Paper 2

Airborne Geophysics – Evolution and Revolution

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ABSTRACT

The past decade (1997-2007) of airborne geophysics has been an exciting time. Mineral exploration activity and expenditures have been cyclical, but the decade has ended in what can only be referred to as "boom times". The airborne survey industry itself has undergone dramatic changes, moving into a period of consolidation during 1999/2001, only to be followed by a period of expansion with new companies being formed and prospering. At the present time there are more independent commercial airborne survey companies operating than before the consolidation. The client base has also been altered significantly. The trend to "buying reserves" instead of "finding them" has resulted in a series of mergers and acquisitions amongst the major mining companies. Fortunately the buoyant financial markets and recent strong commodity prices have allowed the "juniors" to take up the slack and in many cases finance exploration joint ventures with the majors. A cloud on the horizon is the aging and declining pool of experienced people in the industry. Against this background of market dynamics some airborne geophysical methods such as radiometrics and magnetics have experienced incremental, basically evolutionary developments over the decade. One exception to this is the trend towards low level high resolution magnetic surveys employing helicopters and "crop duster" aircraft. Another would be the introduction of UAV's for magnetic surveys although the importance of this survey technology remains to be proven. Much more dramatic developments, or a revolution, have occurred in gravity and electromagnetics. In gravity there have been significant new developments in the measurement of basic airborne gravity. However, the most significant development for mining applications has been the introduction of airborne systems to measure gravity gradients, termed airborne gravity gradiometers (AGG). Airborne electromagnetic developments present a bit of a paradox. In both helicopter and fixed wing frequency domain systems developments have been incremental and primarily focused on new applications. The true revolution has occurred in the development and application of helicopter time domain (HTEM) systems and to a lesser degree in fixed wing time domain (FTEM) systems. The last five years of the decade have seen HTEM move from the development stage to capturing a significant portion of the world wide airborne EM survey market. Other FTEM and HTEM developments have included a push to greater bandwidth as evidenced by the introduction of B-field and step response data, the use of square wave transmitters,, new airborne platforms with higher performance capability and improved interpretation techniques.Other related airborne geophysical system developments have included hyperspectral imaging and a revisiting of the natural field airborne EM method, AFMAG.There remain enough opportunities (and unresolved issues) to create the opportunity for significant new advances over the next decade.

INTRODUCTION

Airborne geophysics was reviewed as part of the last decennial conference (Reeves et al 1997). This paper, entitled Airborne Geophysics: Old Methods, New Images, described a number of key developments which had characterized airborne geophysical technology over the preceding decade. Amongst these were the broad emergence of accurate positioning based on GPS, the move towards integration of data to give a more complete picture of the exploration environment and the impact of imaging as a means of viewing geophysical information,

In this past decade, those trends mentioned above have persisted and strengthened. Accurate positioning is now expected by both clients and service providers. The integration of data has similarly remained an enduring theme, however, there are now more software tools available facilitate this activity. As to the imaging of data, the present authors agree with the previous chroniclers in that simple image-based assessments of data are not a substitute for proper geologically supported interpretation, regardless of how appealing and seemingly intuitive image analysis may seem.

In addition, we have seen two developments in acquisition capability which will be of significance for some time to come. The first is airborne gravity gradiometry (AGG). (There are various ways of referring to gravity gradiometer systems in the public domain, however, we will use AGG as a generic means of referring to all systems designed to measure the gravity gradient in some fashion.) Although described by Reeves et al (1997),

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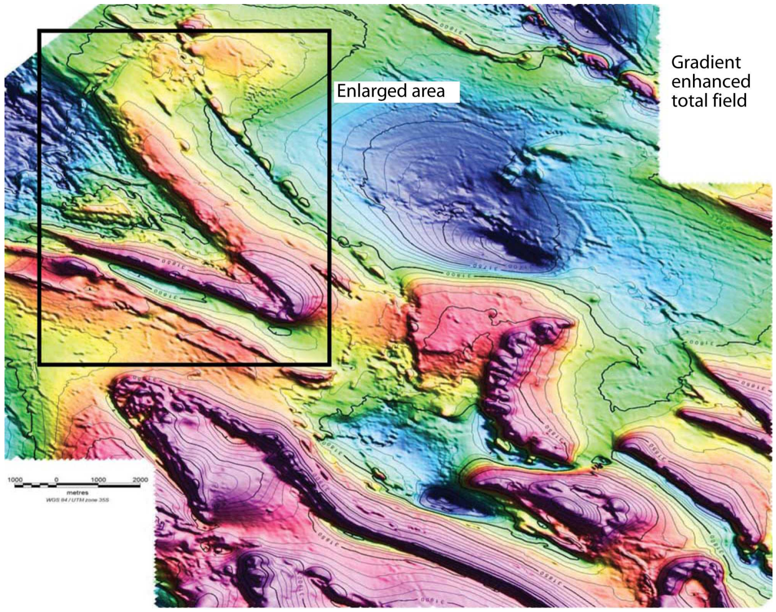

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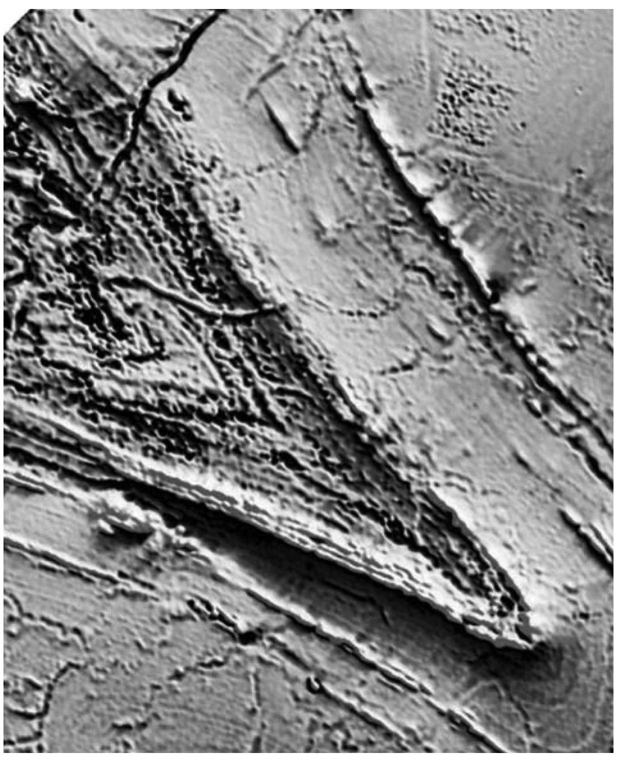

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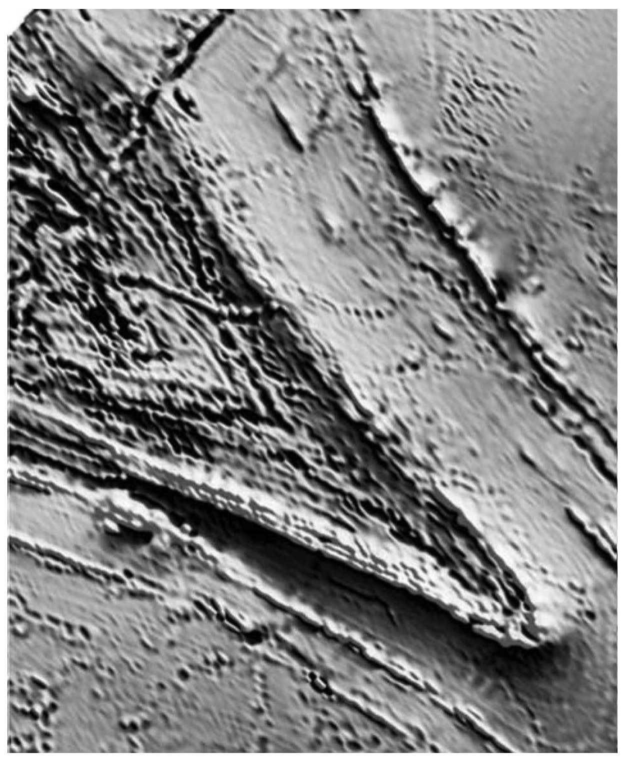

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Figure 1: Illustrates the high spatial frequency content of magnetic data with a multi-sensor helicopter mounted system. a) shows high resolution gradient enhanced magnetics collected at 100 m line spacing; b) is the first vertical derivative-gradient enhanced data within the selected area and c) is the first vertical derivative single sensor data within the same area. Courtesy of New Resolution Geophysics.

airborne gravity gradiometry only became a widely available exploration tool in the past decade. The other significant new system development is the rise to prominence of helicopter time domain electromagnetic systems which have similarly added an important new capability to the explorers' tool kit. In addition to these there have been significant improvements or augmentations in existing systems. Examples of these include the advent and widespread availability of broader band time domain systems and the availability of more practical airborne total field gravity measuring instruments.

Airborne Radiometrics

For airborne radiometrics or gamma-ray spectrometry (AGS), the last ten years have been a period of consolidation and incremental evolution. It is interesting to note that many of these advances and trends are related to non-mineral exploration applications. However, with the recent upsurge in worldwide uranium exploration, the techniques and applications are returning to their historical roots.

The maturation of the AGS technology is benchmarked by the creation of authoritative documentation in four noteworthy volumes (AGSO,1997; RADMAGS, 1998; JER, 2001; IAEA, 2003). This has resulted in improved interpretation methods and greater acceptance of it as a standard technique for both geological mapping and mineral detection. It has become a common partner with other major airborne techniques as part of many mineral exploration programs (Ford, K. et al, 2007; Schetselaar, E.M., 2002).

Along with this has come extension to related mapping applications such as: soil mapping; identification of groundwater recharge areas within catchments; and identification of regolith that could act as salt stores (Pickup, G., 2000; Wilford, J. et al, 2007).

Non-geologic applications (Lahti, M. et al, 2003; JER, 2001) include:

- lost radioactive source location (RADMAGS, 1998);
- nuclear power plant monitoring (Rybach, L. et al, 2001; RADMAGS, 1998),
- emergency response with real time evaluation and isotopic identification, (Bucher, B. et al, 2004)
- radon risk assessment (Barnet, I. et al, 1998; Ford, K. L. et al, 2001)
- are also igniting interest.

Processing techniques have also gained attention and have resulted in an improved understanding of, and more effective application of, NASVD and MNF techniques for noise reduction in multi-channel airborne gamma-ray spectra (Minty, B.R.S., 2003). In parallel there have been improvements in the understanding of atmospheric radon effects, as well as the extension of radon removal technique to use of lower energy peaks (Grasty, R.L., 1997; Jurza, P. et al, 2005)

Recently, interest in understanding the impact of the equipment signal path has resulted in spectrometers which process the individual crystal spectra before summing occurs (RSI, 2006).

Airborne Magnetics

Airborne magnetic surveying, the oldest airborne geophysical method, saw only incremental changes during the past decade. One development path that is being actively pursued is the acquisition of data with higher spatial resolution. This is motivated by applications (mining and environmental) which benefit from more detailed mapping of the near surface magnetic character.

One means of realizing this outcome is to acquire data with a lower mean terrain clearance and more closely spaced flight lines. For fixed wing surveys, this has in some cases resulted in the adoption of "crop duster" type aircraft flown at survey heights below 40 m in conditions where the terrain is appropriately flat and lightly vegetated.

Another way of mapping the magnetic field in more detail is to measure the gradient as well as, or instead of, the total field. This has lead to the increased use of magnetic gradiometer systems and in particular the increased use of transverse horizontal gradient systems on helicopter platforms; the use of gradient data is illustrated in Figure 1.

The ultimate expression of the push to higher spatial resolution is seen in the field of unexploded ordnance (UXO) detection, where boom mounted vertical gradient magnetic systems have been developed, Gamey et al, 2004. In these cases, the purpose is to achieve several parallel, close spaced flight lines of data with one pass of the aircraft in order to detect discrete magnetic sources within a few meters of the surface with high reliability. Specially designed for this purpose is the ORAGS VG-22 shown in Figure 2.

Figure 2: The ORAGS VG-22 system with 11 boom mounted vertical gradiometers (22 total field magnetometers) for UXO detection. Courtesy of Oak Ridge National Laboratory

The more frequent acquisition of gradient data has prompted consideration of methods for extracting more information from it. O'Connell et al, 2005 review implications of handling gradient aeromagnetic data with suggestions for improved methods.

Another development of interest has been the introduction of the UAV or Unmanned Airborne Vehicles (McConnell, 2005 and Doyle, 2005). Partner (2006), describes a commercial application of such a system for surveying offshore in the Gulf of St. Lawrence, Quebec, Canada. The aircraft used is represented in Figure 3.

Figure 3: The GeoRanger, an example of a UAV (Unmanned Airborne Vehicle) designed for geophysical application. Courtesy of Fugro Airborne Surveys

Airborne Gravity

Frank van Kann (2004) states that the quest for airborne gravity is as old as airborne exploration itself. For purposes of this review there will be a discussion of two distinct airborne gravity methods, gravity and gravity gradiometry. Van Kann (2004) and Dransfield (2007) deal with airborne gravity gradiometry extensively.

Airborne Gravity

Direct measurement of variations in the earth's gravitational field from an airborne platform has been, and remains, a challenge. Although airborne gravity systems have existed since the 1980's, they were never widely used in minerals exploration. Most acquisition relied on gravimeter systems which were originally designed for marine acquisition and modified for airborne use. Their characteristics often required careful flying procedures utilizing large aircraft flying at a fixed barometric level which often resulted in highly variable terrain clearances. However, improvements in GPS hardware and processing combined with advances in Inertial Navigation Systems (INS) systems has led to new approaches to creating airborne gravimeters (Sander, S. et al, 2004; Gabell et al, 2004). These systems can largely be installed in common survey aircraft, either fixed wing or helicopter and may use surveying methodology which approaches that of other airborne geophysical techniques. The increased utility of airborne gravimetry is a significant outcome of current system development and these improvements may have contributed to an increase in use of airborne gravity since 1997.

Resolution and accuracy of the final gravity data is dependent on flying speed, line spacing and processing methodology. The best spatial resolution delivered by airborne gravity systems on fixed wing aircraft today corresponds to a half-wave distances of 2.0 kms (Malcolm Argyle and Luise Sander, personal communication). This has limited the applicability of such systems in direct detection of most mineral deposits. However, they can be used for geological mapping related to mineral exploration (see Figure 4) and the technology is well suited to oil and gas exploration.

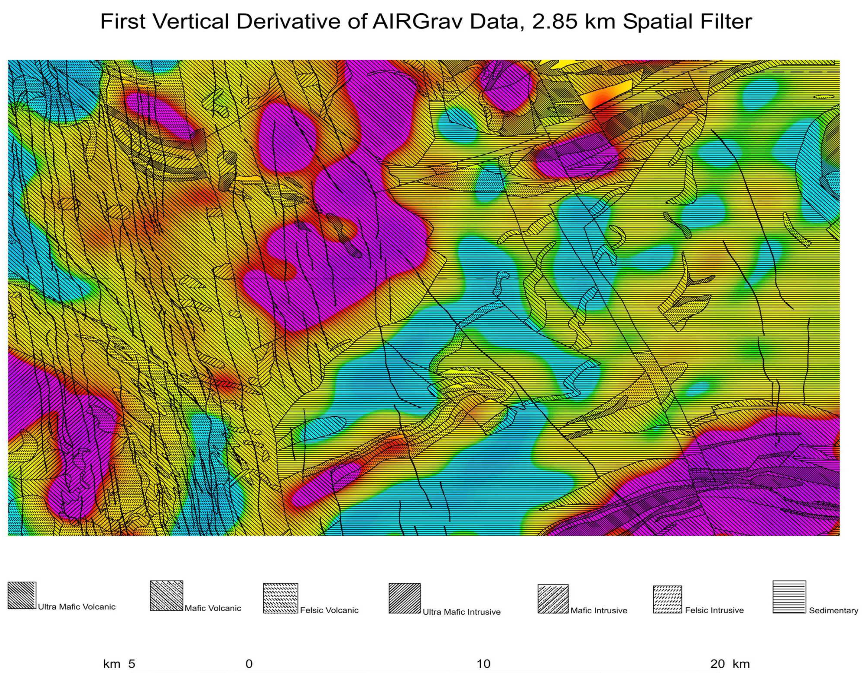


Figure 4: An example of an airborne gravity data set from the area near Timmins, Ontario, Canada. The airborne survey was flown with survey flight lines spaced at 500 m by 5 000 m and at a constant GPS height of 458 m, chosen to safely clear the highest terrain within the survey block. Terrain elevation within the survey block vary between approximately 250 m and 400 m above mean sea level. The information is presented with a geological map overlay on the first vertical derivative of the airborne data-derived grid. Courtesy of Sander Geophysics Limited.

A quite different approach to measuring gravity in the air employs a vibrating string. Designs by (Babayants, 2006; Kontorovich, 2007) utilize a suite of three wide range string gravimeters with a high precision inertial gyro stabilization system. Such systems are reportedly more stabile in high latitudes where inertial navigation systems exhibit instability (Kontorovich, personal communication, 2007).

Airborne Gravity Gradiometry

The challenges associated with airborne gravimeter design motivated several major mining companies to identify and develop means to measure gravity responses from the air that were of comparable precision and accuracy to that obtained with ground gravity surveys for minerals exploration. To achieve this it was suggested that the gradient of the gravity field must be measured and not the gravity field itself (van Kann, 2004; Witherly, 2005). The first operational Airborne Gravity Gradiometer,(AGG) system that was capable of matching the quality of ground-based measurements was the BHP Billiton FALCON™ system, which began flying in 1999 (van Leeuwen, 2000; Lee, 2001). A picture of this system installed in a small survey aircraft is shown in Figure 5. Dransfield (2007) provides a detailed review of AGG developments in the decade since 1997. Arthur Maddever (2007) reviews results from a helicopter-mounted system. Outcomes from a Falcon survey at the Ekati diamond mine, one of the first commercial surveys performed with the technology are shown in Figure 6 (Liu et al, 2001).

Although there are a number of AGG systems available in the commercial market today, they are all still derived from the same underlying technology developed by Lockheed Martin for the U.S. Navy in the 1980s (van Leeuwen, 2000). Differences in the systems relate to the number of independent components of the gravity gradient tensor which are measured, the accuracy with which they are measured and the processing methodology used to produce a final suite of corrected data.

In principle, AGG systems are more sensitive to shorter spatial wavelengths than sensors which attempt to measure the total gravitational acceleration. For comparable sensitivities to that of an airborne gravity system, AGG systems on a fixed wing aircraft can be used to map features typified by half wave distances of 200 m. This corresponds to an order of magnitude better spatial resolution than achieved from total field systems at short wavelengths. As with the total field systems it is also possible to carry out helicopter-mounted AGG surveys resulting in greater spatial resolution. Gradient systems have therefore found wider application in mineral exploration programs and in oil and gas applications where more information on structural complexity is required.

Figure 5: Falcon system installed in Cessna 208B aircraft

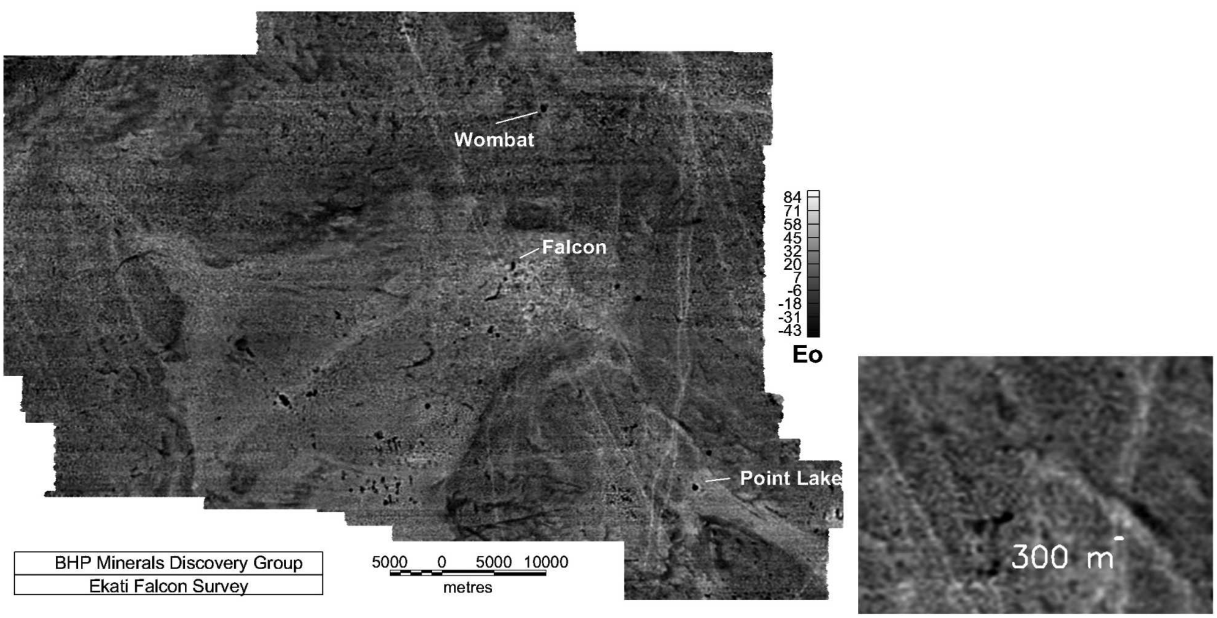


Figure 6: The vertical gravity gradient from a survey near the Ekati mine, Canada. The image on the right shows an enlargement of a section in the lower right of the main image. Two narrow dykes separated by about 300 m (as indicated by the white bar) are resolved by the gravity gradient measurements. After Liu et al, 2001.

Recent attempts to fine tune the use of AGG systems have resulted in new deployment methods. In one attempt to reduce noise and maximize spatial resolution by installing the system in a larger, slower aircraft, De Beers has chosen an NT-07 Zeppelin airship (see Figure 7) as the airborne platform (Hatch et al, 2007). BHPB has taken a different approach by installing the Falcon system in a helicopter and using it in conjunction with a frequency domain electromagnetic system.

Figure 7: De Beers airship used for airborne gravity gradiometry, at its base after a survey. Courtesy of De Beers

Airborne gravity gradiometer research is one of the most active areas of airborne technology development today. There are at least four fundamentally different design concepts being worked on with the stated goal of producing the next generation of AGG system (a noise level of 1Eötvos/Hz1/2 seems to be a common target for these efforts). All AGG systems operating today are "room temperature" systems, meaning that they do not require extraordinarily low temperatures as part of the system design. Most of the second generation systems under development use superconductivity as a design element to increase sensitivity and/or reduce noise (see Figure 8).

In Figure 9 of their review paper, Reeves et al., 1997 showed the sensitivity versus resolution curves thought to characterize airborne gravity and gravity gradiometer systems in 1997. More recently Dransfield (2007) has given an up-to-date assessment of the capabilities of the AGG given the advances which have been seen in the presently operational systems.

Figure 8: An example of a second generation airborne gravity gradiometer system in a cryogenic dewar (blue cylinder) on shaker table undergoing tests. The vertical dimension of the dewar is about 1.1metres. Courtesy of ARKeX

Airborne Electromagnetics

Some of the most dramatic changes in the decade have been in the technology of airborne electromagnetic surveying. Reeves et al (1997) suggested that the capability of present (1997) survey systems offers such enormous potential, that the immediate emphasis was more likely to be on application rather than innovation: coverage of more areas with existing systems rather than the development of new and better systems. For whatever reason, this has proven to be far from the case in many respects.

Both helicopter and fixed wing frequency domain system developments have been evolutionary and primarily focused on new applications with the concomitant modifications of existing systems. The true revolution has occurred in the development and application of helicopter time domain (HTEM) systems and to a lesser degree in fixed wing time domain (FTEM) systems. Since 1997, there have been several historical review presentations on airborne electromagnetics (Fountain, 1998; Witherly, 2000; Fountain and Smith, 2003; Nabighian and Macnae, 2005). The dramatic on-going developments in HTEM, at the present time, will no doubt add a whole new chapter to these review papers.

Frequency Domain Systems

Fixed Wing

The fixed wing frequency domain electromagnetic (FFEM) systems have largely undergone incremental development. Most of these have rigidly mounted transmitter and receiver coils on the wing tips (see Figure 9). Due to their size and frequency range such systems tend to be better suited for relatively near surface mapping applications rather than deeper investigations. Some systems have been developed by adding additional frequencies (Andrey Volkovitskiy, personal communications; Lee, M. and Sandstrom, H., 2004). In other cases the availability of new electronics has prompted alternative designs to appear such as those which afford the user the ability to digitally select the transmitted frequencies.

Figure 9: A typical fixed wing frequency domain electromagnetic system with wingtip mounted transmitter and receiver pods clearly visible. The tail stinger is not a component of the EM system; it contains a magnetometer. Courtesy of GTK

Helicopter

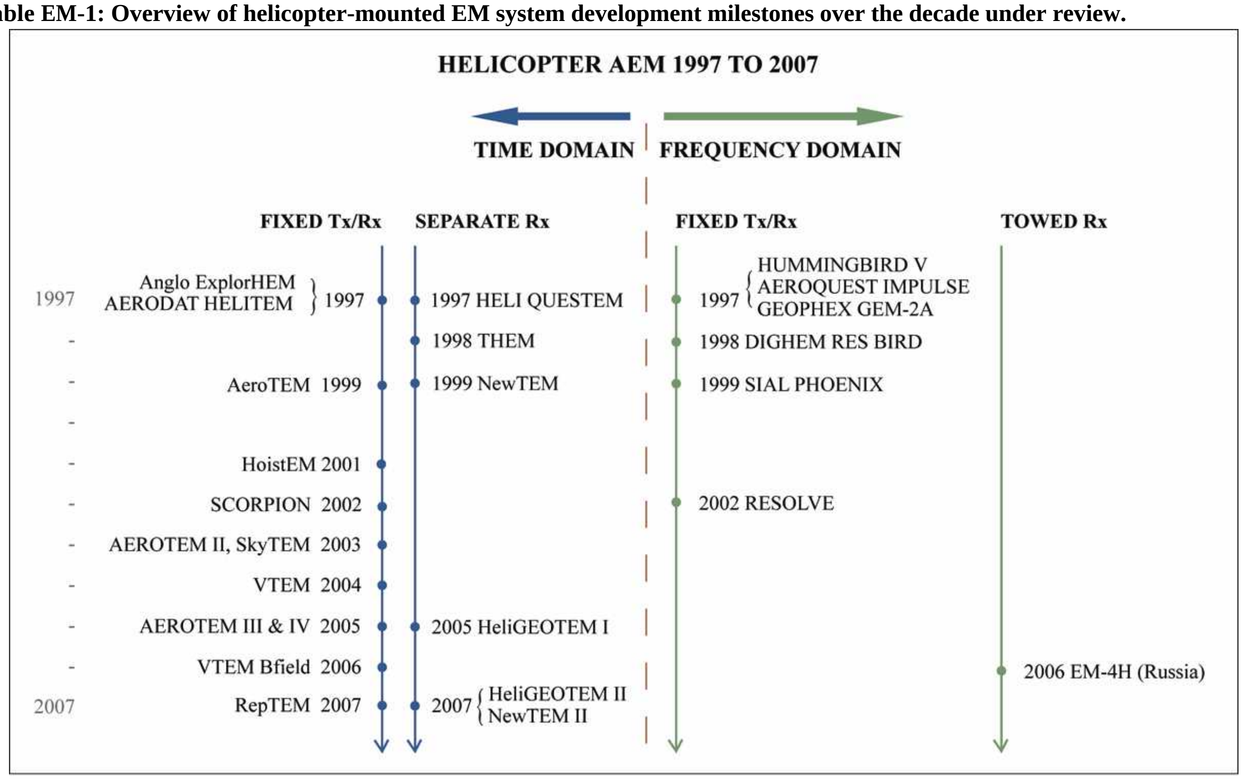
Early in the decade, there were several developments in the conventional helicopter frequency domain (HFEM) "towed tube" EM systems with 1997 seeing the introduction of the three new systems (Table (EM-1)). In a somewhat less-standard configuration, the Geotechnologies Group in Moscow introduced the multi frequency, towed receiver bird EM-4H conductivity mapping system in 2006, (see Figure 10), (Andrey Volkovitskiy personal communications).

Figure 10: The EM-4H conductivity mapping system which uses a transmitter loop attached to the helicopter and a towed body receiver. Courtesy Andrey Volkovitskiy.

Whereas, most helicopter frequency domain "towed tube" systems have a separate coil pair in the bird for each frequency, new electronics made possible the use of wide bandwidth coils with digitally selected frequencies (Holladay and Lo, 1997) similar to the FFEM case previously described, although these systems remain in the minority with respect to commercial availability. The desire to be able to map near surface resistivity structure with increased fidelity also led to the introduction of systems with an increased number of horizontal coplanar (vertical axis) coils (Hodges and Latoski 1998; Hodges, Greg 1999; Huang et al, 1998). All of these fixed Tx/Rx HFEM developments occurred in the first half of the decade with few significant new developments occurring since 2002.

In the period since 2002, perhaps partially due to the emerging position of helicopter time domain EM in the early 2000's, new developments in HFEM technology have fallen off. In their place has been an increased breadth or variety in the application of HFEM technology. Increasingly HFEM methods have been applied to groundwater, engineering and environmental problems. Hammack. et al, (2001) describe the use of helicopter frequency domain EM to locate contaminant flow paths at the abandoned Sulphur Bank Mercury Mine in California, (see Figure 11). The diamond exploration boom and the favourable geologic environment in the Canadian arctic created a continuing large demand for HFEM surveys early in the decade, but with the shift of diamond exploration to other less favourable geological terrains and emphasis on other commodities, this exploration-related demand has fallen significantly.

Table EM-1: Overview of helicopter-mounted EM system development milestones over the decade under review.



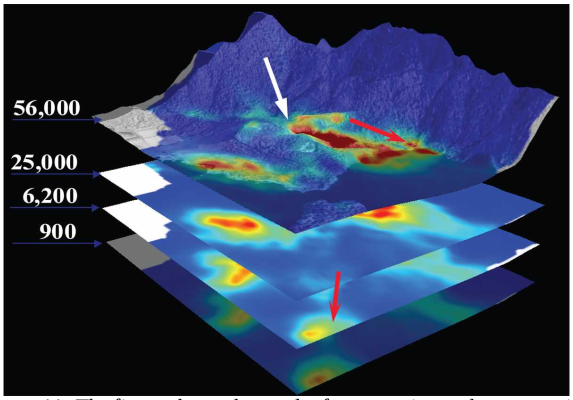


Figure 11: The figure shows the result of a contaminant plume mapping exercise at the Sulphur Bank Mercury Mine in California. Seepage of contaminants is mapped as increased zones of conductivity indicated by the “hotter” colours in the image. The images are separated according to electromagnetic frequency in Hz. Since depth of investigation generally varies as an inverse function of frequency, lower frequencies correspond to information derived from deeper portions of the environment. (Hammack, 2002)

Time Domain Systems

Fixed Wing

The start of the decade saw a number of fixed wing time domain EM systems (FTEM) plying the skies. These were all descendents of the INPUT technology, which first saw widespread use in the 1970’s. The development trend of the previous decade had been towards lower frequencies and more power. Both of these trends were a search for greater depth of investigation in an attempt to open up the search space for the methodology. The trend for greater depth continued in the period from 1997-2007 as more and more powerful versions of the systems were put into production, with dipole moments ranging to well over 1 000 000 Am2.

Two other technical developments of note became available during the decade under review. One – broadband (square wave) transmitter waveforms had been developed in an earlier system (SPECTREM) which was proprietary to DeBeers and Anglo American and was hence not widely available. This changed in 2000 when the TEMPEST system, a collaborative venture between government (CRC-AMET) and industry (Lane 1998 and 2000), became commercially available. The second was an attempt to render the responses from such systems in ways which would “add bandwidth”. In this sense, the generation of the step response from square wave systems and the introduction of B-field data (Annan and Smith, 1998; Wolfgram and Thomson, 1998), were significant developments in the ability of existing systems to represent good conductors (Figure 12). These developments seen together opened up the effective bandwidth of system sensitivity and made FTEM systems more useful over a broader range of mapping and detection.

Along with these capabilities a debate was ignited concerning the main benefit to be gained from the use of time domain EM systems. This debate pitted those advocating the mapping of geology, or holistic mapping, against the detection of discrete target conductors, the so-called “bump finders”. Whether there will ever be a conclusive judgment in this debate remains to be seen, however the fact that the available technology provides a viable platform for supporting either view, should be termed a positive in itself. In practice, the technical advantages allowed new applications such as regolith mapping, deep basin graphitic conductor mapping and nickel sulphide targeting. It is also noteworthy that more recent time domain system developments, such as helicopter time domain EM, incorporate or attempt to incorporate these same characteristics.

Table EM-2: Overview of fixed wing-mounted EM system development milestones over the decade under review.

FIXED WING AEM 1997 TO 2007

	TIME DOMAIN	FREQUENCY DOMAIN	
	TOWED RECEIVER	RIGID COILS	TOWED RECEIVER
1997	1997 GEOTEM B-field		
-	1998 QUESTEM 450, MEGATEM		
-		1999 GEOTECH HAWK	
-	2000 TEMPEST, SPECTREM 2000		2000 DIP-4A (Russia)
-	2001 MEGATEM II		
-	2002 GEOTEM 1000		
-			
-		2004 GTK/BGS 4 Frequency	
-			
-			2006 EM-4 (Russia)
2007			

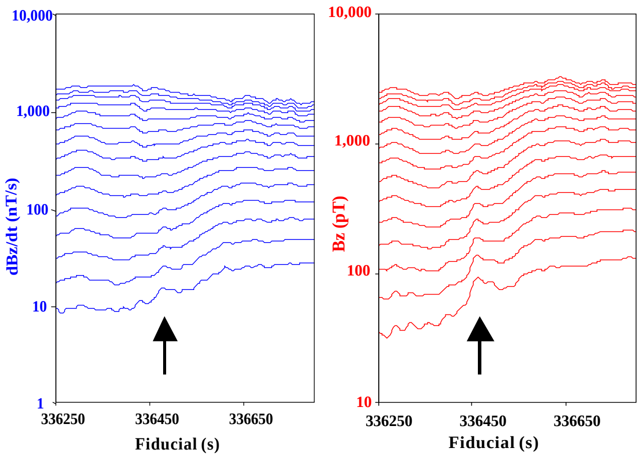


Figure 12: Comparison of a dB/dT and a B-field response. The black arrows indicate the position of a massive sulphide conductor. The dB/dT (response on left) and B-field (response on right) data were gathered concurrently. The enhanced late time (lower channels) of the B-field is (are) clearly evident.. After Wolfgram and Thomson, 1998.

Innovation can also be defined by a less technically complex path. An example of this was the creation of an FTEM system on a large, four-engine aircraft (Figure 13). The genesis of this was driven by the desire to survey at very high altitudes, but a side benefit was a system with increased power capable of mapping at depths approaching 1 000 m in environments such as the Athabasca Basin in northern Canada. (Smith et al, 2001 and 2003; Gingerich and Allard, 2001; Smith and Koch, 2006.)

Figure 13: The MEGATEM™ system was developed for high altitude applications, but also enabled the development of higher power systems as measured by peak dipole moment. Courtesy of Fugro Airborne Surveys

Helicopter

The most significant development during the past decade has been the emergence, especially in the latter decade half, of helicopter time domain EM (HTEM) as a significant instrument for mineral exploration (Fountain et al, 2005). Allard, (2007) has presented an excellent and detailed review of HTEM evolution to its present position. The factors that have led to rapid acceptance of HTEM have been excellent horizontal accuracy (especially for the coincident transmitter-receiver systems), ease of interpretation, cost effective mobilization and good depth of effective exploration.

It is of interest to note that HTEM, like many "new" developments in geophysics, is not an entirely new concept. During the 1970s the CentrGeoPhysica group of the Moscow Geology-Survey Institute flew surveys with the AMPP-2 HTEM system mounted on a Ka-26 helicopter, (see Figure 14) (Andrey Volkovitskiy, personal communications). In North America the HeliINPUT system was well known in the 1980's. Table EM-1 illustrates the system developments that have taken place since 1997. The number of different systems and different variations of each is impressive, but what is not adequately demonstrated by the figure is the total number of operational systems worldwide. At the present time we estimate the total number of available commercial and in-house HTEM systems would be at least thirty, having increased from a handful only four years ago. Allard, 2007, has described the two basic development streams of system configuration – those incorporating a relatively fixed transmitter-receiver geometry and those incorporating a separated transmitter and receiver.

Figure 14: The AMPP-2 is an example of a helicopter time domain system which dates back to the 1970's. Courtesy of Andrey Volkovitskiy

Of the three HTEM systems available in 1997, only the Anglo American/Spectrem Air ExplorHEM system is still operational (Polome, 2006) and presently surveying. The Aerodat HELITEM system (Qian et al 1998) although technically sophisticated, did not prove operationally successful. HELITEM may have been "before its time" and was also caught in the consolidation of the survey industry in 2000. Development and trial surveys of the "in house" NewTEM (Eaton, 2004) and HoisTEM (Boyd, 2004), Normandy, systems began in 1996. However, production surveys did not occur until 1999 and 2001 respectively (Perry Eaton, personal communications; Eaton et al, 2004). Since Newmont was one of the mining industry leaders in developing time domain EM during the 1960s, it is not surprising that they also chose to develop a helicopter-based time domain system.

On the commercial side, the visionary risk takers (Allard, 2007), who have led the advance into HTEM, include Bernard Kremer with THEM in 1998, (Bodger et al, 2005); Wally Boyko with AeroTEM in 1999 (Boyko et al, 2001 and Balch et al, 2003); and Ed Morrison with Scorpion in 2002 (Witherly et al, 2004 and Witherly et al, 2005). These developers certainly deserve praise for working in an economic vacuum during a rapidly collapsing mining exploration market to bring these systems to fruition. Since 2003, the resurgence of exploration activity has made this task much easier. Improvements to many of these systems have been introduced in the intervening years and other developers have also entered the HTEM fray with their own designs. When faced with the problems one encounters in creating a practical HTEM system, the developer has a number of different choices. This many-possible-paths approach is another reason so many different systems have come into existence. However, every design choice tends to have both a benefit and a disadvantage and the final balance of these can lead to profound implications for the overall utility of a given design. The configuration of the Geotech VTEM system in 2004 is shown in Figure 15. Time will tell as to which of these systems will prevail.

Figure 15: A typical modern helicopter time domain system – in this case, VTEM (circa 2004), which used a non-rigid coplanar transmitter-receiver geometry. Courtesy of Geotech Limited

Although not designed for mineral exploration as such, the ORAGS-TEM system is an interesting time domain helicopter EM system introduced during the decade and is shown in Figure 16. The system is designed to survey as low as 1-2 m above ground level in order to detect unexploded ordnance on former military test ranges (Beard et al, 2004).

Figure 16: The ORAGS-TEM system developed for unexploded ordinance detection where high near-surface spatial resolution and reliability of detection is required. Courtesy of the Oakridge National Laboratory

Natural Field and Semi-Airborne AEM

Ward et al, (1958) describe mineral prospecting by the use of natural alternating magnetic fields of audio and sub audio frequencies Ward (1960) and Shaw (1962) describe airborne AFMAG surveying. The airborne AFMAG method was applied by McPhar Geophysics Limited with some success in the 1960s and early 1970s but the system was limited by electronics and analogue handling of the data. More recently, with markets showing increasing interest in new exploration technologies and backed by the availability of improved electronics and digital processing techniques, the decade since 1997 has seen a renewed interest in natural field airborne EM methods (Fountain, 1998 and Fountain and Smith, 2003), (Table EM-3).

Table EM-3: Overview of passive and semi-airborne EM system development milestones over the decade under review.

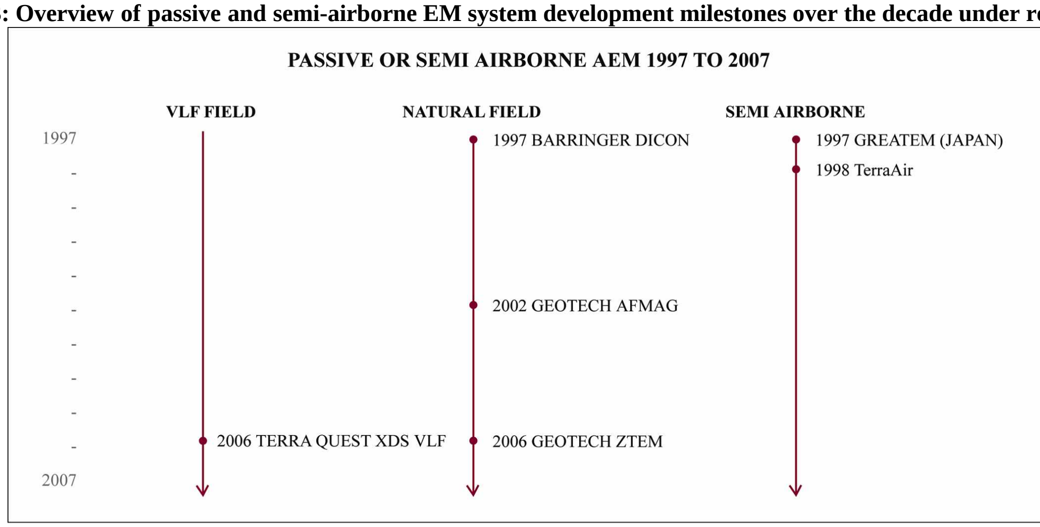


Figure 17: Geotech Ltd.'s AFMAG system showing Z axis receiver in foreground and ground-based monitoring coils in background.

Among those re-introduced include VLF methods (Howard Barrie, personal communication; Pedersen, 1998) and AFMAG-type systems. In 1997, Barringer Geosystems introduced the DICON system formerly known as Q-Trac. In 2002 this genre received a makeover in the form of a helicopter towed bird system (Lo and Kuzmin, 2004 and Lo and Kuzmin, 2005). Subsequent incarnations include a system with an eight metre diameter, vertical dipole axis receiver coil, towed by a helicopter coupled with an orthogonal horizontal dipole axis ground base station (Figure 17).

Early in the decade there were some on-going developments in semi-airborne methods in which part of the system (typically the transmitter) is positioned on the ground and the receiver is installed on a survey aircraft. The goal of such systems is to extract benefit from the specific advantages of both ground-based (more field strength into the ground) and airborne (ease of spatial coverage) systems. Elliot (1998) and Tohru Mogi et al (1998) describe some of these and Richard Smith et al (2001) present a comparison of semi-airborne data with airborne and ground EM data.

AEM - Processing and Interpretation

The decade since 1997 has seen significant developments in the handling of airborne electromagnetic data that in many cases cover the full range of system types. These include the almost universal use of conductivity depth sections (Lane, 2000), (see Figure 18),, more widespread use of layered earth modelling and inversion programs, access to discrete conductor forward modelling and inversion programs (Cheng et al, 2006) and transformation of data to discrete conductor sections (Smith and Salem, 2006). Each of these is an approximation to varying degrees and their use must be tempered with sensitivity to the limitations of the method, but they have brought airborne data into a more intuitive realm of understanding for many users.

A less obvious development, but still one of practical significance is the progress in off-the-shelf toolkits for the processing and presentation of airborne data. These include the Geosoft, Encom and Intrepid suites of software and make it possible for users of airborne data to administer, view, manipulate, modify and model large airborne data sets with relative ease. This means that users can increasingly concentrate on the data and its meaning rather than the mechanics of dealing with it and is an important step in making airborne data more valuable to the end user. For a detailed exposition on this topic the reader is referred to Pratt and Oldenburg, 2007. Condor Consulting have prepared a list of references to the major papers in AEM processing and interpretation over the last decade and these are included separately in the references section if the reader wishes more information. The authors do wish to note that generally speaking, the separation of processing from the acquisition of airborne data is becoming less clear. It could be argued, for instance, that the processing of airborne gravity and gravity gradiometry data is as important as the method of acquisition. As processing becomes more sophisticated, we feel that the separation of acquisition and processing will come to be seen as an increasingly arbitrary distinction.

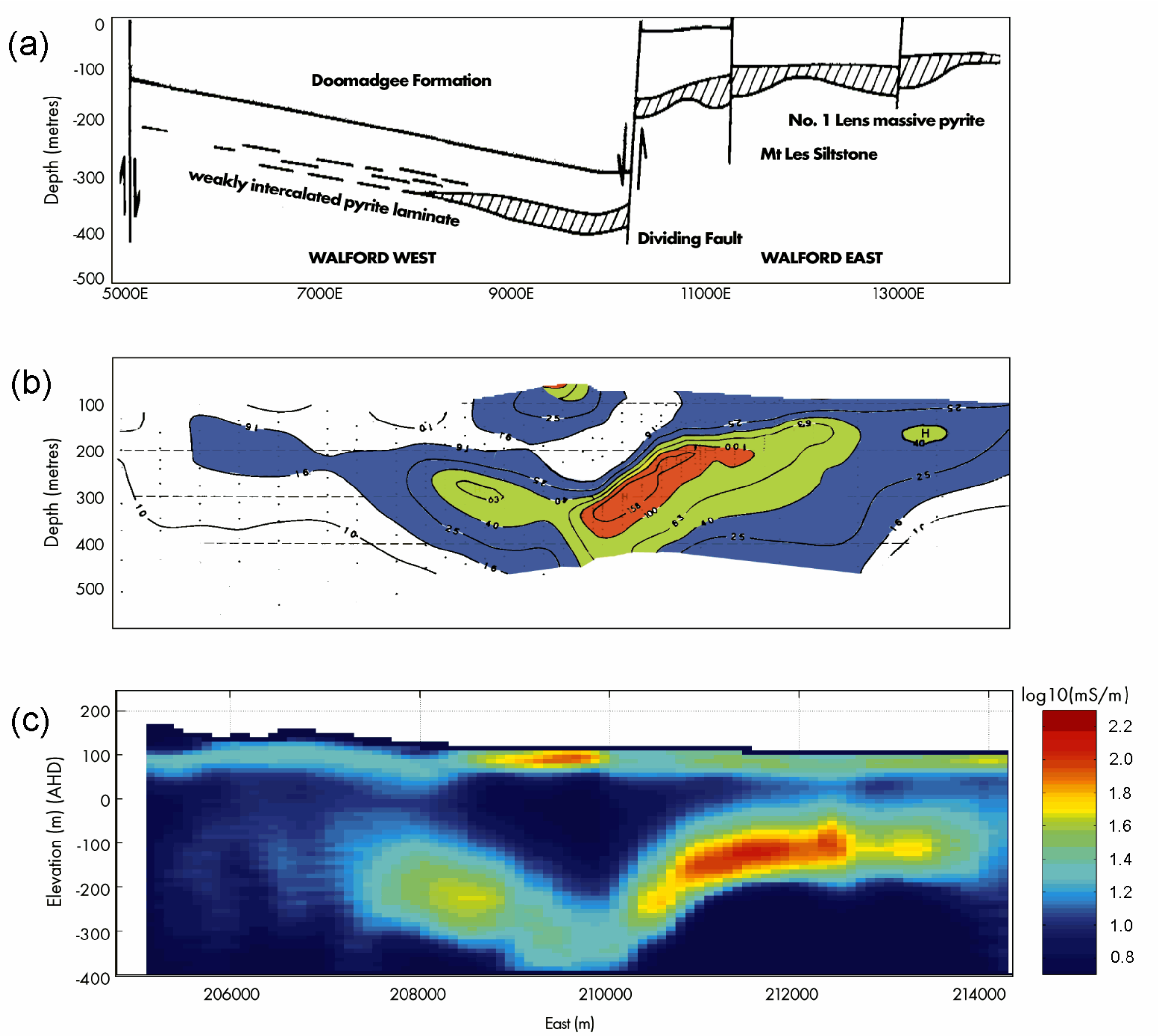


Figure 18: Example of a conductivity depth section. (a) Schematic long section, (b) conductivity section based on ground EM, and (c) conductivity section derived from TEMPEST AEM data for 8030100 mN at the Walford Creek Prospect. (a) and (b) are reproduced from Figures 3c and 3b of Webb and Rohrlach (1992). Note that the vertical scale for (a) and (b) is depth below surface, whilst for (c), it is elevation above sea level. After Lane et al, 2000.

Remote Sensing/Hyperspectral

The last decade has seen significant technical progress in the "remote-sensing" field. Historically, remote sensing generally meant analysis of data from satellite-based Landsat imagery. Since 1997, the availability of higher resolution, commercially available, aircraft-borne hyperspectral technology now justifies that this source of spectral information to be included as well.

This hyperspectral technology has been commercialized by companies such as ESSI and HyVista . The spectral scanners on which these systems are based have the roots in the JPL – developed AVIRIS system. Both LANDSAT TM and Hyperspectral focus on the visible and near Infra-Red part of the electromagnetic spectrum , i.e. 0.4->2.5 um, but whereas the former divides this bandwidth into seven spectral bands, hyperspectral systems typically divide the same bandwidth into 128 or 224 bands. As well, the horizontal resolution of hyperspectral systems is of the order of 1->10 m, depending on flying height, versus 50m for LANDSAT. Integrated Spectronics of Sydney, Australia have been the key instrument manufacturer that has brought about this revolution in commercialized hyperspectral remote sensing.

The increased spectral detail allows more discriminative characterization of minerals from the library of mineral reflectance curves used as the basis for interpretation. The practical ramification of this is portrayed in Figures 20 and 21 where a Landsat image from Chile is compared to a processed image of ESSI's Probe-1 data over the same area.

Commercial surveys have now been carried out on all five continents, but the exploration application has been primarily in Chile, North America and Australia. The method works best in semi-arid, lightly vegetated areas with little transported cover.

In spite of the availability of good quality instrumentation, it remains to be seen as to what position hyperspectral technology will take in the broader spectrum of airborne exploration tools. According to the experience of one of the authors (Watts) the technique is highly weather dependent and still requires relatively large efforts in both processing and interpretation to reach the end result. Coulter et al, 2007 and Agar and Coulter, 2007 offer further perspectives on the utility of hyperspectral technology and a more detailed discussion of developments.

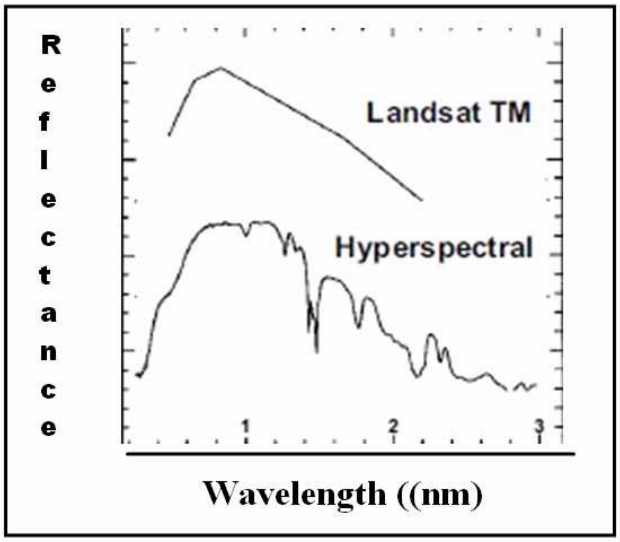


Figure 19: Comparative representation of the spectral resolution of satellite-based Landsat versus airborne hyperspectral. The detailed character of the reflectance curves provides discriminatory information for the mineral type. Hyperspectral is therefore potentially a more powerful tool for the categorization of minerals. After .Stevens and Zamudio, undated web publication).

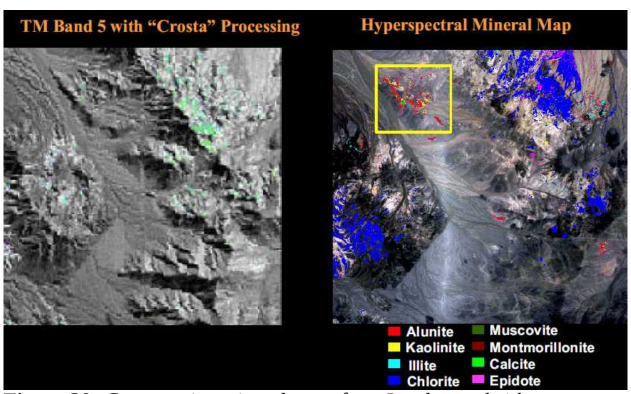


Figure 20: Comparative mineral maps from Landsat and airborne hyperspectral over an area of Chile. The area delineated by the yellow box is shown below. After Stevens and Zamudio, undated web publication.

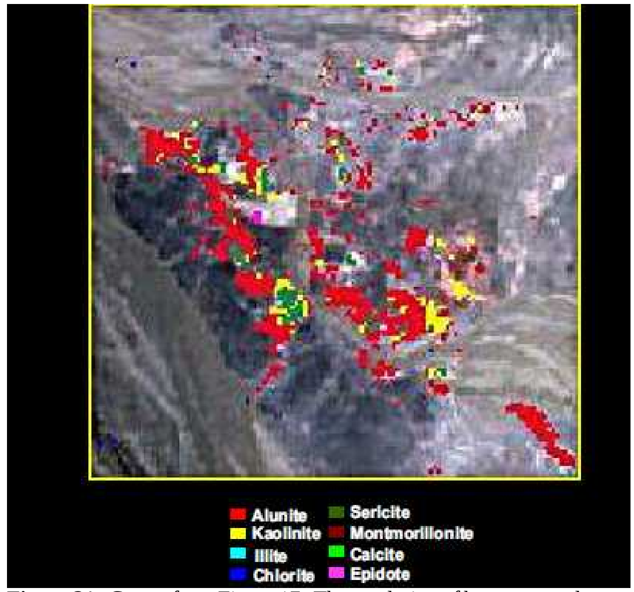


Figure 21: Cutout from Figure 17. The resolution of hyperspectral technology can create a detailed suite map of related minerals. After Stevens and Zamudio, undated web publication.

Ongoing Developments and Future Trends

As much progress as has been made over the last decade, there remain many areas in which advances would be beneficial.

In airborne radiometrics the "holy grail" continues to be finding an alternative to present detector crystals (Rozsa, C.M. et al). This may gain momentum from US government efforts in homeland security applications. In a more mundane, but technically relevant context, a better understanding of biomass and moisture effects is to be expected over time.

In magnetics, there is a general interest in the creation of airborne magnetic gradiometers. Some of these will likely include ongoing development of SQUID sensors. An airborne low temperature SQUID magnetic gradiometer has been extensively tested in South Africa during 2004 and 2005. Additional tests have been carried out during 2006 on a number of properties in South Africa, Namibia and Botswana (Polome, 2006). Production surveys with the SQUID magnetic gradiometer are planned to commence in late 2007, (Rompel, 2007). Development work is also likely to continue on the operation of UAV-borne magnetics systems, although their advantages have yet to be convincingly demonstrated.

The next decade will see extensive new developments in the area of airborne electromagnetics. The impetus for many of these developments is the continuing recognition that as new technologies become available, goals previously thought too difficult to achieve will come within reach.

As with magnetics and radiometrics sensor technologies will be especially interesting. Early in the last decade, BHP in conjunction with CSIRO, did considerable work on the development of SQUID sensors in place of conventional induction coil sensors in the receiver bird for FTEM systems (Foley and Leslie, 1998; Lee et al, 2001; Lee et al, 2002).

However, based on this early work, it was determined that from a practical standpoint that they did not offer significant advantage over other methods of determining the B-field response (Smith and Annan, 2000). However, interest in the use of low temperature SQUIDS as sensors has been reawakened and their incorporation into a helicopter time domain system is being planned (Polome, 2006; LeRoux, 2007). There no doubt will be reports on this development in the future and in the 2017 review of airborne geophysics. Likewise there has been success recently in using fluxgates for ground-based electromagnetic systems and their inclusion in airborne systems could be seen in the future.

Even though there has been some success in the development of broader band electromagnetic systems in the last ten years there is still a long way to go to detect and discriminate targets from the air that have very high conductance such as Norilsk or Kabanga. At the same time explorers are increasingly interested in looking deeper. The challenge will be to develop a high power, low frequency (<5Hz) system perhaps capable of making a true in-phase measurement.

On a broader front, there is a question as to whether the growth of helicopter time domain systems will eventually see them largely replacing fixed wing time domain technology.

In the combined area of airborne gravity and gravity gradiometry there are several systems under development and this is, and will continue to be, one of the most active areas of airborne technology development. The successful creation of a second generation airborne gravity gradiometer with a 1 Eötvos/Hz1/2 sensitivity would be a major accomplishment, given that it has proven to be so elusive to date. The quest for airborne gravity is as old as airborne exploration itself and one looks forward to where we will be in 2017.

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