 2—Platform-Related Magnetic Interference: To carry an airborne magnetic mission, the platform's magnetic interference must be reducible to levels significantly below those of the targeted signals. To obtain the necessary levels, mounting locations for magnetometer sensors typically must be removed from the aircraft as in a pod, stinger, or "bird". Magnetic-interference levels in these appurtenances can be estimated by appropriate testing.

Both flight tests and ground tests corroborate, with an indication of magnetic interference levels reducible to roughly 0.6 nT rms at a location 12 feet aft of the tail "bubble".

Recommendation: The inferred noise figure for the Canberra is quite good, being about 10 dB below the mission noise envelope. Therefore from the platform magnetic interference standpoint, this aircraft is recommended.

Issue 3—Radiated Interference from the proposed IFSAR system: The proposed magnetic mission will be flown together with an IFSAR system. The IFSAR will radiate high levels of RF power in the KU band with modulation and pulsing at a variety of other frequencies. A small percentage of this radiation is expected to reach certain components of the magnetometer system. The effects of this radiation have not yet been measured but are expected to be either insignificant or else they can be removed by appropriate shielding.

Recommendation: Test the effects of the expected radiation on the proposed magnetometer systems (Cesium, Potassium, Helium, and vector magnetometer sensors, drivers, and cables).

Recommendation: Be prepared to add radar absorptive material and aluminum mesh or foil shielding around all magnetometer-system components.

Issue: Magnetic Interference from the IFSAR transmitter/antenna system

Experience indicates that magnetrons and wave-guides produce magnetic fields. The specific effects from this radar system are not known this time.

Recommendation: Conduct experiments at the first available moment to determine whether either of these components will cause a problem.

Issue 4—Magnetic Interference from the IFSAR power systems: In addition to RF interference, the IFSAR power systems, running on 28 Vdc and 115 V 400 Hz, are expected to produce electrically induced magnetic fields that can be sensed by the magnetometers. In a dedicated surveying aircraft all power is delivered through twisted-pair wiring that cancels the magnetic fields. However in this installation, some of the 28-Vdc is expected to have airframe return paths. This will result in ground loops that can substantially increase the platform magnetic interference.

Recommendation*:* Provide additional funding for twisted pair wiring throughout the 28 Vdc systems.

Recommendation: Where twisted pair wiring absolutely cannot be installed, shorten current paths by placing the source and load as close together as possible. Confine the airframe return currents to a particular structural member, such as the main wing spar, and minimize loop areas by running the outgoing wire as close as possible along the return-current member. *It is of utmost importance that the chosen return path has substantially lower resistance than any other path so that the loops cannot change their physical locations and dimensions.*

Recommendation: Dedicate each (of the 4 generators) to a single set of systems; *do not serve any system with more than one generator*. If this is not done, the generators will "trade-off" and produce current loops of unpredictable magnitudes, sizes, and locations, which will render a magnetic mission impossible.

Recommendation: Install a current-sensing device on one leg of **each** anticipated 28-Vdc current loop and record its output as a separate data stream. These data will be used in a compensation algorithm to remove the effects of the current loops.

Recommendation: Set up a means of cycling (on and off) each ground loop system during compensation flights. It may be possible to do this on the ground, but further development and understanding of these systems will be necessary before finalization.

Recommendation: Work closely with the IFSAR power-system designers to ensure that the most effective possible constructs are implemented. This would include onsite testing and computer modeling of proposed wiring configurations.

Recommendation: Run a 4^{th} "green" wire with all 3-phase 400-Hz wiring to keep this frequency out of the airframe.

Recommendation: Collect data at 160 samples per second so that 400-Hz noise folds back to Nyquist.

Recommendation: Choose a compensation algorithm that will incorporate both the extra inputs from the current sensing devices and the inputs from the various anticipated magnetometers.

<u>Diurnal/Reference Field/Base Stations/Tie Lines</u>

By the External and Core Magnetic Field Corrections Focus Group (Chaired by Jeff Phillips)

Issue 1—Secular Variation: Secular variation is the time variation of the earth's internal geomagnetic field. This has amplitudes of 20-25 nT/year (Table 1). Ravat (2002) has shown that the IGRF and DGRF are inadequate for removing secular variation from magnetic surveys, and that a Comprehensive Model (CM) (Sabaka and others, 2002) provides a much better way to remove both secular variation and seasonal variations of the external magnetic field.

Recommendation: Construct a Comprehensive Model (Sabaka, and others, in press) from the high-altitude magnetic survey data, data from semi-permanent and permanent magnetic observatories, and data available from the three geomagnetic satellites flying during the high-altitude mission (Oersted, Oersted2, and CHAMP) and use the CM to remove secular variation from the high-altitude survey data.

Issue 2—Ionospheric Noise: Time–varying magnetic fields produced in the ionosphere will generate magnetic anomalies in the high-altitude survey data having wavelengths identical to those of crustal magnetic anomalies (Table 2), and with amplitudes that exceed the noise envelope of the high-altitude mission (Table 1). These external fields must be identified and removed from the data in order to recover accurately the crustal anomaly fields.

Recommendations: (1) Establish telemetered magnetic base stations to supplement magnetic observatory data in measuring the external field variations. By establishing magnetic base stations at six USGS telemetered seismic station sites in the western United States, nine sites in the eastern United States, and three sites in Alaska, a network can be established such that the high altitude survey measurements will never be more than 600 km from a base station. At this distance, within the conterminous

United States, we expect errors of up to 14 nT in the external field corrections, based on the equation in Bevan and others (1993):

$$\text{Error (nT)} = 2 \text{ times } [\text{Distance (km)}]^{0.3}$$

By using linear interpolation between base stations, we expect the error can be reduced to about 7 nT for the area internal to the network of base stations. Errors are expected to be much higher in Alaska, but there is no practical way to decrease the base station spacing in Alaska. (2) Request that HAMM fly their missions at night in order to reduce the expected amplitudes of ionospheric noise at low mid-latitudes. (3) Conduct research into extending the CM to accommodate short-time variations of external fields as a way of utilizing the base station data and projecting the base station measurements to the survey altitude. If such an extended CM existed, it could also be used to predict the amplitudes of ionospheric noise at 15-km altitude, and to help optimize base station distributions. (4) Collect base station data during all test flights to aid in developing data-reduction procedures.

These recommendations do not fully address the problem of Auroral Electrojet (AEJ) noise, which is expected to be severe during the Alaska portion of the mission. It is likely that the only way to reduce AEJ noise to acceptable levels is to suspend flights during severe auroral activity.

Issue 3—Tie Lines: During low-level aeromagnetic surveys, data are typically collected along closely spaced survey lines and along more widely spaced perpendicular lines called tie lines. The tie line data are used to help level the data along the survey lines. Tie lines are not needed by the high-altitude radar-mapping mission, and thus represent an additional cost to the magnetic mission.

Recommendation: Tie lines are not needed for leveling the survey lines, as long as the positions along the survey lines are accurately known. Although 4 to 6 north-south tie lines might provide a measure of the overall data quality of the survey, and would also be useful in resolving spatial and temporal aliasing of external fields in building a CM, they are not a cost effective way to get this information. We do recommend that cross-line data be collected when flying between the airports and the survey line ends. These cross-line data will be useful for verifying results of the survey.

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Table 1 -- Expected components of the time varying field at 15-km altitude

Component	Origin	Amplitude	Treatment
Ring-current (Dst)	magnetosphere	20 nT +/- 5 nT	Model out (CM)
Solar-quiet (Sq)	ionosphere	10-50 nT during daytime at low-mid-latitudes and at all times at high-latitude. < 5nT or 10-20 nT at low-mid-latitude night.	Low-mid-latitude night flights/Base stations/CM
Auroral electrojet (AEJ)	ionosphere	10-3000 nT transients (high latitudes only)	?
Coupling Currents	ionosphere	< 5 nT (small at night at low-mid-latitudes). Scalar fields are not affected.	Low-mid-latitude night flights/Base stations/CM
Secular variation (SV)	core field	20-25 nT/year	Geomagnetic satellites/ Observatories/CM

Table 2 -- Equivalent wavelengths at 400 knots

Crustal anomaly wavelength (km)	External field period (min)
25	2
50	4
100	8
200	16
400	32

Compensation and Calibration of Aeromagnetic Data
By the Aircraft Magnetic Effects Focus Group (Chaired by Doug Hardwick)

Introduction: Both compensation and calibration are required for the mission. Compensation consists on eliminating maneuver-related noise and minimizing heading-related DC offsets. Compensation does not necessarily guarantee absolute (DC) accuracy of the magnetic measurements. Thus, a calibration procedure is required. This usually consists of flying tie lines or accurately flying the aircraft, in normal survey configuration, over a designated point that has an established relationship to a ground station. Calibration and compensation are separate procedures. Because the DC magnetic signature of a large, complex aircraft systems are known to vary from flight to flight, preliminary flight tests in full survey configuration may show the necessity of at least one calibration per flight. The discussion that follows draws upon the results of the October, 2002 ground and in-flight tests.

Frequency of Compensations and Calibrations: In formulating an operational plan, our objective is to minimize non-survey flight time.

a) Compensation – Pull-away and other ground tests of the bare aircraft indicate that its magnetic signature is reasonably stable and the flight test showed that the maneuver noise is eminently compensatable. The magnetic signature of the fully operational aircraft is, of course, a large variable. If magnetic flight tests are done incrementally as the radar is developed and installed, a new compensation will be necessary for each equipment addition or change. However, once the operational configuration has been frozen, it is conceivable that a single compensation could cover a large part of the project, *provided that* there are no changes of equipment. There will probably be some deterioration of the maneuver compensation from flight to flight, but these effects can be handled in two ways without recompensation:

1. Line-by-line “trim-ups” – On the run-in to each survey line, trim-up maneuvers, consisting of several small pitches and rolls, should always be done. These maneuvers add almost nothing to flight time and enable good compensation over the survey line while retaining the DC calibration.
2. Maneuver noise can often be attenuated by filtering at the several characteristic frequencies of the aircraft.

Compensation maneuvers should consist of a four-heading square, with two sides oriented to the average survey directions, with pitches and rolls on each heading. Because the Canberra’s natural maneuver frequencies are very low, with wavelengths (periods at least 20 seconds) approximating magnetic anomalies, the compensation pattern should be flown in an area of minimally low gradient, to prevent the compensation coefficients from being biased by magnetic anomaly signals.

b) Calibration – One pass over a calibration point on the current survey heading, should be sufficient to set the DC calibration. This is assuming excellent real-time GPS guidance and that the relative lags in the GPS and the magnetic measurement have been established. Some flight time would be required to verify the repeatability of the procedure. Depending on flight test results, for a two-heading flight (out and back), it might be desirable to calibrate on both headings. In any case, to minimize flight time, it makes sense to have the calibration point near the home airport on the transit path to the survey. It should be in a low gradient area (this is not as critical as for the compensation) and at as low an altitude as commensurate with the operation of the radar systems. The initial calibration point should be established by another survey aircraft with proven absolute total field measurement capability; hence the desirability of having the point at a low altitude. Once the initial point has been established, it could actually be transferred to another location ***by the Canberra itself***, by means of a carefully formulated procedure.

It should be noted that calibrations notwithstanding, careful quality control will be required to check for and correct possible on-line DC shifts in the data. Moreover, the cost-benefits of flying tie lines as opposed to doing calibrations, are being studied.

Compensation Hardware and Software Details: The hardware requirements for compensation are as follows:

- Identical transfer functions for the cesium magnetometer and the tri-axial vector magnetometer, as well as for any other inputs that may be required for the compensation.
- Precise time synchronization of all sampling.
- Suppression of all spurious signals above roughly half the sampling frequency that could be aliased into the measurement frequency band.
- Decimation of the front-end sample train to the output-sampling rate.

Because of limited rack space in the Canberra, all compensation will be post-flight. However, the operator and pilot should have a positive visual indication that the magnetic data collection is operating correctly. The above hardware requirements can be met with existing front-end hardware, but the preference is to record raw data at a sufficiently high data rate, taking advantage of compact storage media, and then to do the "front-end" processing post flight. A data stream of 10 Hz is more than adequate for the type of magnetic data expected and a recording frequency of 160 Hz would give optimum primary anti-alias protection.

The post-flight compensation algorithm can be conventional, but because of the high DC currents associated with the radar, current sensors will probably have to be added to the compensation hardware suite and the algorithm will include dynamic modeling.]

Issue 1: What are the compensation-specific data acquisition components and their specifications?

Recommendation: There must be a system for matching the transfer functions of both the primary total-field and the compensating tri-axial magnetometers. In other words, each magnetometer should have the same transient response. This can be accomplished by use of a suitable front-end circuit board that combines counters and A/D converters. However, because off-the-shelf boards that perform this function are not easily obtained, matching may be accomplished in post-processing by using a high data-sampling rate. This is a reasonable approach because of the fast computation rates and large storage capacities now available. The recommended sample rate for analog and magnetometers systems is 160 samples per second, with anti-aliasing methods that attenuate frequency content above 80 Hz.

Recommendation: Analog DC-current monitors placed on large current loops (as described below) should be sampled in a similar manner to the magnetometers, with anti-aliasing and matching in post processing.

Issue 2: How do we properly compensate for the magnetic effects generated by the Canberra and IFSAR system?

Recommendation: The algorithm should be a "conventional" compensation model, augmented with compensation for variable DC current inputs from the IFSAR power-current monitors. Lack of available rack space rules out real-time compensation, but the operator should have an indicator to ensure that good data are being collected and stored.

Recommendation: The flight pattern for establishing compensation coefficients should be a "standard" square oriented to the survey flight-line directions with maneuvers on each of the four legs. Details of the procedure must be worked out after installation of the IFSAR power systems and after subsequent flight-testing to quantify magnetic effects.

Issue 3: Should calibration points be established?

Recommendation: Calibration points will ensure proper absolute DC calibration and would correct DC drift in the aircraft magnetic signature. Test flights should be carried out to determine how often a calibration should be flown. However, ground tests indicate that the DC drift is relatively slow. For these test flights, a calibration point should be established at 16,000 feet or lower, referenced to the nearest magnetic ground station, and located in a nominally low-gradient area. At the end of the test flight, the calibration point should be reoccupied.

If it is determined that calibration points should be flown periodically during the mission, the points should be tied to observatory reference points using survey aircraft with proven total field absolute measurement stability. Although calibration points are normally crossed on four headings, particular attention should be paid to ensure that they are done accurately for the line magnetic tracks (or headings) being flown for data collection.

Issue 4: How often will compensation maneuvers be necessary?

Recommendation: Compensation stability may be an issue because the magnetic effects of an aircraft can change from flight to flight. If the changes are found to be large enough, additional compensation or calibration procedures may be required, which lead to substantial additional flight costs. Consequently, extensive test flights are needed to determine compensation stability. Should problematic instabilities occur, their source would be from "perm" fields that can only be characterized if a calibration point is included in the compensation maneuvers? For ground tests, eight-heading compensation data would define the in-flight compensated residual (except for small eddy current effects and for separation of vertical "perm" and vertical induced components).

During flight tests, deterioration of maneuver compensation will appear as a correlation between magnetic data and the inertial or vector magnetic data at the characteristic maneuver frequencies of the aircraft. In some cases, filtering at these frequencies would resolve the problem. Also, miscompensation on a line-by-line basis can always be corrected by "trim-up" maneuvers (several small pitches and rolls), while preserving the DC calibration. Trim-up maneuvers should be done on the run-in and run-out of every line for quality control.

Ground testing indicates that the DC magnetic stability of this aircraft is fairly good. Therefore, it is expected that the compensation coefficients will also be fairly stable, assuming that the radar system does not adversely affect the stability. In any case, trim-up maneuvers should always be done, but it is anticipated that full-blown compensation maneuvers (and calibrations) need not be done more often than every ten flights.

Issue 5: Do the existing test data provide information to predict compensation stability?

The pull-away tests indicate that magnetic data collected in a tail stinger should be compensatable, as discussed below, but data in a nose stinger probably cannot be compensated. In other words, uncompensatable noise appears fairly small in magnitude at the rear of the aircraft. The big variable is the unknown effect of the radar systems, which may include large, varying 28 V DC current loops (partially returned through the airframe), and high radio-frequency gradients affecting the magnetometers. Current-monitors may provide a means of modeling the 28-V DC variations, and radio-frequency effects may be remedied by shielding. Finally, there may be inverter-imposed waveforms on the 28 V DC. These could lead to aliasing of the magnetic fields and a remedy would need to be imposed.

Proposed Instrument Package

By the Instrument Package Focus Group (Chaired by Rob Bracken)

Issue 1—Conditions at High Altitudes: The conditions to which the instrumentation will be subjected are extreme. For all locations other than the pressurized cabin, temperatures range from -40 to -75 degrees C and the pressure is 1.6 psi, about $1/10^{th}$ of an atmosphere. Under these conditions and during transitions to and from altitude the following can be expected: coronal discharge, freezing and brittleness, severe thermal expansion and contraction, condensation, failure of hard-drives, and limited heat dissipation rates.

In the pressurized cabin, temperatures range from +16 to +20 degrees C but can reach +40 degrees while taxiing. The pressure is 4.5 psi, about $1/3^{rd}$ atmosphere. Here, the following can be expected: coronal discharge, failure of hard-drives, and limited heat dissipation rates.

Recommendation: Before installation, all equipment should be certified and tested against failure under the anticipated conditions. Special attention should be given to certifying against release of smoke, fire, dangerous fumes, explosion, implosion, and catastrophic decompression.

Issue 2—Primary and Secondary Magnetic Mission Objectives: Considering the characteristics of the magnetic field at 50,000 feet and the attainable noise floors in various likely measurement points, measurement of certain quantities can be considered and others quantities rejected. Because of the protracted effort associated with this mission, it is important to obtain data of every kind possible. On the other hand, it would be a waste of resources to attempt measurement of quantities that are below the noise floor.

Recommendation: Total-field magnetic data collection should be considered the *primary* magnetic mission objective because the variations in this quantity will be well above the expected noise floor and will yield the greatest amount of geologically interpretable information. Vector magnetic data collection should be considered as a *secondary* magnetic mission objective because, although the signal is reasonably above the noise, its noise floor is about 15 dB higher than that of total-field magnetic-field data. Total-field gradient and gradient-tensor measurements are not possible along any axis because the baseline required to match the noise floor is about 150 feet; and at that, a minimum 10 dB of headroom is still lacking.

***Issue 3*—Noise and Error Budget:** In designing the instrumentation package and data reduction methods, it is useful to have established a target noise level based on the expected signal. Maximum amplitudes of crustal magnetic field intensity are estimated to be ± 100 nT over minimum 100-km wavelengths. To ensure clear definition of anomalies, the maximum noise level should be at least 30 dB below the expected signal.

Recommendation: Further investigation must be done to establish a rationale for the allowable noise limits. However, based on the above intensity and wavelength estimates, intuitively based guidelines can be suggested. The total noise envelope for the primary mission objective (total-field measurements) should not exceed 1.75 nT rms or 5 nT p2p (peak-to-peak). If the noise power is divided equally between the residuals of aircraft-generated noises and geomagnetic temporal variations, then each category is allowed a maximum noise envelope of 1.25 nT rms or 3.5 nT p2p. The secondary mission objective (vector magnetic measurements) is expected to be about 15 dB above the primary, yielding 7 nT rms or 20 nT p2p per component. Adding the geomagnetic temporal variations yields 8.3 nT rms or 24 nT p2p.

Issue 4—Sensor Mounting Location and Appurtenance: There is an optimum location and means to mount sensors based on both platform-generated noises and engineering considerations.

***Recommendation**:* All of the sensors should be placed within a 12-foot tail stinger that is rigidly mounted in place of the existing tail "bubble". The stinger should have a constant inside diameter of at least 7 inches and be constructed as a continuous unit (no joins) from an extremely rigid, non-conductive, non-magnetic material such as G-10 epoxy fiberglass. If tests show that an excessive thickness of radar absorbent material is necessary for shielding, the inside diameter must be increased to accommodate that excess. No foreseen scenario would favor a nose stinger over a tail stinger.

Recommendation: If radiated or magnetic noise from the radar system precludes successful compensation at the tail location, an alternative must be considered. A reasonable option is to fly a total-field magnetometer and a fluxgate compensating magnetometer in a 6-foot bird at 75 feet behind the tail assembly. The cable would attach and the bird would dock on top of the vertical stabilizer. The bird would fly nearly horizontally behind its tow point and would therefore be above most turbulence. Due to expected roll instability, it would be necessary to select a total-field magnetometer that has minimal heading error and vanishing dead zones. A potassium magnetometer is suggested in this instance.

Issue 5—Redundancy: The costs of reacquiring data due to equipment failure will be greater than the costs of duplicating equipment. Additionally, if configured to run in gradient mode, redundant systems will indicate whether a magnetic effect has been generated locally. With some development work, local gradients can be used to model and remove effects of current loops.

Recommendation: All essential systems should be redundant, being duplicated such that if one system fails or becomes noisy, another independent system will continue collecting data unaffected.

Recommendation: Development work should be done to incorporate total-field and vector longitudinal gradients into the compensation algorithm.

Issue 6—Sensor Instrumentation: The sensors and associated equipment should be placed together in the tail stinger in a manner that best suits each method's noise envelope and engineering constraints.

Recommendation: The tail stinger should have the following pieces of equipment listed in order from the farthest aft location:

11' - TF (total-field) magnetometer sensor #1 and orienting bracket
8' - TF magnetometer sensor #2 and orienting bracket
5' - Vector magnetometer sensor #1 (or fluxgate compensation sensor #1)
3' - Vector magnetometer sensor #2 (or fluxgate compensation sensor #2)
0' - Drivers for TF #1 and TF #2

Recommendation: The tail stinger should be removed from the aircraft and the sensors and drivers installed. The stinger should then be tested as an independent unit before reinstalling to the aircraft.

Recommendation: The TF magnetometers will be existing Geometrics G-823a Cesium sensor and driver assemblies. The cabling should support both the rs-232 output from the onboard counter as well as the Armor signal for each unit. The Armor signals can then be counted in gradient mode and transfer functions matched with the output of the fluxgates. These sensors are recommended because:

1) Cesium magnetometers are available for the mission and are extensively known and recognized in the airborne geophysics community. Specifications and operation are well documented and tested; precisions and accuracies are undisputed and unambiguous.
2) Geometrics will back their product with expertise and support. If breakdown occurs, a replacement can, in most cases, be delivered within 24 hours.
3) We have tested G-822's (same as the G-823a's only without the on-board counter and rs-232 feed) in the rigorous environment of high altitude flight and we know that they work reliably under those extreme conditions.

Consideration will be given to also installing alternatives to the Cesium's, such as Potassium or Helium magnetometers, if available. These alternative magnetometers may be preferred if they are more compatible with the terrain mapping system.

Recommendation: The vector magnetometers should be tri-axial fluxgates of the design provided by NASA (Mario Lacuna). These have been developed for use in satellite applications and are the result of many years of research that overcomes a great many problems extant in commercially available fluxgates. Precision and accuracy are within the attitude-constrained mission noise envelope for the vector measurements.

Issue 7—Data-Acquisition Instrumentation: The data acquisition system is pivotal to the mission. It must perform a variety of functions in real time or facilitate them in post-processing, including:

Operate at a 160-Hz sample rate
Count Armor signal;
Match transfer functions of the TF and vector magnetometers;
Acquire with sample and hold serial, parallel, Ethernet, and analog data;
Acquire and process a TTL time-synch pulse;
Reconcile data-stream latencies;
Store huge amounts of data in redundant independent non-volatile storage;
Boot and operate with no operator input;
Gracefully handle all errors with minimal data loss; and,
Produce visual warnings and digitally log all error conditions.

The data acquisition system must fit into a 19" rack space, 11" high and 21" deep, as well as operate under the conditions of the cabin space at a 30,000-foot pressure altitude.

Recommendation: Custom build a data-acquisition system from circuitry supplied by a company that specializes in such systems. Magnetometer front-end processing should be done either with a dedicated instrument (if it can be fit into the remaining rack space), or as add-on boards to the data-acquisition system.

Issue 8—Noise Characterization Instrumentation: There are two noise sources that must be monitored during all data acquisition periods. One is the heavy 28-Vdc currents that flow to the IFSAR power systems. The other is the motion of the tail stinger relative to the main wing spar.

Recommendation: Install a current-sensing device on one leg of **each** anticipated 28-Vdc current loop and record its output as a separate data stream. These data will be used in a compensation algorithm to remove the effects of the current loops.

Recommendation: Install a couple of high precision vector magnetometers in the aft bay or bomb bay and run them in gradient mode along with the two vector sensors in the tail stinger. These will help characterize the magnetic fields produced by the IFSAR power currents. Also, consider installing vector magnetometers in the wings inside anticipated current loops.

Recommendation: Install a series of relative motion sensing devices to measure the transverse, vertical, and torsional motions of the tail stinger relative to the main wing spar.

Issue 9—Logistics: Bringing all of the equipment together and integrating it into the aircraft must be carefully planned and executed.

Recommendation: Hire or appoint somebody to oversee this task, to delegate duties and subtasks, and to coordinate activities with the radar installation.