APPLICATION OF REMOTE SENSING AND GEOPHYSICS TO THE DETECTION AND MONITORING OF ACID MINE DRAINAGE

MEND Project 4.6.3

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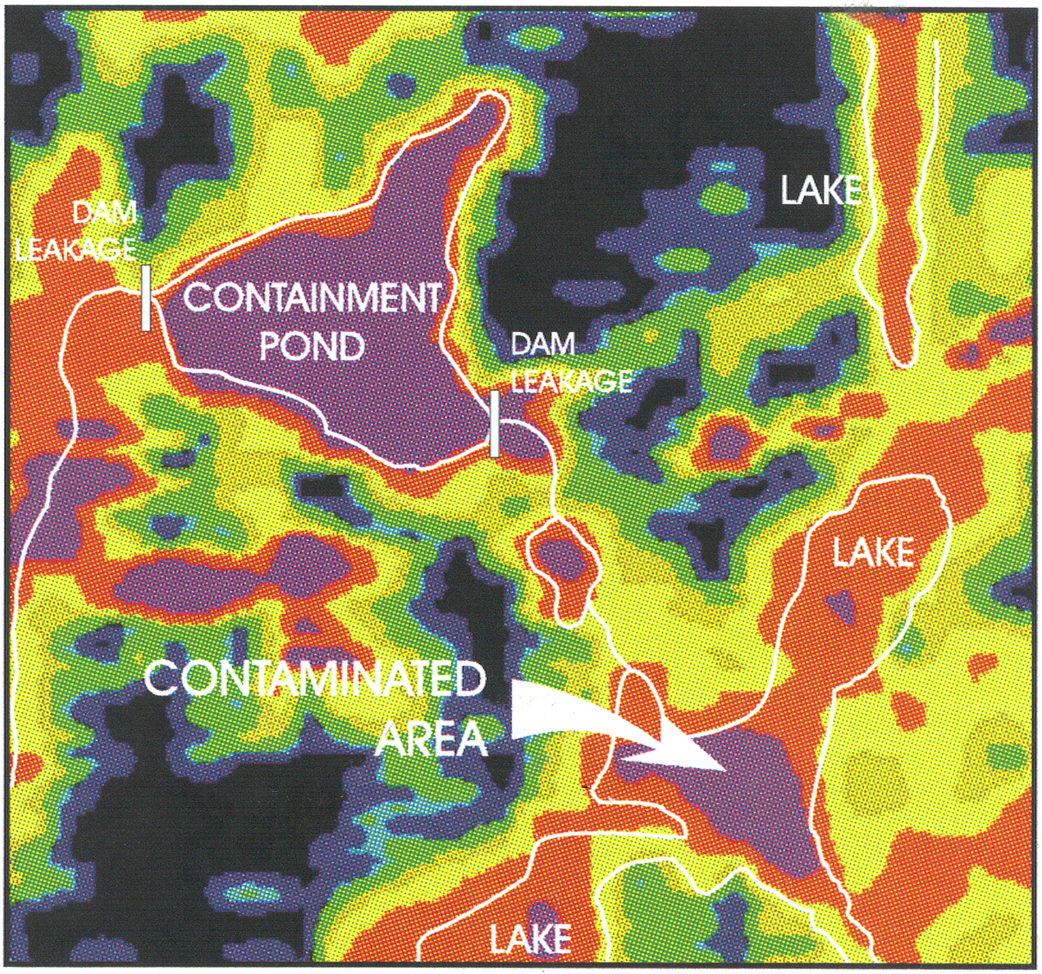
Application of Remote Sensing and Geophysics to the Detection and Monitoring of Acid Mine Drainage

A COMPENDIUM OF TECHNIQUES



A project under the Mine Environment Neutral Drainage (MEND) Program

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Executive Summary

The application of remote sensing and geophysics to the detection and monitoring of acid mind drainage is beyond the experimental stage and is being applied in the management of waste from a number of producing and abandoned mines. Experimental studies, mainly in North America and Australia, have shown that non-invasive measurements by satellite, airborne, ground and waterborne platforms can be used effectively in recognising and mapping the movement of acid effluents in and around mine workings. Some methods can only recognise changes in the first meter or so of the ground surface; others are limited to depths of one to five meters; others are capable of detecting plumes at depths of several tens of meters or more. Some methods are qualitative in nature while others can provide quantitative answers within various degrees of accuracy and reliability. Studies, mainly sponsored by government agencies, but supported in many cases by industry, are attempting to establish the effectiveness of a wide variety of methods and techniques, mainly by conducting test surveys and examining available data in the vicinity of abandoned mines. Possibly the most ambitious of these studies has just been carried out in the Sudbury area, Ontario, under the MEND program by INCO Exploration and Technical Services Limited, (King, 1994). This study establishes useful parameters for applications of specific techniques in a specific geological environment. Similar studies are urgently needed to expand the range of methods and applications and extend into other geological and topographic settings.

Important progress has been made in the establishment of guidelines for the cost-effective application of both remote sensing and geophysics for AMD problems. To begin with, the non-geophysical remote sensing techniques are most effective in establishing terrain and thematic mapping parameters required for the proper monitoring of changes in condition over time for both potential and active mine drainage environments.

Mapping of vegetation encroachment, die-off, stress and morbidity, as well as percentage and distribution of ground cover and type, are effective techniques in monitoring for the impacts of AMD seepage, and any remediation of such conditions. While we can confidently recommend LANDSAT and other satellite-borne remote sensing data for preliminary studies, recent activity in airborne multi-spectral techniques would indicate that this is a more effective process, by nature of its improved resolution, both spatial and spectral.

The direct detection and effective mapping of surface moisture from seepage, ponding, and drainage patterns, uses the traditional techniques of air photos for generation of three dimensional terrain or drainage mapping, and satellite and airborne multi-spectral data for mapping of ponds and detection of surface penetrating seepage. Detection of sub-surface moisture uses thermal infrared techniques or the indirect method of monitoring stress and vigor patterns in the vegetation and ground cover. Other indicators may be found in mapping open pit mines, diversion channel silting, dam failure and changing conditions leading to imminent dam failure all of which can be detected using combinations of air photo, multi-spectral and infrared monitoring.

While traditional remote sensing methods, with the possible exception of near-infrared measurements, are generally considered to be limited to the direct detection of very shallow seepage conditions, the use of multi-spectral techniques, both satellite and airborne, provides an ability to detect changes in the vegetation or ground cover that are indicative of sub surface AMD problems. These techniques are quite recent and represent an area that deserves, and will likely see, more active duty in the near future.

The use of spectroradiometers is a relatively new field that is growing rapidly. The collection of reference spectral signatures has become an important component for site characterization for environmental remediation. In addition, geologists are starting to use spectroradiometers for mineral exploration in arid and semi-arid environments and for characterizing mine tailings and waste rock. Image analysis software vendors are beginning to market software that enable analysts to use collected reference signatures or access existing spectral libraries that can be used as an integral part of the analysis of airborne or satellite data.

The real strengths of these methodologies are to be found, not so much in the raw data, but in the ability to analyze and integrate this data with other data sources, homing in on the actual realities contained in a series of inferential data sets. It is the image analysis and GIS (Geographic Information System) systems that make this possible. AMD is an application where this ability to integrate is crucial. As the necessary sources of information are quite diverse, not only do the multiple remote sensing data sets have to be properly analyzed and integrated, but a wide range of geophysical data must also be incorporated into, and analyzed through, this process.

Conventional airborne geophysical survey data, primarily electromagnetic, but also magnetic and gamma-ray spectrometry, can be used as baseline information to establish the natural physical parameters of the ground, and in the detection and ongoing monitoring of changes caused by acid mine effluent. Depending upon the magnitude and composition of the seepage, changes may be detected to tens or possibly hundreds of meters below ground.

Ground geophysical techniques are being used widely in the waste management industry to map contaminant plumes as well as the structure and stratigraphy of disposal sites. These techniques are commonly followed by traditional drilling and in-situ chemical and physical monitoring procedures. The geophysical surveys act as inexpensive reconnaissance techniques to recognise and establish limits for seepage problems, to direct cost-effective drilling programs and to monitor changes taking place outside the drilled areas.

Borehole geophysical logging is widely used to determine physical parameters that are affected by acid contamination and to identify zones of contamination detected by surface measurements. Borehole-to-borehole and surface-to-borehole measurements are being tested to provide three-dimensional images of zones of anomalous electrical conductivity or acoustic impedance. Borehole methods are outside the scope of the present study but are referred to briefly in the text. References are included in the General Bibliography.

All of these geophysical techniques have, as a second objective, the determination of stratigraphy, bedrock structure, waste-pile architecture etc. that can assist in the design of a testing and remedial follow-up program.

Ground geophysical methods of greatest potential in AMD studies appear to be wideband or multi-frequency EM, ground penetrating radar (GPR), Induced Polarization (IP) and, oddly, Self Potential (SP). All three methods provide direct information on contaminant plumes as well as indirect data on the structure of the ground and potential leakage pathways. The SP method is the only one that can sense the actual movement of acid contaminant.

One message that repeats itself again and again in the available literature is the importance of integrating methods in order to remove ambiguities and improve identification of acid drainage. Very frequently an anomalous condition might be caused by a change in lithology or the presence of acidic groundwater. The use of a second method can often eliminate one of these possibilities. Another important message that applies to geophysical surveys is that neither raw nor processed data, presented as profiles, contours or pseudo sections of measured parameters is nearly as effective for understanding subsurface conditions as inverted data. Data inversion, whether 2- or 3-dimensional, attempts to present a physical property distribution in the ground, which should correspond to the properties encountered in a drill program. Techniques for inverting most types of geophysical data are now available but are only very recently finding their way into the industrial marketplace. The authors believe that this is an area where important advances will be made in the next few years.

This handbook is the result of an in-depth literature search, an information survey of more than 900 organizations, synthesis of catalogues from suppliers of equipment and services, and numerous discussions between the authors and scientists working in the remote sensing and geophysical disciplines. None of these phases is, by itself, complete. For example, the information survey failed to reach a number of organizations active in the remote sensing and geophysical fields. However, our analysis of the state of the art in terms of methods and applications, again through a synthesis of information from the above sources, is believed to be fairly accurate.

With respect to specific techniques and instrumentation, it has not been possible to include full details of all of the systems available for remote sensing and geophysical surveys. Readers are encouraged to contact the customer services departments of the firms listed in Chapters 5 and 12 and to consult professional directories for other suppliers that have been omitted in this compendium.

Finally, it should be recognised that while the technologies described in this manual are, for the most part, relatively mature, their application to environmental problems in general and AMD in particular, is quite new. The authors have attempted to identify additional ways of applying remote sensing and geophysical methods to AMD problems. Readers are encouraged to conduct their own experiments, thereby adding to the existing experience and information base.

SOMMAIRE À L'INTENTION DE LA DIRECTION

L'application de la télédétection et de la géophysique à la détection et à la surveillance des eaux acides de drainage minier (EADM) a dépassé l'étape expérimentale; en effet, on utilise ces techniques pour la gestion des déchets d'un bon nombre de mines en activité et abandonnées. Des études expérimentales, réalisées surtout en Amérique du Nord et en Australie, ont permis de montrer que des mesures non invasives réalisées à partir de plates-formes satellitaires, aéroportées, terrestres et maritimes peuvent servir à reconnaître et à cartographier de façon efficace le déplacement des effluents acides dans les chantiers de mines et autour de ceux-ci. Certaines méthodes ne permettent de déterminer que les modifications se produisant dans le premier mètre environ de la surface du sol; d'autres sont efficaces pour des profondeurs allant de 1 à 5 mètres. D'autres, par contre, permettent de détecter des panaches à plusieurs dizaines de mètres ou plus sous la surface du sol. Certaines méthodes sont qualitatives, d'autres permettent d'obtenir des données quantitatives offrant divers degrés de précision et de fiabilité. Des études, parrainées essentiellement par des organismes gouvernementaux, mais appuyés dans de nombreux cas par l'industrie, visent à déterminer l'efficacité de toute une gamme de méthodes et de techniques, surtout par des essais et par l'examen de données dont on dispose pour les alentours des mines abandonnées. L'étude la plus ambitieuse à ce jour est peut-être celle qui vient d'être effectuée dans la région de Sudbury en Ontario dans le cadre du programme NEDEM (Programme de neutralisation des eaux de drainage dans l'environnement minier) par l'INCO Exploration and Technical Services Limited (King, 1994). Cette étude établit des paramètres utiles à l'application de certaines techniques dans un milieu géologique donné. Il est nécessaire que des études semblables soient effectuées le plus rapidement possible pour augmenter la gamme des méthodes utilisables et des applications possibles et permettre d'étendre celles-ci à d'autres milieux géologiques et topographiques.

De grands progrès ont été réalisés dans l'élaboration de lignes directrices pour l'application rentable tant de la télédétection que de la géophysique aux problèmes des EADM. Par exemple, les techniques autres que d'application géophysique de télédétection sont particulièrement efficaces pour déterminer les paramètres de cartographie thématique et de terrain nécessaires à une surveillance adéquate des changements des conditions qui se produisent avec le temps dans les milieux de drainage minier tant actifs que potentiels.

La cartographie de l'envahissement par la végétation, de la mortalité massive et de la morbidité des plantes ainsi que du stress qu'elles subissent, de même que la détermination du pourcentage et de la distribution de la couverture végétale par type, constituent des techniques permettant d'évaluer efficacement les effets de l'infiltration des EADM et de toute mesure de dépollution. Bien que nous recommandions avec confiance les données LANDSAT et autres données satellites de télédétection pour les études préliminaires, des recherches récentes réalisées sur les techniques multispectrales aériennes semblent indiquer qu'il s'agit-là d'un processus plus efficace, à cause de la meilleure résolution tant spatiale que spectrale qu'il permet.

La détection directe et la cartographie efficace de l'humidité superficielle liée à l'infiltration, à l'accumulation d'eau et aux configurations de drainage passe d'abord par l'utilisation des techniques traditionnelles de la photographie aérienne pour la production de cartes tridimensionnelles des zones de drainage ou du terrain, puis par l'utilisation de données satellites et multispectrales aériennes pour la cartographie des étangs et la détection des infiltrations. Pour déceler l'humidité sub-superficielle, on utilise des techniques à infrarouge thermique ou la méthode indirecte de surveillance du stress et des caractéristiques de la vigueur de la végétation et de la couverture végétale. Citons, comme autres indicateurs potentiels : la cartographie des mines à ciel ouvert, de l'alluvionnement des chenaux de dérivation, de rupture de barrages et de la variation des conditions menant à une rupture imminente de barrage. Ces indicateurs peuvent tous être décelés au moyen de photos aériennes et de surveillance par images multispectrales et infrarouges.

Alors que, d'un avis assez général, les méthodes de télédétection classiques, (à l'exception peut-être des mesures infrarouges), ne permettent que la détection directe de conditions d'infiltration très peu profonde, l'utilisation de techniques multispectrales, tant satellites qu'aériennes, permet de déceler des changements dans la végétation ou la couverture végétale qui révèlent des problèmes d'EADM sous la surface du sol. Ces techniques sont plutôt récentes, et méritent - ce qui se produira probablement - qu'on s'y attarde plus dans un proche avenir.

L'utilisation des spectroradiomètres est relativement nouvelle et se répand rapidement. La collecte de signatures spectrales de référence est devenue une composante importante de la caractérisation des sites à des fins de dépollution de l'environnement. En outre, les géologues commencent à utiliser les spectroradiomètres pour l'exploration minérale en milieux arides et semi-arides et pour la caractérisation des résidus miniers et des stériles. On voit apparaître sur le marché des logiciels permettant aux analystes d'utiliser les signatures de référence recueillies ou d'avoir accès aux banques spectrales existantes, ces données pouvant faire partie intégrante de l'analyse des données aériennes ou satellites.

Les véritables points forts de ces méthodes ne sont pas tant les données brutes que la capacité d'analyser et d'intégrer ces données à d'autres sources de données en cernant avec précision la réalité décrite par un ensemble de données inférentielles et ce, grâce à l'analyse des images et aux systèmes SIG (système d'information géographique). Cette capacité d'intégration est cruciale dans le cas des EADM. Étant donné que les sources d'information nécessaires sont très diversifiées, il faut non seulement analyser et intégrer adéquatement les diverses séries de données de télédétection, mais il faut aussi incorporer à ce processus une vaste gamme de données géophysiques et les analyser.

Les données de levés géophysiques aériens classiques, surtout électromagnétiques, mais aussi de spectrométrie magnétique et gamma, peuvent être utilisées comme information de base pour établir les paramètres physiques naturels du sol, et pour déceler et surveiller en continu des changements causés par des effluents de mine acides. Selon l'ampleur de l'infiltration et la composition des effluents, les changements peuvent être décelés à des dizaines et parfois à des centaines de mètres sous la surface du sol.

On utilise largement les techniques géophysiques terrestres dans l'industrie de la gestion des déchets pour cartographier les panaches de contaminants ainsi que la structure et la stratigraphie des sites d'enfouissement. Ces techniques sont souvent suivies des forages habituels et d'une surveillance par des méthodes physiques et chimiques *in situ*. Les levés géophysiques constituent des techniques de reconnaissance peu coûteuses permettant de déterminer et d'établir les limites des problèmes d'infiltration, de diriger des programmes de forage rentables et de surveiller les changements qui se produisent au-delà des zones forées.

Les diagraphies géophysiques sont largement utilisées pour déterminer les paramètres physiques touchés par la contamination acide et pour trouver les zones de contamination décelées au moyen des mesures en surface. On combine les mesures faites entre les sondages et de la surface à des sondages pour tenter d'obtenir des représentations tridimensionnelles des zones d'anomalies de la conductivité électrique ou d'impédance acoustique. Les méthodes de sondage ne font pas l'objet de la présente étude. On y fait brièvement référence (voir bibliographie générale).

L'objectif second de toutes ces techniques géophysiques est de déterminer la stratigraphie, la structure du substratum rocheux, l'architecture des stériles miniers, etc., qui peuvent aider à élaborer un programme de vérification et de suivi des mesures correctrices apportées.

Les méthodes géophysiques terrestres qui semblent présenter le plus grand potentiel pour les études des EADM font appel à l'électromagnétique (larges bandes ou multifréquences), au géoradar, à la polarisation induite et, étonnamment, au potentiel spontané. Les trois premières méthodes fournissent de l'information directe sur les panaches de contaminants ainsi que des données indirectes sur la structure du sol et les trajectoires potentielles d'infiltration. La méthode du potentiel spontané est la seule qui permette de détecter le déplacement des contaminants acides.

La documentation actuelle souligne sans cesse l'importance d'intégrer les méthodes afin d'éliminer toute ambiguïté et d'améliorer l'identification des zones de drainage d'effluents acides. Il arrive très fréquemment qu'une condition anormale résulte d'un changement de lithologie ou de la présence d'eaux souterraines acides. L'utilisation d'une seconde méthode peut parfois aider à éliminer l'une de ces deux possibilités. Dans le cas des levés géophysiques, on insiste sur le fait que ni les données brutes, ni les données traitées, présentées sous forme de courbes, d'isolignes ou de pseudosections des paramètres mesurés, ne permettent de comprendre aussi efficacement les conditions souterraines que les données inversées. L'inversion des données, qu'elle soit bidimensionnelle ou tridimensionnelle, permet de présenter la distribution d'une propriété physique dans le sol, laquelle devrait correspondre aux propriétés observées lors d'un forage. Il existe maintenant des techniques d'inversion de la plupart des types de données géophysiques, mais ce n'est que depuis très récemment qu'elles sont utilisées dans l'industrie. Selon les auteurs, il s'agit d'un domaine qui connaîtra des progrès importants au cours des quelques prochaines années.

Ce manuel est le fruit d'une étude approfondie de la littérature, d'un sondage de plus de 900 organismes, de synthèses de catalogues de fournisseurs de matériel et de services et de nombreuses discussions entre les auteurs et des chercheurs travaillant dans le domaine de la télédétection et de la géophysique. Aucune de ces étapes n'est complète; par exemple, pour le sondage, bon nombre d'organismes oeuvrant dans les domaines de la télédétection et de la géophysique n'ont pu être rejoints. Toutefois, nous croyons que notre analyse de l'état des connaissances en ce qui a trait aux méthodes et aux applications, est plutôt précise, grâce à la synthèse que nous avons pu faire de l'information provenant des sources précitées.

Il nous a été impossible d'inclure les données concernant tous les systèmes (techniques et instruments) que l'on peut utiliser pour effectuer des levés de télédétection et géophysiques. Les lecteurs sont priés de s'adresser aux services aux clients des entreprises dont les noms figurent aux chapitres 5 et 12 et de consulter des répertoires de professionnels pour connaître d'autres fournisseurs que ceux qui ont été mentionnés dans le présent manuel.

Finalement, nous tenons à souligner que les technologies décrites dans le présent manuel sont pour la plupart relativement éprouvées, mais que leur application aux problèmes environnementaux en général et aux EADM en particulier est récente. Les auteurs ont tenté de découvrir d'autres façons d'appliquer les méthodes de télédétection géophysique aux problèmes des EADM. Nous encourageons les lecteurs à faire leurs propres essais, ajoutant ainsi à la base d'information et d'expérience existante.

Introduction

THE PROGRAM

This handbook is the product of a study sponsored by CANMET through the Ontario Mineral Development Agreement and on behalf of the Mine Environment Neutral Drainage (MEND) program.

CONTRACT REFERENCE

SSC File Number 015SQ.23440-3-9028
Contract Number 23440-3-9028/01-SQ
Date July 20, 1993

THE HANDBOOK

The handbook describes and outlines various monitoring technologies that are used to determine the presence and progress of Acid Mine Drainage (AMD). Some of the technologies described are currently in use; others are being tested for AMD applications. In addition, possible improvements of current AMD monitoring techniques and possible new techniques, are also discussed.

THE PARTICIPANTS

Paterson, Grant & Watson Limited (PGW) are consulting geophysicists headquartered in Toronto, Canada. Having conducted projects in most countries in the world PGW have experience in planning, supervising and interpreting a wide variety of geophysical surveys, and consulting on many different methods and instruments. Clients include mining and petroleum companies, most international development agencies, a large number of overseas governments and many civil engineering and environmental organizations.

Geomatics International Inc. (Geomatics) are environmental consultants that speciallize in the application of remote sensing and GIS technologies pertaining to resource management issues. Activities include the development of GIS and remote sensing databases, data conversion, digital data acquisition, digital data analysis, technology transfer and user needs analysis. Having offices in Canada, United States, Germany and the Czech Republic, Geomatics offers a wide range of services worldwide. Clients include exploration and mining firms, federal and provincial governments, educational institutions and private environmental firms.

MAY 20, 1994

INTRODUCTION

LE PROGRAMME

Ce manuel est le fruit d'une étude parrainée par CANMET dans le cadre de l'Entente Canada-Ontario sur l'exploitation minérale et pour le Programme de neutralisation des eaux de drainage dans l'environnement minier (NEDEM).

RÉFÉRENCE, CONTRAT

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20 juillet 1993

LE MANUEL

Le manuel décrit et passe en revue diverses techniques de surveillance qui sont utilisées pour déterminer la présence et le déplacement des eaux acides de drainage minier (EADM). Certaines des techniques décrites sont utilisées à l'heure actuelle; d'autres font l'objet d'essais d'application aux EADM. On traite aussi des possibilités d'amélioration des techniques de surveillance actuelles des EADM ainsi que de nouvelles techniques potentielles.

LES PARTICIPANTS

Paterson, Grant & Watson Limited (PGW) est une société d'experts-conseils en géophysique dont le bureau central est à Toronto, Canada. PGW a réalisé des projets dans la plupart des pays du monde et a ainsi acquis de l'expérience dans les domaines de la planification, de la supervision et de l'interprétation d'une vaste gamme de levés géophysiques ainsi que de la prestation de conseils touchant de nombreux instruments et techniques différents. On compte, au nombre de ses clients, des entreprises d'exploitation minière et des pétrolières, la plupart des organismes de développement international, un grand nombre de gouvernements étrangers et de nombreux organismes oeuvrant dans les domaines du génie civil et de l'environnement.

Geomatics International Inc. (Geomatics) est un groupe de consultants en environnement qui se spécialise dans l'application de la télédétection et des techniques de SIG liées aux questions de gestion des ressources. Leurs activités comportent l'élaboration de bases de données de télédétection et de SIG, la conversion de données, l'acquisition de données numériques, l'analyse de données numériques, le transfert de technologies et l'analyse des besoins des utilisateurs. Geomatics, qui a des bureaux au Canada, aux États-Unis, en Allemagne et dans la République tchèque, offre une vaste gamme de services. On compte, au nombre de ses clients, des entreprises d'exploration et d'exploitation minière, les gouvernements fédéral et provinciaux, des universités et des entreprises privées oeuvrant dans le domaine de l'environnement.

20 MAI 1994

THE COVER The data presented here was collected with a DIGHEM multi frequency helicopter-borne geophysical system. This map of the calculated electrical conductivity shows higher values associated with mine waste as warm colours (red and yellow) in the center of the map. A breach in the containment dam is noticeable on the right side of the containment pond. The fluid mine waste has flowed into the drainage system contaminating the center of a small lake downstream, indicated by the red contours in the lower right corner of the map.

Preface

As shown in the following table of contents, Remote Sensing and Geophysics are dealt with separately in Parts 1 and 2 respectively. The reason for doing this is that the methodologies are quite different and require separate discussions and evaluations.

Methods discussed in the handbook are "remote" or "non-intrusive". Techniques requiring the drilling of boreholes, though widely used for both monitoring and mapping, are mentioned briefly but not discussed or analyzed.

The book is not a textbook on the application of remote sensing and geophysical methods to AMD problems. Nor does it attempt to explain the various technologies in detail. Interested readers are encouraged to consult the review articles listed in the General Bibliographies after Chapters 7 and 13 and, more specifically, those listed in the Selected References in Chapters 6 and 13. What is presented in this handbook is a summary of the state of the art and a compendium of information on methods currently in use, organizations active in the field, suppliers of equipment and services, and lists of available products and equipment. Presented in tabular form are guides to the applicability and effectiveness of various techniques to AMD detection and monitoring. In addition, each technique is discussed in narrative form in Chapters 5 and 12, to provide the reader with an evaluation of the technique, based on all of the information gleaned during the course of this study.

In Chapters 7 and 14 the authors summarize the strengths of the available technology and identify probable directions in the development of new technology.

For further information readers may contact any of the references cited or, for the names of appropriate contact individuals, the MEND Secretariat at the address given on the inside cover.

ACKNOWLEDGEMENTS

The authors are indebted to the MEND Program for initiating this study and to Marcia Blanchette for coordinating it successfully and providing many useful inputs. Thanks are due to the respondents to the questionnaire mailed in November 1993 for taking time to fill out yet another form. The custodians of databases accessed during the literature search were extremely cooperative and helpful. Special thanks go to Sari Burgoyne, Ron Slater, Keith Low, Kit Curtis and Marg Ahearn.

During the course of this study, conversations were held and correspondence exchanged with more than 60 individuals active in the industry. Much valuable information was derived thereby and additional literature uncovered. Their names are not listed here, but if they happen to receive a copy of this handbook they may recognise their individual contributions.

Authors

REMOTE SENSING	Roberta Stanton-Gray Emery Miller Stephen Silverthorn
GEOPHYSICS	Robert Hearst Dennis Robertson Norman Paterson

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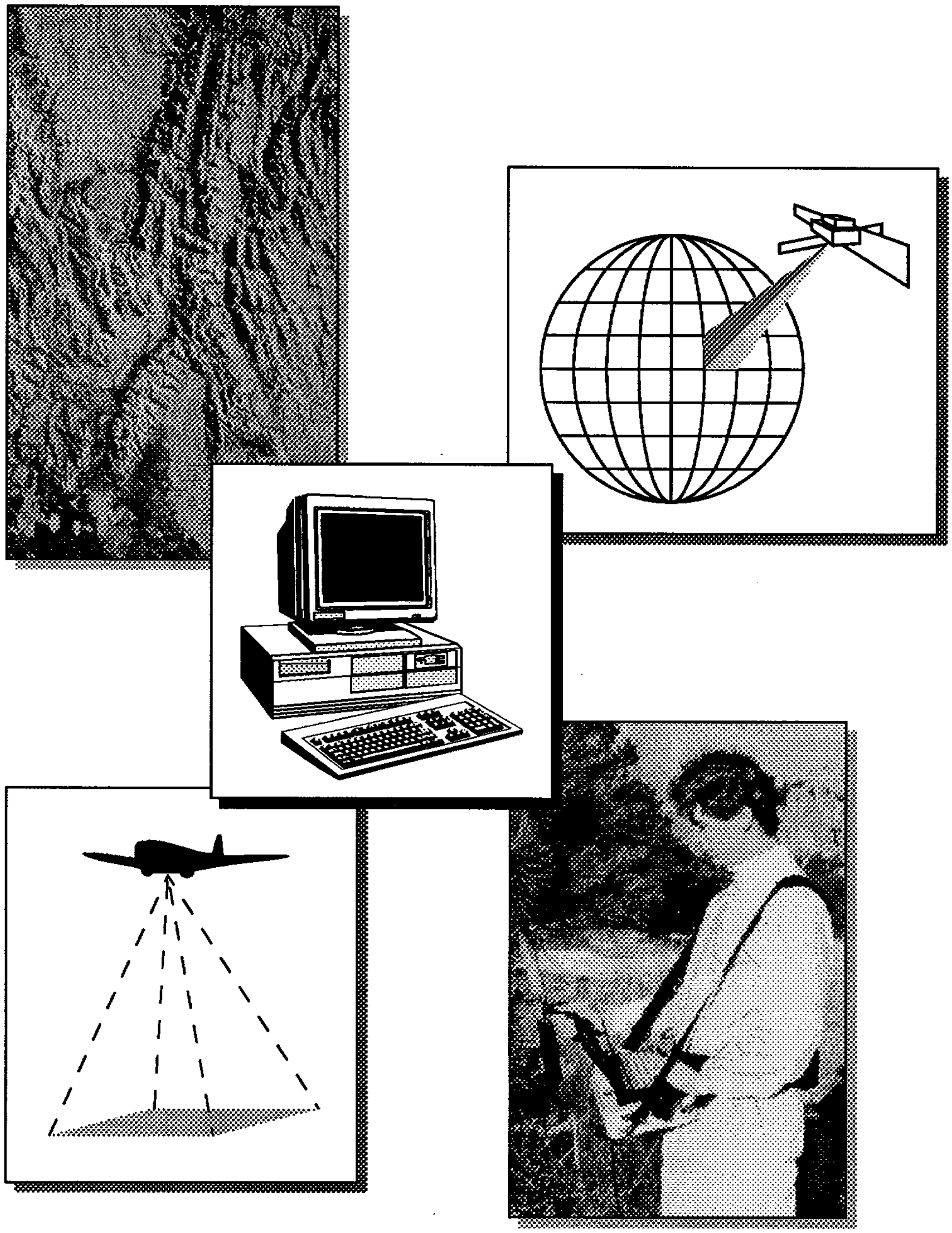
Remote Sensing



Chapter 1

1.0 STATE OF THE ART

Remote sensing relies on devices designed to acquire and enhance the collection of remote information. In its loosest definition sight and hearing are the most fundamental of remote sensors. At the other end of the spectrum are state of the art devices which run the gamut from sophisticated cameras to complex gamma ray spectrometers with a plethora of devices in between. This section focuses on devices common to "traditional" remote sensing: instruments based on film, video, radar and multi-spectral imaging. Excluded are instruments such as airborne magnetometers and gamma ray spectrometers; devices that are more properly unique to geophysical assessment and covered under the section on Geophysics in Part 2 of this document.

The compilation of, and reference to, statistical results in this chapter, and the remaining chapters of this section, were derived from a recent industry survey (Appendix A). Of nine hundred and twelve (912) questionnaires mailed out to key mining corporations, institutions, government bodies and universities worldwide, about 1/3rd of those responded. Phone follow up was made where significant responses were not returned. Of all respondents, 61% used remote sensing methodologies in their geological applications (as constrained in the first paragraph above). Statistical reference that is not derived from these figures will be so noted in the text.

Aerial photography, the backbone of remote sensing for well over 60 years, remains the predominant method for acquiring remotely sensed data. The survey indicates that photography is used in geological applications only about 7% of the time. However, note that photography was not one of the defined choices on the questionnaire. Consequently, respondents had to fill in an "other" category for photography that would, comparatively, disadvantage this group. Especially since photography remains the fundamental mapping tool or reference to which other forms of data are generally tied in all other forms of mapping. Therefore, it may be assumed that photography still represents a significant component of the mapping function of remote sensing, even in geological applications, although it certainly was not uppermost in the minds of the respondents. With the exception of one or two specifically noted uses this likely indicates that photography is used for little else but base mapping. Other major sources of data acquisition and the percent usage are as follows:

1. Satellite imagers 98%
2. Airborne imagers 35%
3. Airborne video 4%

The application of these devices, specific to acid mine drainage (AMD), was, from a survey perspective, disappointing. Only 8% of the respondents were using remote sensing techniques applied to AMD. The use of specific technologies within this grouping was as follows:

1. Satellite imagers 88%
2. Airborne imagers 63%
3. Airborne video 13%
4. Aerial photography 0%

While this sampling is (necessarily it seems) small, there are some conclusions which can be drawn from this data.

- Aerial photography was not, with two exceptions, used as a methodology in the search for AMD monitoring, although certain research results indicate that this might be a mistake. This is discussed in greater detail in Chapter 4 under Methods of Remote Sensing - Specific to AMD.

- In the satellite category, the majority of users involved in acid mine drainage have used Landsat MSS (75%), TM (75%) and SPOT (63%) data. However, many of the users are involved in a variety of other projects and the type of data used in the acid mine drainage studies was not directly specified in the questionnaire. Some of the respondents doing acid mine drainage work listed ERS-1 (Radar satellite) and NOAA's Advanced Very High Resolution Radiometer (AVHRR) data. It is unlikely this data was used for acid mine drainage work because of the nature of the data (radar) and the ground resolution of the AVHRR (1 km).

- There was no preference given to any particular airborne imager. The limiting factor in choosing an imager seems to be availability. However, there are real limitations in a production environment as most of the available instruments are "one-of" test or research devices with no guaranteed availability, longevity or serviceability. Of the imaging devices covered: Daedalus, AVIRIS, AIS, TIMS, MEIS II, CASI, GER63 and Geoscan; only the CASI and GER63 imagers and Daedalus scanners are commercially marketed products. To be fair, both the Geoscan and MEIS II are offered in a quasi-commercial context, although both are "one-of"s with no backup should something go wrong.

From an application perspective, about 30% of the respondents are using remote sensing for activities with a bearing on mine related problems, as opposed to AMD specifically. This point is noteworthy since the techniques and methodologies being used in the other applications (such as the detection of stressed vegetation) are directly applicable to AMD detection and monitoring.

In a research report prepared for the Atomic Energy Control Board (AECB) (Remote Sensing to Monitor Uranium Tailing Sites - A Review, Intera Kenting, 1992) the key processes in remote monitoring for Uranium tailing sites obtained from discussions with AECB personnel and the recommended techniques for each of those processes were as follows.

The criteria fall under three different categories:
- vegetation,
- moisture and
- soil/rock.

These are further subdivided as follows:

VEGETATION

Five, vegetation related, criteria were identified as being important components of any long-term monitoring program. These included: vegetation encroachment, die off, stress and morbidity, coverage and type. Although these phenomena are closely related, each one has unique qualities and can be addressed independently.

Encroachment
Vegetation encroachment refers to monitoring the extent of vegetation cover over time. The concern is in identifying either the presence or absence of vegetation. Each state can suggest something about the soil and water conditions of the site. Any of the multi-spectral imagers is ideal for this function.

Die Off
Vegetation die-off is concerned with the health of the plants. It is, generally, a localized phenomenon, which suggests the use of an airborne system (as opposed to satellite). Again this is a function which demands the use of multi-spectral data.

Stress and Morbidity
Stress and morbidity concerns plant vigour, similar to vegetation die off, with the difference being the level of severity. The importance of detecting stressed vegetation is that it may be indicative of leaks in tailings ponds or soil moisture and chemistry abnormalities. Stress and morbidity are more localized than die-off. This is an application which requires multi-spectral data from an aircraft.

Coverage/Type
Coverage/type refers to monitoring the extent of, and differences between, several species of vegetation. Good discrimination requires good multi-spectral data. This lends itself to satellite TM data for large relatively homogeneous areas but requires airborne multi-spectral for more localized sites and areas of more heterogeneous vegetation.

MOISTURE

There are three monitoring criteria that fall under the moisture category. These are drainage, ponding and seepage. For all of these, satellite sensors can provide information, but only at a relatively coarse scale due to the limitations of the spatial resolution.

Drainage
For both satellite and airborne sensors a single infrared band may be sufficient for identifying drainage patterns. Water absorbs reflected infrared wavelengths. Therefore, if a drainage network consists of a number of channels with standing or running water, these can be readily identified by isolating the low reflectance levels in an infrared band. Such information, however, should be obtained in stereo or accompanied by stereo capable data sets as relief is a major consideration here.

Ponding
Ponding has the same sensor requirements as drainage monitoring although stereo viewing would not be a requirement. Either reflected or thermal infrared data would provide the ability to monitor this criterion. Single band data would be sufficient and little processing of the data would be required.

Seepage
A certain amount or seepage could be permitted from a tailings pond. This, of course, would depend on the location and amount involved. What would be of concern is large amounts, or several leaks in proximity, which could indicate potential containment problems. The quality of the seepage is also important. Moisture seepage or variable amounts of moisture in surface sediments could be monitored using thermal infrared data.

SOIL AND ROCK

The soil/rock category deals with a number of criteria associated with tailings structures.

Dam Failure
The potential for dam failure may first be detected using thermal infrared data to detect seepage indicating a weakness or failure in the structure. Dam failure occurs when the structure itself is observed to have failed. If the monitoring program is successful, dam failure should not occur.

Surface Erosion
Assuming a non-vegetated surface, stereo aerial photographs would be a good sensor for monitoring surface erosion. SPOT panchromatic data would be an appropriate satellite product for slightly lower resolution monitoring.

Sub-aqueous Erosion
Sub-aqueous erosion refers to drainage within sediments and sediment ooze. This type of monitoring would require an airborne electro-optical imager in the visible and infrared portions of the spectrum.

Diversion Channel Silting/Erosion
Satellites can be used to monitoring the diversion channels for silting and erosion provided the channel is of sufficient size. The use of an airborne scanner such as CASI with filters in similar wavelength regions would enable the monitoring of smaller channels.

Waste Rock/Open Pits
Waste rock pits and open pits tend to be of a size where the use of satellite data would be sufficient. SPOT panchromatic, Landsat TM, or Soyuzkarta data could be used for monitoring these features Landsat MSS is also applicable although the spatial resolution of 60 x 80 meters is a limiting factor.

Multi-spectral work (covering both satellite and airborne) over the past fifteen years has seen the application of these techniques in chlorophyll detection related to plant health (Horler, 1983), mining waste monitoring (Boldt and Scheibner, 1987: Gagnon et al., 1977), environmental impact of mining activities (Moore et al., 1977), categorization of eroding, stable and depositional environments around small streams and drainage channels (Pickup and Nelson, 1984), exploration geology and geobotany (Hornsby and Bruce, 1986), location of drainage channels within tailings ponds and detection of effluent plumes at deposition locations (Aronoff, 1978), to mention but a few of the applications with relevance to AMD problems and supportive of the conclusions drawn in the AECB review.

In general the question seems to be less which basic technology to use but more which specific platform to select. The decision to use satellite imaging versus airborne imaging lies in the requirement for:

1. Spatial resolution
2. Spectral resolution and content
3. Frequency and timeliness of coverage and
4. Area to be covered and financial considerations.

Airborne methodologies favour spatial resolution, spectral resolution and content as well as frequency and timeliness of coverage. Satellite methodologies favour large area coverage and (assuming the ability to produce satisfactory results) cost effectiveness.

In the case of AMD the areas involved are relatively small and generally less suited to the application of satellites than to airborne techniques. Further information contained in the Research Report published by the Atomic Energy Control Board of Canada (Remote Sensing to Monitor Uranium Tailing Sites - A Review, 1992) provides an assessment of the applicability of a variety of air and space borne sensors to the *Monitoring of Mine Tailings* is provided in table form (tables 3.2 and 3.3, in AECB) wherein it is clear that airborne multi-spectral imaging is the only methodology that meets all the monitoring requirements. The second placing methodology was, ironically, photography. However, the applicability of the methodology, in these tables, was exclusive of the cost of the process and so should not necessarily be viewed as the ultimate answer. The cost effectiveness of satellite methodologies can, in many instances, be an overriding consideration.

With the exception of the applicability of photography the survey results seem to concur with these findings. A more detailed analysis of the issues at play here are found in Chapters 4 and 5 which discusses methodologies and technologies, respectively.
This document (Remote Sensing to Monitor Uranium Tailing Sites - A Review) also provides a detailed generalization of the processes and costs involved in the application of satellite, airborne imagery and radar to the monitoring of tailings and is recommended reading.

As a general comment, there is a strong body of evidence indicating that current state-of-the-art methodologies and technologies can go a long way to significantly improving the process of monitoring Acid Mine Drainage. It also seems evident that no one process or piece of technology provides a panacea for the solution of all problems or even that one device or process provides a complete solution for any given situation. A combination of instruments, processes and methodologies, on the other hand, would appear to be able to provide complete, thorough and cost effective solutions to AMD monitoring. That the body of evidence to support this is meagre and sporadic at best should in no way be construed as a testament to the effectiveness of current methodologies but more a testament to the inertia of the industry in general. The technology available to the industry is relatively new and holds significant potential - it needs to be exploited. Hopefully the information provided in Chapters 4 and 5 will shed some light and some interest in these processes and help to remove the inertia that is currently holding back a significant and real set of productive tools.

Chapter 2

2.0 WHO USES REMOTE SENSING

A mailing list, of approximately 1,000 corporations and organizations in, or related to, the mining sector and geophysics, was compiled. This list included organizations from Europe to Asia, Australia, and North and South America. Two hundred and fifty-nine (259) responded to the geophysics portion of the questionnaire and one hundred and fifty-seven (157) responded to the remote sensing portion. The distribution of the remote sensing responses were as follows:

Mining Corporations 37%
Other geophysical related corporations.......26%
Government..23%
Universities 14%

Based on statistics from other remote sensing sectors, these figures seem to be disproportionately weighted towards the private sector. Generally there is a higher portion of usage within the government. Even recognizing that the industrial (private sector) use of remote sensing is generally higher within the geophysical disciplines we still believe that the government figures are low. Responses from government departments where there are many users may explain this apparent anomaly. However, not having any reasonable basis on which to modify these figures we will accept this distribution with the noted caveat.

In terms of application, the results show that the following percentages of the users are using remote sensing in the following general categories:

Geological Mapping...................................77%
Mining Exploration....................................76%
Land Use/Cover 40%
Change Detection.......................................38%
Geobotany 36%
Planning 31%
Mine Site Mapping.....................................31%
Environment/Site Reclamation 21%
Acid Mine Drainage.................................... 9%
Drainage.. 4%

With respect to AMD about 30% of the users are applying techniques that have applicability to AMD monitoring.

Chapter 3

3.0 APPLICATIONS OF REMOTE SENSING

The questionnaire asked what applications of remote sensing the respondents were using. The results, by category, accompanied by the percentage of users that are applying the technology in that category, are listed below.

Geological Mapping	77%
Mining Exploration	76%
Land Use/Cover	40%
Change Detection	38%
Geobotany	36%
Planning	31%
Mine Site Mapping	31%
Environment/Site Reclamation	21%
Acid Mine Drainage	9%
Drainage	4%

In the "other" category we find respondents using remote sensing for monitoring snow cover, developing digital elevation models, crop monitoring, coastal surveys, landscape pattern analysis, forest productivity, land disturbance, monitoring of coal mine fires, water quality and a variety of environmentally related activities such as pollution monitoring and environmental impact assessment. All of these activities were unique to one or two of the respondents, at best, and not in sufficient quantity to warrant a category of their own.

The technologies involved are all image based technologies. They produce pictures or images used to assess conditions and situations. Where they part company is in their ability to display very different images of the same subject based on their different sensor characteristics. Some are sensitive to microwave transmissions which are best suited to imaging the topography and distinguishing between broad classes of ground cover. Others are sensitive to thermal radiation (thermal infrared) well suited to the detection of the presence (or absence) of water which by extrapolation can be used to detect leaks in dams or moist ground indicative of seepage (both above and below ground) from containment vessels. Still others are highly sensitive to visible and near infrared radiations which can be effective in discriminating differing species of ground cover as well as the general stress or vigour in that vegetation. Finally, at the far end of the spectrum there are sensors that are sensitive to ultraviolet radiations effective in the detection of certain hydrocarbon based substances. Obviously each sensor has greater or less applicability in different applications dependent on what characteristics are of importance in that application.

Noting that the bulk of the respondents were using remote sensing for geological mapping and mining exploration comes as no surprise as this is, after all, based on respondents from the field of geology. These are mature processes well documented over the years. These applications generally rely on satellite imagery and the ability to extract lithologic, structural and geobotanical information difficult or impossible to detect using other methodologies. Samplings of such applications may be found in "Evaluation of Landsat Thematic Mapper Imagery for Geologic Applications (Lees, Lettis, Bernstein - IEEE June 1986)"; "Discovery of new mineralized area in Lomblen Island of Indonesia indicated by the remotely sensed image data (Kouda, Suwijanto, Suhariono, Miyazaki, Muraoka, Ninomiya - 1988)"; and "Application of remote sensing techniques in structural, geologic and geobotanical interpretation in parts of Gadchiroli district, Maharashtra (Tomar - ACRS Nov. 1988).

Land use and land cover applications ranked next below exploration and geological mapping. If the papers covering this application are any indication, it would seem that its roots (from a geological perspective) are founded in evaluation and assessment of potentially reclaimable mine areas as covered in papers such as "A Land Cover Classification of a Portion of the Western Kentucky Coal Field Utilizing Multi-Temporal Thematic Mapper Simulator Data (Spahn - ACSM-ASP Sept. 1983)"; "The Use of Remote Sensing for Describing and Evaluating the Regeneration Potential of an Abandoned Mining Waste Site, Western Quebec, Canada (Gagnon, Bruce, Crowder - Symposium on Surface Mining, Dec. 1985)"; and "Updating Thematic Maps of Mining Districts. An Operational Demonstration of Remote Sensing in the South West of England (Legg - Remote Sensing Society, Sept. 1989).

Change detection, next on the list, is a sub application within the other categories as it potentially applies to most all the other applications, representing a multi-temporal look at those data. Any application such as environmental monitoring, detection of increased pollutants, new seepage from storage tanks, vegetation encroachment, increased stress or improved vigour, all rely on change detection. The literature referenced under the other applications will undoubtedly provide an insight into change detection techniques and applicability.

Geobotany appeared next, used by 36% of the respondents. This is a surprisingly high percentage of the users considering the relative immaturity of this process and the mixed results that seem to have been obtained to date. On the other hand it has been shown that anomalous mineralization can lead to unique responses in plant's morphological factors, in the vegetation's community structure and in the manner in which the plants reflect or absorb electromagnetic radiation (The Response of Vegetation to Geochemical Conditions - Mouat - ERIM, 1982; and Remote Sensing of Vegetation: a promising exploration tool - Hodcroft, Moore - Mining Magazine - Oct. 1988). The ability of remote sensing techniques to directly distinguish between differing types of mineralization through vegetation has, on the whole, been unsuccessful as a global application (although some success has been obtained in site dependent and site specific studies). On the other hand, remote sensing has been successful at detecting stress as an indicator of potential mineralization (Linear discriminant and profile analysis. An aid in remote sensing for geobotanical investigation - Saraf, Cracknell - Dec. 1988; and Reflectance spectra of vegetation growing on mine sites in the Canadian shield - Singhroy, Kenny - IGARSS, July 1989).

Planning and Mine Site Mapping followed Geobotany, both used by 31% of the respondents. These processes are relatively self explanatory although the ability to detect mine sites from satellite data has had mixed results (The use of Landsat Imagery in the detection of mine sites and mine wastes in the Sudbury, Ontario Region - Robitaille, Dempsey, Gallie - Geologic Remote Sensing Conference, April/May 1991).

Environment and Site Reclamation followed at 21% with Acid Mine Drainage (9%) and Drainage (4%) bringing up the rear. This group shares sufficient similarities in technological requirements and methodologies that they can be readily grouped from an applications perspective. Our focus, of course, is on the acid mine drainage problem. In spite of the weak response in the questionnaire to this category there are a reasonable number of papers on the use of remote sensing in this and similar applications (impact assessment studies, detection, mapping and monitoring of tailings and their impact on the environment, etc.). An excellent overview of the issues at stake and the application of remote sensing in AMD is found in a research report prepared for the Atomic Energy Control Board (Remote Sensing to Monitor Uranium Tailing Sites - A Review, Intera Kenting, 1992). Assessments of specific technologies as in colour and colour infrared photography (A colour and colour infrared study of acid mine drainage in Rich Run of Jackson County, Ohio - Johnson, 1972), satellite imagery (Landsat thematic mapper for evaluation of the environmental effects of acid mine drainage - St. Arnaud, Oct 1992; The use of Landsat Imagery in the detection of mine sites and mine wastes in the Sudbury, Ontario Region - Robitaille, Dempsey, Gallie - Geologic Remote Sensing Conference, April/May 1991) and airborne multi-spectral imagers (Delineation of mine tailings in Southeastern Kansas - Fenstermaker, ACSM-ASPRS 1990) can be found in various papers, although there appears to be a lack of application of combined and complementary technologies in the search for monitoring solutions to AMD problems.

One of the key issues in generating viable solutions, using remote sensing techniques and data, lies in the ability to integrate and manipulate these data sets with external data sources, be they point, line, area or textual data. As will be clear under the discussions of methods (chapter 4) and techniques (chapter 5) there are a number of different sources of data that are each pertinent to distinct and separate aspects of AMD monitoring which, if they are to have maximum value must be properly integrated.

Remember the three basic areas and sub topics to be monitored as outlined in the AECB study. The sensor and methodological requirements will differ for each of the areas and sub-areas as reiterated below.

VEGETATION,
• vegetation encroachment,
• die off,
• stress and morbidity,
• coverage and type

MOISTURE
• drainage,
• ponding and
• seepage

SOIL/ROCK
• dam failure
• surface erosion
• sub-aqueous erosion
• diversion channel silting/erosion
• waste rock/open pits

The key to the integration of this information lies in the proper application of Geographic Information Systems (GIS) designed specifically to integrate spatial data as well as to incorporate textual information within this database. Any multi-disciplinary solution will demand such a capability and AMD monitoring should be considered in this vein. By way of example the paper "Spatial modelling of abandoned mine tailings for environmental assessment - the Kam Kotia test site (Mussakowski, Chan, Goba - Geographic Information Seminar, 1993)" is interesting reading that sheds light on the application of GIS (the building of the database) in the context of developing environmental solutions to mine wastes.

Chapter 4

4.0 METHODS OF REMOTE SENSING

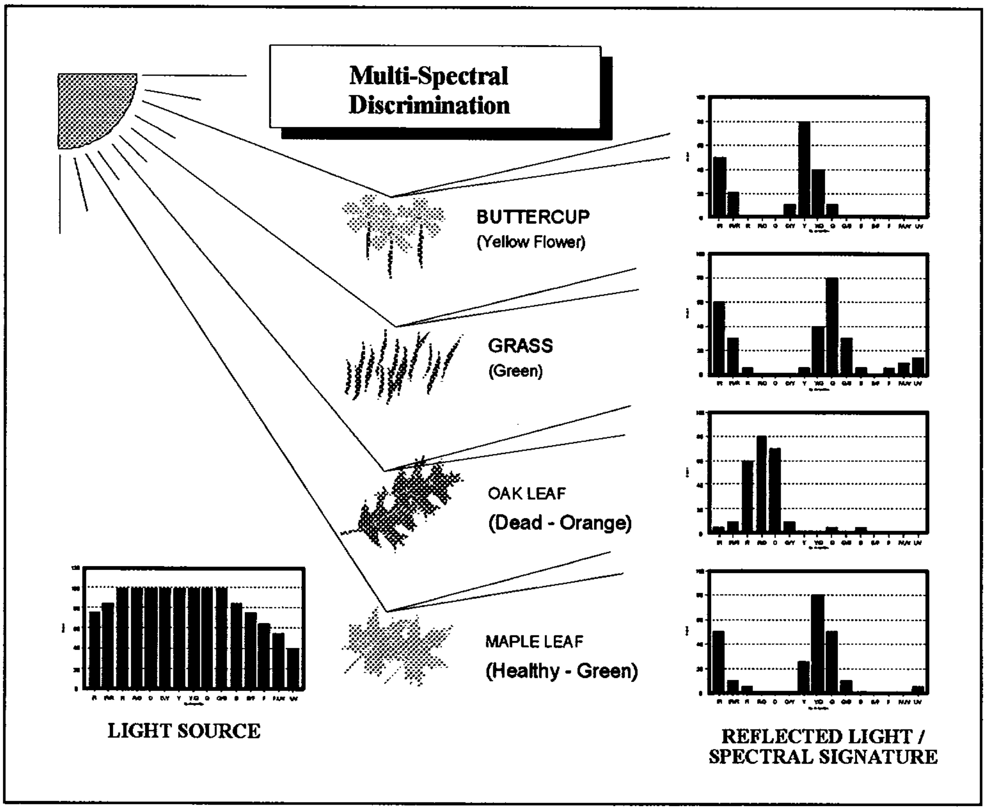
An excellent description of the underlying principles of remote sensing is found in the following excerpt from the AECB study "Remote Sensing to Monitor Uranium Tailing Sites - A Review".

The analysis and interpretation of remotely sensed data requires an understanding of the nature of interaction between electromagnetic energy, the atmosphere, and Earth surface materials and features. The amount of solar energy, incident on, and emitted or reflected from, the ground surface is attenuated by scattering and absorption processes which occur throughout the atmospheric volume.

Electromagnetic radiation is either absorbed, transmitted or reflected depending upon the specific wavelengths involved and the physical properties of the material or surface receiving the radiation. For example, water generally appears blue to the observer because its reflectance peak occurs within the visible blue portion of the spectrum. On the other hand, water appears black in thermal infrared imagery because energy at these wavelengths is absorbed. Furthermore, water in glacier fed lakes appears greenish due to the effects of the fine suspended sediment which enhances reflection of green wavelengths.

The premise of these methodologies is based on the fact that all objects reflect light at specific wavelengths and in specific proportions that are unique to their makeup. These reflectance characteristics provide "spectral signatures" that can be used to identify those objects, as illustrated in Diagram 4.1.

DIAGRAM 4.1



These techniques are used in many applications such as the monitoring of changes in vegetation health and vigour. Again, taking an excerpt from the AECB report ...

It has been found, for example, that for many species, there is a high correlation between reflected radiation and leaf chlorophyll content (Horler et al. 1983). As chlorophyll content increases, the reflected light in the .70 µm range shifts to progressively longer wavelengths. The position of the edge of this curve then becomes a good measure of the chlorophyll content. The shifting of this reflectance curve towards shorter wavelengths has been termed the blue-shift or red-edge shift. The presence of vegetation can be determined from chlorophyll absorption bands which exist at .45 µm and .65 µm. The condition of vegetation can be assessed using data between 1.0 µm and 2.5 µm which denote the presence or absence of hydrous and carbonate minerals. In addition, the region from 1.5 µm to 2.5 µm responds to leaf water content which allows for study of soil and plant moisture conditions. Changes in the chemical properties of soils can be manifested by changes in the vegetation cover characteristics. Furthermore, morphological and physiological changes are often due to anomalous concentrations of specific metals. Reflectance data acquired between 0.5 µm and 1.1 µm may be used to determine the presence or absence of iron-oxide or hydroxide minerals in soils.

Another aspect to consider, in terms of the interpretation of remotely sensed data, is the changing appearance of features due to the controlling influence of factors such as water content, sun angle, time of year, and condition. For example, an unvegetated sand area occurring beside a stream will appear much different, in terms of its characteristic reflectance, than a sand bar just a few meters away. Despite the homogeneity of the sand material, the controlling factor in this case is the amount of moisture in the sand. As a result, the interpreter must have some background knowledge of these factors rather than relying on comparison to characteristic reflectance curves. In order to properly analyze and interpret remote sensing data, it is critical to first have an adequate understanding and appreciation of surface and atmospheric processes and energy interactions.

Regardless of the sensor or its platform these basic principles guide the field of remote sensing as we know it today.

4.1 GENERAL METHODS AND PLANNING

Fundamental to any successful project will be good planning. Good planning requires that the project be well specified. In the case of remote sensing this means that you must know:

a) What you are looking for or expect to find.

b) What the direct and indirect implications of those issues are on the surrounding environment.

c) What type of sensor will detect the direct and indirect indicators of each of the items or issues being looked for.

d) What resolution is required in the source data to detect these indicators.

e) What positional accuracy is required of the data sets and whether that level of accuracy is available from the data source.

f) What outside influences will affect the acquisition of data. Whether or not the acquired data differs under different temperature or weather conditions, etc. If so, what are these differences and can they be properly accommodated?

g) What frequency of data acquisition is required. Is it important to acquire data within a specified window of opportunity?

h) What volume of data will be acquired and what the processing and data storage implications of this data acquisition are.

i) What specific processing will be performed on the acquired data and whether those functions are available to the user. If not, where can that capability be acquired?

j) What additional data sets need to be incorporated into the analysis of the acquired data and how this data will be integrated into that analysis.

k) What format or formats the end results will be prepared in and where and how this output be prepared.

The preceding presumes a working knowledge of the different sensors and data acquisition techniques available as well as the techniques and equipment required to analyze, integrate, process and prepare the final output and reports. These issues are discussed in detail in Chapter 5.

4.2 SPECIFIC TO ACID MINE DRAINAGE

This section examines AMD and how the preceding issues and the current methods of data acquisition apply. Firstly, consider the basic areas of remote sensing where meaningful data can be acquired with respect to AMD and then what corresponding data sources will best suit each of those areas. Next each of these components will be discussed in light of the general guidelines set out above.

VEGETATION

Vegetation encroachment

Since this is fundamentally a change detection issue digital data sources would be advantageous from a convenience, timeliness and processing perspective.

This is a direct indicator since we are looking at the vegetation itself to determine encroachment and are not concerned with indirect or inferential phenomena. Since it will be necessary to distinguish the vegetation from the surrounding area the use of multi-spectral data with information in the visible and near infrared regions will be required. This provides the user with two basic data sources - satellite and airborne. If the area under consideration and the level of encroachment are large enough, then satellite data (Landsat, SPOT) are the obvious choices, otherwise airborne multi-spectral techniques should be applied (CASI, GER, Daedalus, Geoscan, MEIS and airborne video). However, it must be considered that short term changes, regardless of the size of area under consideration, are not likely to be great enough to be detected by satellite, therefore satellite data should only be considered in long term monitoring (around 1 year in temperate climates). Some caution needs to be exercised in the acquisition of data in this case since it is possible that in very wet weather and during seasonal changes the imagery will not classify (discriminate) as accurately as might be expected or anticipated.

In this application it will be essential to select an airborne system that has both the ability to correct the data for attitude motions of the aircraft as well as to be able to position (geocode) the data accurately on the ground. This is not a concern with satellites as their platforms are stable but the same is not true of airborne data. This will be true for any multi-temporal application of airborne multi-spectral data.

Processing and data storage requirements for this function are not likely to be overwhelming and should be adequately handled by most image processing and GIS systems on the market. Output products are likely to consist of simple maps and area reports, also well within the basic capabilities of most imaging and GIS systems. A not of caution is appropriate here in that the initial structure of the database in the GIS system will be important and the setup must consider the final output as well as the interim analysis that will be performed on the data. This is a general caveat and applies throughout.

Die off

This is another direct indicator and much the same requirements are demanded here as are true for encroachment except that die-off tends to be a more localized phenomenon suggesting the use of airborne techniques as opposed to satellites. Information in the visible and near infrared are sufficient for this application.

Stress and morbidity

Stress and morbidity, again direct, are similar to die-off except the level of severity is less than that of die-off causing this issue to be less apparent than die-off and even more localized. This is strictly an airborne multi-spectral solution. Information in the visible and near infrared are sufficient for this application.

Coverage and type

Functionally this is similar to the three preceding operations except that the processing requirements are somewhat more demanding of the image analysis system and the system operator. Data sources are again limited to airborne multi-spectral techniques (although satellites could work on large areas with relatively homogeneous growth).

MOISTURE

Drainage

Another indicator that can be detected directly this application really requires multiple data sets as there are two basic requirements that need to be satisfied. One, the topography of the land, its elevation model and slope data, are important in assessing the drainage of the area and two, the detection of water and wet or damp soil is essential to this function.

In the first case, stereo aerial photography is still the best solution. In the second case information in a single infrared band should be sufficient. This could be either airborne multi-spectral or satellite. Airborne thermal infrared would be even better.

This function will demand that the GIS and imaging systems have 3-dimensional capability with the ability to "drape" imagery over digital terrain models. A nice feature to look for in this context would be a "fly-through" and perspective functions on the imaging and/or GIS systems.

Ponding

Although similar to drainage the requirements for this function are not demanding and imagery from reflected visible light or thermal infrared should be sufficient. In this instance there are no processing demands as single band imagery can be used and the feature should show up without any enhancement. Additionally, there is no need for stereo data and elevation modelling in this case.

Seepage

Seepage presents a considerably more difficult problem and represents a feature that must be detected indirectly. Seepage will affect the moisture content in the surrounding soils creating comparative differences in the areas of seepage. This increased water content in the soil is best detected using thermal infrared. In many cases the reflected near infrared will be inadequate in detecting these differences.

Detection of the quality of seepage is an even more difficult problem. Petroleum based contaminants may be detected using ultraviolet based sensors and there is some hope that geobotanical techniques (reflected visible and near infrared multi-spectral imaging) may be applied to detect the effects of trace minerals or contaminants. However, experience indicates that this is very much a site specific issue and we do not want to imply that there is a global or generic solution to this issue. The image analysis functions required to quantify and qualify these components are of a relatively high order and require a knowledgeable operator.

SOIL/ROCK

Dam failure

While dam failure occurs when the structure is observed to have been breached. A good monitoring program will detect indicators of the onset of failure before the event occurs. Potential for dam failure may be detected using thermal infrared data to detect seepage indicating a weakness or failure in the structure and all of the comments applying to seepage would apply here. An actual failure, on the other hand, could likely be observed from any of the satellite sensors mentioned.

For monitoring actual movement of material targets might be placed on dam slopes. This process requires the accuracy, resolution and stereo capabilities of aerial photography.

No unusual processing or systems requirements are demanded of this application except those intrinsic to the monitoring processes mentioned.

Surface erosion

Aerial photography, or for larger sites SPOT satellite (Panchromatic) data, would suffice for this function.

No special processing or systems requirements are encountered here.

Sub-aqueous erosion

This type of monitoring, as it refers to drainage within sediments and sediment ooze, would require an airborne multi-spectral imaging in the visible and near infrared. The AECB report also suggests that airborne SAR (radar) data might also be effective since some surface penetration is possible depending on the water content in the sediments.

Aerial photography, and thermal infrared data would not be appropriate for monitoring this criteria.

Data processing requirements should include 3-dimensional capabilities.

Diversion channel silting/erosion

This lends itself to detection in the shorter wavelengths of Landsat TM satellite data and can be handled by satellite if the channel is large enough. For smaller channels an airborne multi-spectral system in the visible and near infrared should be used.

Processing requirements are nominal image analysis and GIS functions.

Waste rock/open pits

These features are usually of sufficient size as to be detectable by any of the satellite sources (Landsat TM, SPOT and Soyuzkarta).

The processing functions are straight forward mapping functions.

Finally the monitoring plan will likely have two components:
1) Long Term and
2) Short Term

Long term programs would monitor for gross changes, would be based on an annual cycle and could probably be largely accomplished using satellite data sources.

Short term programs would be concerned with minor changes, require the resolution of airborne techniques and would likely follow a monthly cycle.

These comments are very general in nature and the user will have to decide, based on the individual and specific requirements of each program, the extent to which the preceding applies and where it needs to be modified to accommodate the particular idiosyncrasies of the task at hand.

Chapter 5

5.0 INSTRUMENTATION AND TECHNIQUES

5.1 INTRODUCTION

The survey indicated that 98% of the respondents were using satellite based remote sensing in their geological applications - well ahead of the airborne imagers (35%) and video (4%), although these percentages changed somewhat when considered in light of AMD with Satellite = 88%; Airborne imagers = 63%; and airborne video = 13%. One apparent omission is aerial photography, with 0% response in the survey, but which has been shown as an effective and necessary tool for certain forms of data collection in the AMD process.

The following material looks at the capabilities, limitations and differences between the various sensors and presents some background on the data handling and processing requirements fundamental to the application of remotely sensed data.

5.2 INSTRUMENTATION GROUPING

Many of the instruments are similar in structure and function yet each operates to a select set of criteria and serves a unique set of functions and concomitant applications.

From a methodological perspective it is important to understand the basic differences between the classes of instruments and what separates them from an applications perspective. To do this it is first necessary to understand the basic types of sensors available, the rudiments of how they function and why they are grouped as they are, allowing that the following grouping of instruments is arbitrary to this discussion.

The methods for data acquisition fall into two main categories:
1) Spaceborne platforms and
2) Airborne platforms.

Within each of these groupings data is acquired one of two ways, either:
1) Digitally or
2) Photographically.

The instruments themselves fall into two basic categories:
1) Active and
2) Passive.

5.2.1 SPACEBORNE SENSORS

From orbits hundreds of miles above the Earth's surface these sensors provide a view and perspective not available through other sources or methodologies. Satellites are particularly adept at providing the "big picture". On a more commercial note, satellites are generally subsidized by the owner's governments bringing a concomitant economy to the acquisition of data from these sources.

Spaceborne data becomes less attractive when high resolution is required, when specific timing of data acquisition is important (satellites operate in fixed orbits) and where arbitrary and selective frequency (electromagnetic frequency) of data is necessary.

5.2.2 AIRBORNE SENSORS

Airborne sensors are the antithesis of satellites. They are more expensive per square kilometre of data and their view is limited by the height that the aircraft can fly. However, aircraft provide a logistic freedom that allows the acquisition of data at frequencies and at times of the user's choosing (except in poor weather conditions), at electromagnetic frequencies of the user's choice and at resolutions unequalled by satellites.

It is extremely important that the user should be aware that the airborne platform is not a stable platform and that the raw imagery is distorted by aircraft motion. Some systems provide the ability to correct for these distortions and others do not. If motion correction is not available the user should be aware that the precision of the data will be suspect and it may be almost impossible to properly tie the imagery to the ground. This will not be a major issue in some applications, however, in others it can be absolutely critical.

For those systems or services offering motion correction there are three basic types of correction:

1) Roll Correction
2) Full Attitude Correction (pitch, roll and yaw)
3) Geocoded data.

Roll correction removes roll distortion, which is the most severe component of aircraft motion and may be sufficient for some applications. It should be noted however that it is not possible to provide geocoded data from roll only corrected imagery (geocoded data is data where every pixel is referenced to a real latitude and longitude on the ground).

Full attitude correction removes all components of aircraft motion providing an image that can be geocoded and can serve well for multi-temporal applications, although geocoding is not intrinsic to attitude correction. In areas with very good base mapping and visible reference this may be sufficient for most applications. In areas where the base mapping is poor and there is little visible ground reference geocoded data becomes imperative.

Geocoded data, if available, is always best. When it is not available it is important to consider the points noted above before deciding to proceed. The accuracy of any multi-temporal analysis is limited to the accuracy with which you can reference one data set to the other. Geocoding assures that this is not an issue.

5.2.3 AIRBORNE VIDEOGRAPHY AND DIGITAL FRAME CAMERAS

Airborne videography is an established technique used primarily in large scale, site-specific applications and are less expensive than airborne scanners. They provide the same logistic freedom as airborne scanners and also allow for the acquisition of data at frequencies chosen by the user. The most significant limitation of videography in relation to other sensors its low spatial resolution which is restricted by television scanning standards. In addition, video images must be converted to digital format through the use of an image analysis system and then all spectral bands must be registered to one another and to a ground reference system.

In the past five years, digital frame cameras (DFCs), consisting of solid-state arrays with more than 1024 x 1024 photosites, have become broadly available in the imaging sensor marketplace (King 1993). DFCs are the next generation imagers where digital images are obtained directly from solid-state video cameras. Recent advances in this technology includes the incorporation of GPS positioning (Everitt and Escobar, 1993), laser profiling (Jacobs et al. 1993), and radiometers (Neale, 1992) to airborne video imaging. DFCs produce digital frame images that are not restricted by television standards.

The main advantage of DFCs over line scanners is that the DFC produces a stable two dimensional, digital frame exposure which results in a simpler geometric correction. This method of data acquisition resolves aircraft motion problems inherent in the multi-spectral imagers. DFC images are easily corrected and incorporated into a GIS for further analysis.

5.2.4 SPECTRO-RADIOMETERS

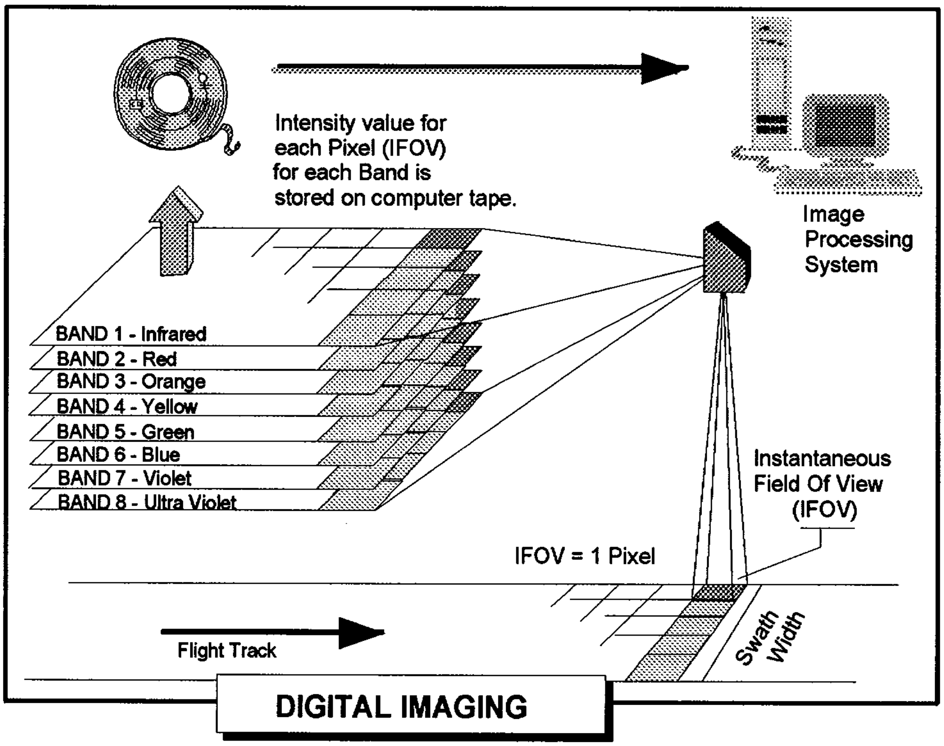
Most airborne remote sensing surveys require some form of reference data. One form of reference data is the collection of ground-based measurements of the reflectance and/or emittance of surface materials to determine their spectral response patterns. Spectroradiometers measure, as a function of wavelength, the energy coming from an object within its view. It is used primarily to prepare spectral reflectance curves or signatures for various objects. These representative spectral signatures are used by the image analyst in conjunction with airborne multispectral and/or satellite data collected over the same area. It aids the image analyst in defining a methodology that can be applied to the airborne or satellite data for discriminating features related to the presence of acid mine drainage.

The use of spectroradiometers is a relatively new field that is growing rapidly. The collection of reference spectral signatures has become an important component for site characterization for environmental remediation. In addition, geologists are starting to use spectroradiometers for mineral exploration in arid and semi-arid environments and for characterizing mine tailings and waste rock. Image analysis software vendors are beginning to market software that enable analysts to use collected reference signatures or access existing spectral libraries that can be used as an integral part of the analysis of airborne or satellite data.

5.2.5 DIGITAL DATA

Digital data is image data that is acquired in a digital format. In simple terms, a picture encoded as a string of numbers which can be decoded on a computer to produce a photographic like representation. There are significant advantages to digital data. It can be manipulated by computer to enhance and analyze the information intrinsic in the imagery. It can be stretched, shrunk or warped to fit different projections or produce 3-dimensional simulations. It can be integrated and combined with other digital data sets. It can be added to or subtracted from other data sets, particularly advantageous in multi-temporal analysis. And, it can be readily transported and modified by a variety of users making the data more broadly applicable and introducing concomitant economies. Diagram 5.1 illustrates the basic concept.

DIAGRAM 5.1



Data volume, for large areas at high resolution, and absolute resolution are the main drawbacks to digital imaging.

5.2.6 PHOTOGRAPHIC DATA

Photographic data has three fundamental advantages. It provides higher spatial resolution than digital formats, it can be acquired in stereo and used for the generation of elevation data and it is relatively inexpensive (compared to its digital counterparts).

Its drawbacks are that it does not contain good spectral resolution and it lacks the flexibility and advantages of the digital medium as noted above.

All the instruments discussed, except for aerial photography and the Soyuzkarta satellite, provide digital data and even Soyuzkarta data can be obtained in digital form. It should be noted, however, that this data is derived from digitizing the film and consequently does not offer the analytical capability of true multi-spectral imagers such as Landsat and SPOT.

5.2.7 ACTIVE INSTRUMENTS

Active sensors are those that emit a signal and detect changes to the returned signal or the effect of the signal on the target. Radar is the most common of this class of instrument. Generally speaking active systems are expensive to run and maintain. Other than radar, most active systems are highly specialized having been developed for specific applications.

5.2.8 PASSIVE INSTRUMENTS

Passive sensors represent the bulk of devices in common usage today and are based on sensing naturally emitted or reflected electromagnetic radiation. This group encompasses photography and all of the airborne and satellite systems referred to in this section of the document, with the exception of radar and reference to a laser flourosensor.

All the sensors in this group, both satellite and airborne, and except for the photographic processes (aerial photography and Soyuzkarta), are digital instruments based on similar concepts. They all acquire data in one or more selected portions of the electromagnetic spectrum, through a filtering process, and record the information digitally as previously illustrated in Diagram 5.1. Each "band" of data represents the spatial output of one filter. Each spatial band of data is composed of a grid of "pixels" representing the measured reflectance or emission of electromagnetic energy, at that band's frequency, for each "pixel" sized point over the object.

Sensors of this type come in two varieties: scanners and pushbroom imagers as illustrated in Diagrams 5.2 and 5.3 respectively. Essentially, the scanner collects data one pixel at a time whereas the pushbroom imager collects data one line (or row of pixels) at a time. There is no intrinsic advantage to one methodology over the other. Any advantage lies in the implementation.

The filters define what the imager "sees" and what is excluded. It is the number, range and positioning of these filters that provides the fundamental distinction between one device and another. Speed of data acquisition, angle of view and detector resolution are additional issues that may be important considerations in some circumstances.

Besides the sensors and platforms, the methodology, if it is to have any chance of success, must include at least two additional components:

1) an image analysis system; and
2) a GIS system.

DIAGRAM 5.2

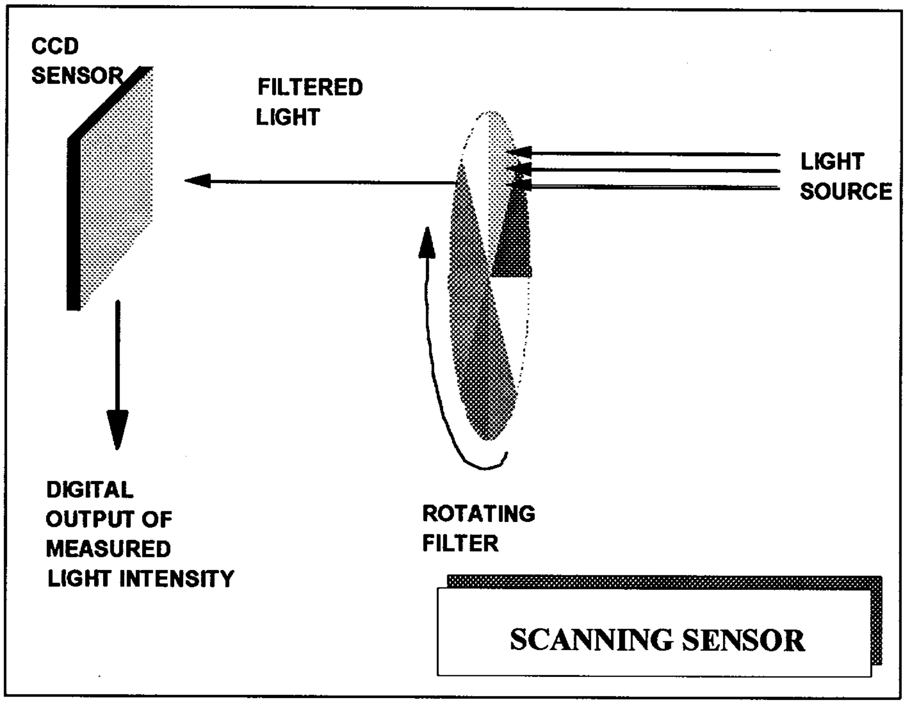
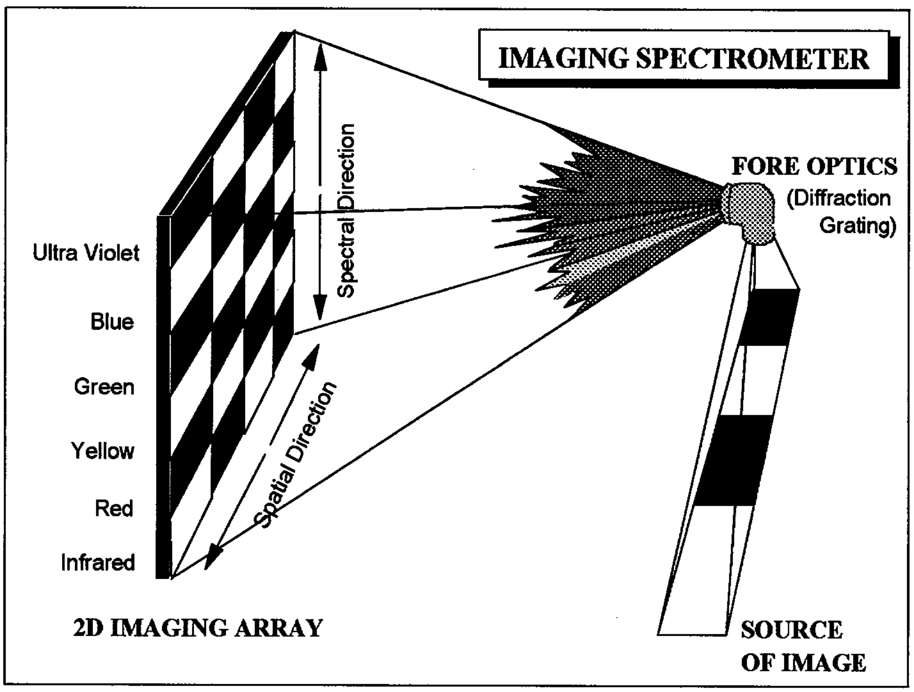


DIAGRAM 5.3



These are systems designed to process and analyze the digital data provided by the sensors (image analysis system) and to store and integrate the produced imagery with other images and data from other sources (GIS System).

5.2.9 IMAGE ANALYSIS SYSTEM

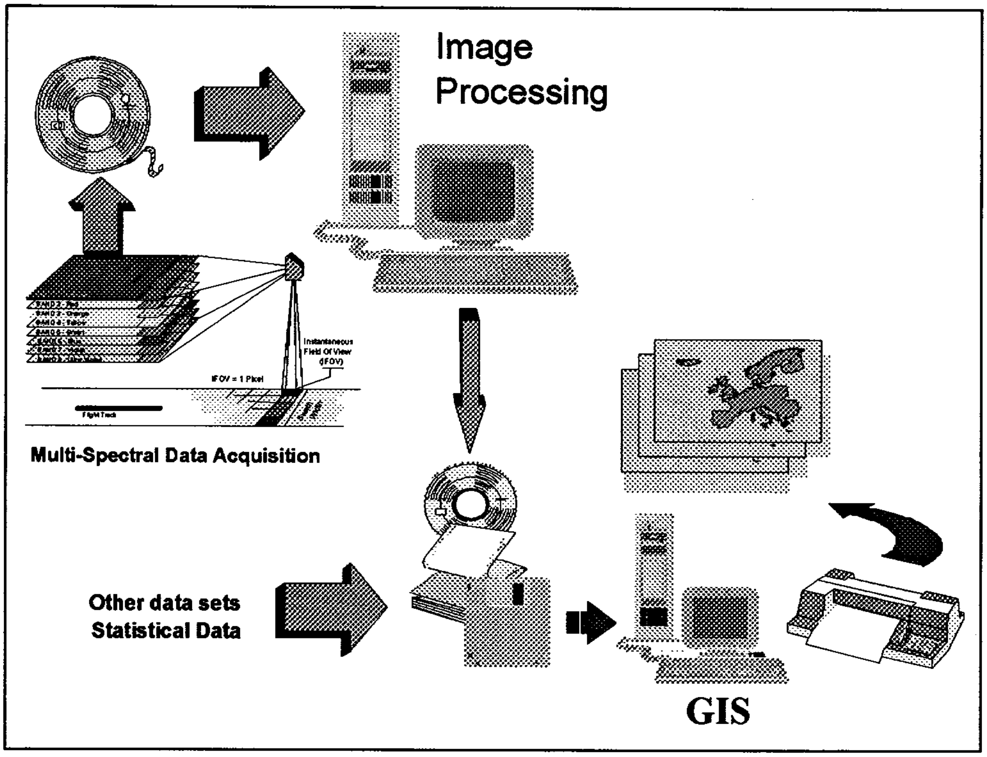
A system for the processing and analysis of the digital imagery provided by the platforms alluded to above. Information from these sensors, in its raw, unprocessed, form contains virtually no information of value. The image analysis system extracts the value from the information provided through enhancement or comparison of the data with other data collected at the same time. Consider it the developer for digital imagery.

5.2.10 GIS (GEOGRAPHIC INFORMATION SYSTEM)

A database oriented system is designed to accept, manipulate, organize and combine images and data from different sensors, different sources and different times. This is the operational tool of the remote sensor. It is the database, the archives, the cartographer and the printer all rolled into one.

The general flow and concept of these processes is illustrated in diagram 5.4 below.

DIAGRAM 5.4



5.3 SPECIFIC

5.3.1 SATELLITE TECHNOLOGY

Since 1972, satellite remote sensing has been recognized as a valuable tool for monitoring the Earth's natural resources. Satellites provide a relatively inexpensive, repetitive data set that can be used independently or augment ground based monitoring programs. Satellite data can provide an instantaneous view of surface phenomena over large areas that are often inaccessible to ground crew. In addition satellite data represents an accessible archive of historical information.

Current operational satellite platforms exhibit a wide range of spectral and spatial resolutions that are summarized in Table 5.1.

TABLE 5.1 Summary of satellite based sensor characteristics (Lillesand and Kiefer 1987, Massom 1991, and Intera Kenting 1992).

Satellite/Sensor	Data Type and Swath Width	Spatial Resolution	Spectral Resolution
Landsat			
Multi-Spectral Scanner (MSS)	Multispectral 185 km	80 metres	Band 4 .5 - .6 µm Band 5 .6 - .7 µm Band 6 .7 - .8 µm Band 7 .8 - 1.1 µm
Thematic Mapper (TM)	Multispectral 185 km	30 metres	Band 1 .45 - .53 µm Band 2 .52 - .57 µm Band 3 .63 - .69 µm Band 4 .76 - .90 µm Band 5 1.55 - 1.75 µm Band 7 2.08 - 2.35 µm
		120 metres	Band 6 10.80 - 12.50 µm
SPOT			
High Resolution Visible (HRV) (Multispectral & Panchromatic Modes)	Multispectral 60 km at nadir (Stereo Pairs)	20 metres	Band 1 .50 - .59 µm Band 2 .61 - .68 µm Band 3 .79 - .89 µm
	Panchromatic 60 km at nadir (Stereo Pairs)	10 metres	Band 1 .51 - .73 µm
Indian Remote Sensing Satellite (IRS-1A)			
Linear Imaging Self-Scanning (LISS)	Multispectral 148 km	72.5 metres	Band 1 .45 - .52 µm Band 2 .52 - .59 µm Band 3 .62 - .68 µm Band 4 .77 - .86 µm
Marine Observation Satellite (MOS-1)			
Multispectral Electronic Self-Scanning Radiometer (MESSR)	Multispectral 100 km	50 metres	Band 1 .5 - .6 µm Band 2 .6 - .7 µm Band 3 .7 - .8 µm Band 4 .8 - 1.1 µm
RESOURCE F-1 (Soyuzkarta)			
KFA-1000	Spectrozonal (Photographic Output Only)	5 metres	Band 1 .57 - .68 µm Band 2 .68 - .81 µm
KATE-200	Panchromatic (Photographic Output Only)	20 metres	Band 1 .48 - .60 µm Band 2 .60 - .70 µm Band 3 .70 - .85 µm

Satellite/Sensor	Data Type and Swath Width	Spatial Resolution	Spectral Resolution
RESOURCE F-2 (Soyuzkarta)			
MK-4	Spectrozonal and Panchromatic (Photographic Output Only)	8 metres	Band 1 .635- .69 µm Band 2 .81 - .90 µm Band 3 .515- .565 µm Band 4 .46 - .505 µm Band 5 .58 - .80 µm Band 6 .40 - .70 µm Band 7 .57 - .68 µm Band 8 .68 - .81 µm
European Remote Sensing Satellite (ERS-1)			
Along-Track Scanning Radiometer: Infrared (IR) Radiometer	Near and Thermal Infrared 500 km	1 km	Band 1 1.6 µm Band 2 3.7 µm Band 3 11.0 µm Band 4 12.0 µm
Along-Track Scanning Radiometer: Microwave Sounder (M)	Radar Look angle 23° 80 km	30 metres	C-Band 5.7 cm
Japanese Earth Resources Satellite-1 (JERS-1)			
Visible and Near Infrared Radiometer (VNIR)	Multispectral 150 km (Stereo pairs)	18.3 x 24.2 metres	Band 1 .52 - .60 µm Band 2 .63 - .69 µm Band 3 .76 - .86 µm (nadir looking) Band 4 .76 - .86 µm (forward looking) Band 5 1.6 - 1.71 µm Band 6 2.1 - 2.12 µm Band 7 2.13 - 2.25 µm Band 8 2.27 - 2.4 µm
Synthetic Aperture Radar (SAR)	Look angle 35° 75 km	18 x 30 metres	L-Band 23.5 cm
Radarsat*			
Synthetic Aperture Radar (SAR)	Look angles 20° to 49°	25 metres	C-Band 5.7 cm
Operational Mode	100 km		
High Resolution Mode	Look angles 37° to 48° 45 km	9 metres	C-Band 5.7 cm

* Canadian developed satellite scheduled for launch in 1995.

5.3.2 AIRBORNE IMAGERS

Airborne imagers have been around since the early 1950's but have not, even today, become mainstream devices. A major part of the problem lies in being able to properly position collected information in perspective to the real earth, in other words geocoding the information. Because of aircraft motion (pitch, roll and yaw) imagery collected on airborne platforms has induced distortions proportional to the motion of the aircraft. The removal of, or compensation for these distortions is no simple task and only since about 1989 has there been a practical solution to this problem, and then only for certain sensors. In a fundamental research environment this may not be a serious drawback but in an industrial, production type environment the lack of highly accurate and reproducible positioning of the information can be critical to the success of the operation. It is essential that the user carefully assess the repeatable accuracy of the data required and the ability to generate this level of accuracy from the data source.

There are three basic forms of attitude correction.

Gimbal Mounting: where the sensor is mounted in a gimbaled rack removing the sensor head from the direct motion of the aircraft. This process is relatively successful at removing the more severe attitude distortions of the aircraft and reducing the remaining distortions to a lower order problem. It does, nonetheless, leave some distortions, which are not able to be modeled and can be removed only by tying the image to reference maps. This can be an adequate solution in well and accurately mapped areas with good visual references. It is less satisfactory for highly homogeneous regions where visual reference is poor and for areas with poor or nonexistent maps.

Roll Correction: where the rolling motion of the aircraft is measured and the output data adjusted accordingly. There are two approaches to this correction, dependent on the type of sensor being used. In scanning sensors the roll data is recorded on tape along with the data being collected and the correction is mathematically applied to the data in post flight processing. In pushbroom type imagers the roll information can be applied to the data in real time, recording the acquired data with an offset which is applied on playback of the imagery. Roll correction removes the most severe of the three aircraft motions and is an adequate solution in many cases. However, it does not provide data that will stand up to rigorous mapping standards nor does it provide sufficient accuracy for applications where change detection must be determined within 3 pixel. The need to meet such requirements should be assessed on a case by case basis.

Full Attitude Correction: is the third method, where all motion components of the aircraft (pitch, roll, yaw) are measured and applied to the data in post flight processing. This is the only method that is capable of providing map standard accuracy and is the preferred methodology for applications requiring precision data. As of the writing of this article, this process was only available for pushbroom type imagers and only the CASI and MEIS imagers were configured to collect the requisite information to apply this technique.

The preceding processes *do not* provide or correct for position, only attitude. In order to attain positional or georeferenced data some form of appropriate navigation data, such as GPS, must also be collected and tagged to the acquired imagery. Alternately the processed imagery must be referenced and tied to existing maps. It is important that the user be aware of these considerations when considering the use of airborne multi-spectral data. These are not issues in the use of satellite imagery or aerial photography because the data is generally already corrected for these criteria before being presented to the user.

There are three categories into which multi-spectral airborne imagers fall, with respect to commercial use and availability. There are those manufactured for sale: others which are "one-of" devices being offered as a service by a single operator: and research instruments built and operated, generally, by some government department or agency. Of the three categories those being offered for sale are the most secure from a long term operation perspective as they are available (as a service) from more than one source and can be properly serviced and maintained by the original designers. The second category is less secure since the device is available from only one source and timing conflicts with other users can be a problem. In addition, there is no back-up or alternative source should the equipment break. The final category offers almost no security since the device is not, generally, offered commercially and these instruments should be viewed as research tools for specific, single flight, issues only.

5.3.2.1 MANUFACTURERS

Daedalus - Various

Daedalus Enterprises Inc. of Ann Arbor Michigan is the world's major supplier of airborne multi-spectral imaging devices. They manufacture a number of different scanners that can acquire data in anywhere from 1 to 128 bands ranging from ultraviolet through the thermal infrared (.32 µm to 13 µm). Effective ground resolution down to about 1 meter/pixel are obtainable (device and platform dependent). The Daedalus scanners cover a broader spectral range than any of the other offerings.

Itres Research - CASI (Compact Airborne Spectrographic Imager)

ITRES Research in Calgary, Alberta manufactures the CASI airborne imager. It is a pushbroom type device using a two dimensional array which is capable of detecting up to 288 bands of data in the visible and near infrared range between .4 µm and .9 µm. The location and spectral resolution of bands are user programmable. The CASI is capable of an effective ground resolution of down to about 1.5 m/pixel. The CASI also offers a full attitude correction system.

GER 63

Geophysical and Environmental Research Corp. (GER) out of Millbrook New York manufactures an airborne imaging spectrometer. This spectrometer has three detectors that can collect spectral information ranging from .35 to 2.5 µm in 63 programmable bands. Another detector can collect up to 6 bands of thermal infrared information ranging from 8.0 to 12.5 µm. Ground resolution ranges from 2 to 20 m.

5.3.2.2 SERVICE OFFERED COMMERCIALLY

MEIS (Multispectral Electro-Optical Imaging Scanner)

The MEIS imager is an 8 band pushbroom type imager built for CCRS (the Canada Centre for Remote Sensing) in 1978 and operational since 1982. Its particular strengths are in its sensitivity, it rapid data acquisition rates, its resolution, its ability to collect stereo data (unique) and the availability of a full attitude correction system. The spectral range of the MEIS is in the visible and near infrared spanning .35 µm to 1.1 µm. The effective ground resolution of the MEIS (at about 40 cm/pixel) is about twice that of any of the other imagers. The MEIS is a "one-of" product currently residing at CCRS.

Geoscan

The Geoscan is produced by Geoscan Pty. Ltd., a division of Aston Mining in Perth, West Australia. Geoscan is a multispectral imaging spectrometer that records 24 wavelength bands during a single flight. The wavelength designation of these bands are: ten bands between 0.522 and 0.955 µm (visible and near infrared); eight bands between 2.044 and 2.352 µm (short wave infrared); and six bands between 8.64 and 11.28 µm (thermal infrared). These data have an 8-bit dynamic range (0 to 255). The Geoscan imaging spectrometer collects reflectance-mode data differently from all other airborne imaging spectrometers. Detector gains and offsets are adjusted to measure relative radiance, which approximates reflectance. In other words, solar illumination and atmospheric filtering are done in real time with no post-acquisition processing.

Geoscan's new MK II airborne scanner will be able to collect up to 47 bands ranging from the visible through the near, short-wave, middle and thermal infrared.

5.3.2.3 RESEARCH PRODUCTS

TIMS - (Thermal Infrared Multi-spectral Scanner)
All matter above 0° Kelvin radiates energy at thermal infrared wavelengths 3.0 μm to 14.0 μm. NASA's Thermal Infrared Multi-spectral Scanner is a multi-spectral scanner that operates exclusively in the thermal infrared portion of the spectrum. Thermal infrared technology is sensitive to thermal, or radiating, heat energy and is used to detect targets which are significantly warmer or cooler than their surroundings. It utilizes six narrow bands located between 8.2 μm and 12.2 μm. The spatial resolution of these systems is approximately 1 meter, with a thermal resolution of 0.2°C.

Imaging Spectrometry
Imaging spectrometry refers to the acquisition of images in many, very narrow, contiguous spectral bands throughout the visible, near infrared and mid infrared portions of the spectrum. Several imaging spectrometers have been developed by NASA. These spectrometers use linear array detectors to collect data in 128 or more spectral bands and produces data with sufficient spectral resolution for the direct identification of materials. Two airborne imaging spectrometers have been developed by NASA, the Airborne Imaging Spectrometer (AIS) and the Airborne Visible-Infrared Imaging Spectrometer (AVIRIS). These spectrometers are used mostly for research purposes.

AIS - Airborne Imaging Spectrometer
The Airborne Imaging Spectrometer collects 128 channels of data which are approximately 9.3 nm (<0.01 μm) wide, in contiguous bands between 1.2 μm and 2.4 μm. The system is operated at an altitude of 4200 meters above the terrain which results in a narrow swath 32 pixels wide beneath the flight path with a pixel ground resolution of approximately 8 x 8 meters.

The AIS was designed primarily as an engineering test bed for detector development.

AVIRIS - Airborne Visible-Infrared Imaging Spectrometer
The AVIRIS collects data in 224 bands 10 nm wide, in the spectral region 0.4 μm to 2.4 μm. It is flown on NASA's U-2 aircraft at an altitude of 20 km. The swath width is approximately 11 km with a ground resolution of about 20 meters.

5.3.3 AIRBORNE VIDEOGRAPHY AND DIGITAL FRAME CAMERAS

Digital frame cameras have been developed over the last five years and represent the next generation of low cost remote sensors (King 1993). Digital frame camera technology for airborne remote sensing is a relatively recent endeavour however, there are several research institutions and consulting firms in the United States working with this technology. In Canada, a DFC system is under development at the Carlton University, Ottawa under the supervision of Dr. King, Department of Geography.

Specifications for the Carlton DFC and one commercial DFC in the United States is presented below.

Airborne Multispectral Digital Frame Camera Sensor (AMDFCS)
The AMDFCS is currently under development at Carleton University in Ottawa. The selection of system components is based largely on the requirements for a multi-purpose airborne remote sensor whose uses include multispectral imaging, photogrammetry/mapping and close-range applications. It consists of a Kodac Megaplus 1.4 DFC camera; a rotating filter wheel housing up to eight, user selected narrowband interference filters with bandwidths ranging from 10 to 40 nm; a reinforced PC computer with a 1280 x 1024 frame grabber; a high capacity buffer and a hard drive. Ground pixel size (spatial resolution) can range from 14 cm to 5 metres. The area covered by each

frame ranges from 180 x 150 metres to 6600 x 5175 metres respectively for a range of altitudes of 300 metres to 11,000 metres. Scenes can be viewed as they are acquired. The AMDFCS is mounted in a standard aerial photographic mount. Spectral resolution of the AMDFCS ranges from .4 µm to 1.1 µm with peak sensitivity between .7 µm and .8 µm. The method of data acquisition resolves the aircraft motion problems inherent in the multi-spectral imagers. In monochrome mode, AMDFC images with 60 percent overlap (stereo) have successfully been used to create digital elevation models.

Ag-Recon

Ag-Recon is another frame (512 x 640 pixels, 240 x 320 pixels for thermal data) based system currently in commercial use in California. It is capable of collecting 5 simultaneous bands of information. The bands emulate the Landsat TM bands 1 (Blue), 2 (Green), 3 (Red), 4 (Near Infrared) and 6 (Thermal Infrared). Bands 4 and 6 are user definable. Band 4 can be set to the ultraviolet (.3 µm - .4 µm), near infrared (.8 µm - 1.0 µm) or any band between .3 µm and 1.1 µm. Band 6 can be set for 8.0-12.0 µm or 3.0-5.0 µm. The system is configured with an aerial camera which can acquire stereo data at the same time as the video data. The camera data are then scanned to create a digital reference file corresponding to the spectral data. While the field of view (at 20) is very narrow and there is less band flexibility in the visible region, this is nonetheless a flexible, low cost solution to problems that can be resolved using Landsat TM data but requiring greater spatial resolution. The method of data acquisition resolves the aircraft motion problems inherent in the multi-spectral imagers.

5.3.4 AERIAL PHOTOGRAPHY

Three types of aerial photography can be acquired: Black and White (Panchromatic); Colour; and Colour Infrared. Photography is capable of producing maps at scales up to 1:500 and larger if required and so is the resolution champ in the field of remote sensing. For extremely fine mapping it is still the best solution.

Black and White is the most common for standard surveys and is generally taken in stereo pairs so that the overlapping images can be used in the generation of terrain elevation models. At the moment this is the only effective way to generate terrain relief information. While it is true that the MEIS offers stereo data the process for generating elevation data is still in the development stages. It is also true that SPOT satellite can provide overlapping and offset images that can be used in the generation of elevation data, however, it should be noted that the derived elevation information is only the equivalent of elevation modelling at 1:100,000 and smaller scales.

Colour photography enhances the spatial image and aids in photo interpretation. It does not, however, provide the spectral resolution of the multi-spectral imagers and cannot be applied in multi-spectral analysis or provide solutions to these types of problems. Colour photography can be very effective in producing orthophotos (stereo data corrected and reproduced as a nadir view at all points in the image).

Colour Infrared is used primarily in those applications where infrared information is valuable. It offers the same functionality as the near infrared capabilities of the multi-spectral imagers except on film.

5.3.5 RADAR

Airborne Radar STAR-1

The STAR-1 is owned and operated by Intera Information Technologies of Calgary, Alberta. In general radar has the ability to collect information through cloud cover and so represents the optimal mapping solution in regions where cloud cover is a serious problem. The equipment and aircraft required for radar surveys are expensive to build and maintain and so radar surveys tend to be cost effective only on larger surveys or in areas of reasonable inaccessibility. Radar does provide elevation data and the Star-1 process outputs geocoded data. Maps can be produced at scales as large as 1:50,000 with a relative accuracy of approximately 15-25 meters in the horizontal and 15-35 meters in the vertical.

Radar can be effective in extracting geological structures, even (or particularly) in areas of thick vegetation.

5.3.6 SPECTRO-RADIOMETERS

Spectron SE-590
Spectron Engineering produces a portable spectroradiometer, the Spectron SE-590. It has interchangeable heads that are used to collect spectral signatures ranging from 350 to 2500 nm. For example, one head measures from 350 to 1100 nm with a 3 nm spectral resolution; another collects data from 400 to 800 nm with a spectral resolution of 1.5 nm; and an infrared head measures energy from 1100 to 2500 nm with a spectral resolution of 20 nm.

FieldSpec Spectrometers
Analytical Spectral Devices, Inc. of Boulder Colorado manufacture and market several high resolution, rapid reading, portable spectrometers. Depending on the instrument a continuous spectra can be obtained ranging from 350 nm to 2,500 nm. Depending on the instrument, sampling intervals range from 0.7 nm to 2 nm and spectral the spectral resolution or bandwidth can range from 3 nm to 10 nm.

PIMA
The PIMA is an Australian made spectroradiometer. Its spectral range is from 1300 to 2500 nm with a spectral resolution of 10 nm and sampling interval of 2 to 4 nm.

GER
Geophysical and Environmental Research Corp. (GER) of Millbrook New York manufacture and market several high resolution, rapid reading, portable spectrometers. Depending on the instrument, continuous spectra can be obtained ranging from 200 to 3000 nm and from 2000 to 20,000 nm (near infrared and thermal infrared). Bandwidths for the various instruments will range from 1.5 nm to 2 nm in the visible and near infrared range and from 25 to 72 nm for thermal infrared spectroradiometers.

5.4 DATA ACQUISITION TECHNIQUES

The processes and techniques involved in the acquisition and application of remotely sensed data could be divided any number of arbitrary ways. Techniques can be subdivided according to function within the application (encroachment, die-off, seepage, etc.), or they could be divided by sensor and sensor type or thirdly, they could be divided by sensor category. We have chosen to discuss these processes by general functionality where the application of techniques will relate to the extraction of pertinent information.

These functional categories are defined as:

I. Basic Mapping
II. Discrimination/Classification
III. Stress Detection
IV. Moisture Detection/Geological Mapping
V. Change Detection

5.4.1 BASIC MAPPING

Good base mapping is fundamental to just about all applications and is no exception in the case of AMD. Photography is still the most predominant form of base mapping and we have seen that the resolution of photography is the only realistic method of measuring materials movement in AMD applications (Intera Kenting 1992). In addition drainage assessment requires elevation modelling which, in turn, requires stereo data and photography is, currently, the only practical method of attaining such information.

Airborne digital frame cameras can also be used for local base mapping. Although the AMDFC at Carlton University is still in the development stages it has successfully been used to create digital elevation models and has acquired single band imagery that simulates air photographs but in digital format. This system could either augment or be used in place of aerial photography in the future however, camera development has not yet reached a stage where it can be considered commercially viable.

It is possible, for larger areas, to use SPOT panchromatic or Soyuzkarta data for base mapping, but stereo data provides an additional level of complexity and it is questionable whether the process involved is worth the relatively minor cost savings.

Radar is currently available from aircraft platforms and will, with the launch of Radarsat in 1995, be available from a spaceborne platform. Radar has the main advantage of being able to penetrate cloud cover, and to some extent vegetation, so it provides a unique method of attaining basic topographic information for inaccessible and cloud covered regions. Resolution of radar data (6 meter pixels) could be a bit coarse for some applications. To date radar has not been used to any great extent in AMD applications.

Since photographic products are not intrinsically digital they need to be digitized to get the information into a GIS or image analysis system to integrate the results with other data sets. There is no magic in this area and these are operations which should be contracted out to one of the aerial survey firms in the users region. The survey firm should be able to provide a digital output ready for the user's GIS system. The survey firm will need to know what GIS system the user has and what format the data should be provided in. Alternately, it may be possible that the base map data is already available as a result of local area surveys run be the regional or municipal government. The user should check these sources first.

5.4.2 DISCRIMINATION/ CLASSIFICATION

The greater part of the work done on AMD, with respect to remote sensing, involves satellite imagery - specifically Landsat MSS and TM as well as SPOT panchromatic and multi-spectral. It is the multi-spectral capabilities of these satellites that allow classification and discrimination within the imagery and which represents one of the basic premises behind the satellite programs. The concept is based on the fact that all objects contain a "spectral signature" (Diagram 4.1) which can be used to separate one species of vegetation from another as well as being able to distinguish between vegetation and other forms of ground cover.

This process (Landsat TM) has been used to discriminate and map clay pits, dumps and reclaimed land at a scale of 1:25,000 (Updating thematic maps of mining districts. An operational demonstration of Remote sensing in the South-West of England - Legg, NRSC - 1989) and it has also shown that this process could be used to update maps on an annual basis (change detection). It has been used to generate land cover classifications over portions of the Western Kentucky coal fields (Spahn 1983) and it has been used in Northern Ontario to locate abandoned mine sites and concomitant AMD problems (Robitaille et al. 1992). Tailing ponds, slag heaps and roastyards were successfully identified.

For more refined work airborne multi-spectral techniques can be applied in the same way as satellite multi-spectral imagery. In fact some airborne sensors and methodologies allow the user to select the spectral bands and band widths to be used in the survey. This can be particularly useful when trying to extract very minute signature differences in species discrimination. There is considerable crossover between Discrimination and Stress and Moisture detection as they are fundamentally the same processes but focused differently and using different spectral bands.

Species discrimination and ground cover classification tend to be best suited to information in the visible and near infrared regions since a key component of vegetation lies in its chlorophyll production process which shows up best as a combination of information in the visible green and near infrared regions. Stress utilizes the chlorophyll information in combination with infrared further down the spectrum but well above the thermal infrared region. Soil moisture, being reflected in its effect on soil temperature is best detected using thermal infrared data.

While it is possible to use photography for discrimination the process is based on spatial information, as opposed to spectral, and there are no model "signatures" in spatial information that can be machine aided, consequently this process requires specially skilled photo interpreters to perform the discrimination. Even with these skills there is generally not sufficient information in the spatial data for the same level of discrimination as with multi-spectral data.

Monochrome images from airborne digital frame cameras like air photos requires specially skilled image interpreters to perform class discrimination. With future camera developments in obtaining multispectral images in a single frame, discrimination based on spectral signatures will be feasible.

Radar data has also been shown to be effective in basic geologic mapping (Intera promotional brochures) and distinguishing broad cover types such as vegetation, bare soil, ponded water and waste rock (Gregory Geoscience, 1975). Although it is not a popular methodology for AMD applications it has been suggested that radar, due to its penetration capabilities, might be effective in monitoring for sub-aqueous erosion (Intera Kenting 1992). For larger areas and remote cloud covered regions radar might also prove to be a useful tool.

5.4.3 STRESS DETECTION

Stress detection and geobotany are similar in nature and might be considered as equivalent techniques. Considerable work has been done in this area and it is clear that stress in vegetation can be reasonably identified. In a study by Saraf and Cracknell (1989) it was demonstrated that TM bands 6 and 7 could be used to detect stress in vegetation over geochemically anomaloús areas. There has been little success in the isolation of specific contaminant or mineralization and so the indirect indicator of stress in the vegetation tends to be the preferred approach to this problem. Mouat (1982) presented at the International Symposium on Remote Sensing on Remote Sensing of Environment in Fort Worth, on the effects of geochemical conditions on plants was suggested to fall into three categories:

1) Structural - including morphological changes to the plant or vegetation (e.g. vegetation density), mutations of leaves, flowers or fruits and phenological changes (changes with the timing or seasonality of physiological events);

2) Taxonomic - including effects on vegetation composition. This may include community structure as well as presence or absence of particular species; and

3) Spectral - which includes the manner in which vegetation interacts with electromagnetic radiation (which may or may not be related to the first two issues).

This does raise the issue that there is more to assessing stress than just looking for a particular "signature" as it is clear that the surrounding environment must also be taken into consideration. The vegetation may be looked at individually but should also be considered in the context of a community as this may be as, or even more, meaningful than the individual plant data.

This is not to suggest that there are not certain general indicators of stress that are reasonably universal. Many of the changes show up in the .53 µm to .8 µm portion of the visible and near infrared spectral range (Diagram 5.5) and include such items as:

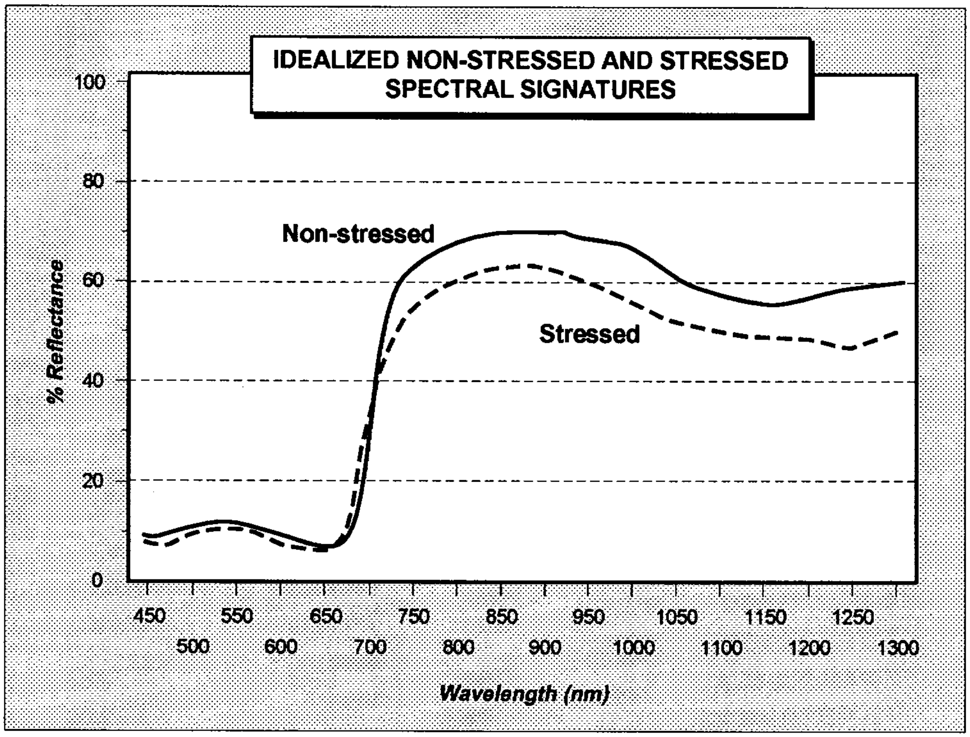
1) the magnitude of the green reflectance at .55 µm (Labovitz et al. 1983; Singhroy 1985; Horler et al. 1983);

2) the magnitude of the .68 µm reflectance at the chlorophyll absorption region - an indicator of vigour (Rock and Vogelman 1985; Singhroy et al. 1986);

3) the position and shape of the red reflectance edge from .68 µm to .8 µm (Horler et al. 1983; Hare et al. 1984; Collins et al. 1981; Singhroy 1985); and

4) changes in the magnitude of the infrared reflectance shoulder which occurs at various wavelengths greater than .78 µm (Rock and Vogelman 1985; Canney et al. 1979; Lyon 1975; Collins et al. 1981).

DIAGRAM 5.5



All of these issues are best detected using an airborne instrument that can be set to narrow bands corresponding to the regions of particular interest. In a study by Springer, Singhroy and Kenny (1989) concludes that *"Sensitivity to spectral change appears to be species dependent. Although all species on the mineralized site showed consistent predictable variations in the spectral curves, the spectral position at which the differences appear varies by species. The magnitude and direction of reflectance changes is also species dependent. All species however showed relatively small blue shifts at the red reflectance edge. .... "*. Clearly this type of spectral analysis can only be accomplished using flexible airborne techniques.

Research at Carlton University is developing an operational methodology (using the AMDFC) for spatial and temporal mapping of forest damage (stress) related to acid mine drainage at the Kam Kotia mine site near Timmins, Ontario. Models are being developed that will incorporate image textural and structural information as well as spectral methods used with airborne multispectral scanner data.

5.4.4 MOISTURE DETECTION

This is an area where photography has been successful, using colour infrared film in detecting saline seeps (Dalsted, Worcester and Brun, 1979) in intermediate and mature stages. It was less successful in detecting emergent or incipient stages where thermal infrared sensing proved to be more effective. Both colour and colour infrared photography have been used to detect the effects of AMD on streams (Johnson and Willson, 1972) where iron content higher than 1.5 parts per million was usually associated with stream pH of 4.0 or less. Streams with higher acidity (pH of 3 to 4) generally photograph in shades of green and basic streams (pH of 7 or more) were blue (Standberg, 1964). The colour photography provides good penetration of water and the IR is beneficial in silted conditions.

Thermal band images acquired using airborne frame video cameras have been successfully used in the detection of leaks and spills at tank farms and pipelines (Olsen, pers. comm. 1993). Hence, thermal imagery collected using airborne digital frame cameras may be useful in detecting near surface seepage from containment structures that may be related to acid mine drainage.

5.4.5 CHANGE DETECTION

Adverse environmental effects, such as those resulting from acid mine drainage, result in a change in "landscape". In order to conduct monitoring studies using remotely sensed data, landscape features must be mapped for different years or selected time interval and "areas of change" determined. Landscape can be mapped using a variety of land use/land cover mapping techniques. Landscape changes are determined using "change detection" methodologies.

Environmental monitoring with respect to acid mine drainage can be done using change detection techniques with remotely sensed data. This type of analysis uses multi-temporal data sets (e.g. data sets from different years) in order to discriminate areas of land cover change between the image dates. Numerous procedures have focused on the development of different procedures for identifying areas of change. Satellite and airborne spectral data, when visually interpreted, can be used successfully for updating existing land use/land cover maps and identifying areas of change with accuracies similar to those obtained from air photo interpretation (Milazzo and DeAngelis 1984). Computer assisted or automated techniques result in maps identifying areas of change and no change however, automated results produce accuracies that are unacceptable for most applications (Stow *et al.* 1990).

For acid mine drainage investigations using remotely sensed data, areas effected by acid mine drainage should be identified using image analysis methodologies for each data set. Visual and GIS techniques and ancillary information should be subsequently used for identifying and quantifying change in a monitoring study.

5.4.6 GIS AND IMAGING SYSTEMS

While these are not particular techniques or sensors they are fundamental mapping tools necessary for the execution of the types of processes outlined in this document. Consequently we felt that they deserved a mention at this juncture.

The need for and application of these tools to the process of remote sensing are illustrated in the paper "Using thermal remote sensing to monitor land degradation and salinization in the Murray-Darling basin of Australia" by Jupp, Walker, Kalma & McVicar of CSIRO and presented at the 23rd Symposium of remote sensing of the environment in Bangkok, Thailand, April, 1990. The need to understand these systems - their proper functioning, application and integration into the process cannot be overstated if the user is concerned about the long term application of remote sensing. If the user is not comfortable with the concepts behind the use and application of these systems they are urged to seek the services of an organization that is.

5.5 DATA ACQUISITION

The bulk of existing data will be found in air photo and satellite archives. Access to archives air photo data will be regionally dependent. Satellite information, on the other hand, is handled by select national or regional representatives and stored at one of the receiving stations around the world. There are currently 19 Landsat and SPOT receiving stations around the world. The location of satellite receiving stations can be obtained from EOSAT, Lanham, Maryland.

A partial list of representatives is provided in Table 5.2. Most receiving stations maintain an archive of all relatively cloud free imagery acquired within their footprint. The length of time that the stations have been operational varies considerably (not to mention the weather) so the user should check with the appropriate agency before assuming that satellite information is available. The user should also be aware that not all areas of the world are covered by the receiving stations so if you have plans to work in these areas you will probably not find any archive information. While it is possible to obtain data for these areas by requesting use of the satellite's onboard recorder the user should be aware that this is not a simple procedure and will require considerable forward planning.

Table 5.2 provides a brief listing of the representative companies for the SPOT and Landsat programs around the world.

TABLE 5.2

Satellite data (SPOT and Landsat) representatives.

SPOT	Landsat
North America	
Canada	
Canada Centre for Remote Sensing (CCRS) - Ottawa Radarsat International - Vancouver	Canada Centre for Remote Sensing (CCRS) - Ottawa Radarsat International - Vancouver
USA	
SPOT Image Corporation - Reston, Virginia	For state listings contact Eosat - Lanham, Maryland
Mexico	
Cosmocolor S.A. - Mexico City	Niveles S.A. de C.V. - Mexico City
South America	
Argentina	
Aeroespacio S.R.L. - Buenos Aires	Aeroterra S.A. - Buenos Aires
Brazil	
Instituto Nacional de Pesquisas Espaciais (INPE) - São José dos Campos Associação Nacional de Empresas de Aerolavantamento (ANEA) - Brasilia	Instituto Nacional de Pesquisas Espaciais (INPE) - São José dos Campos
Bolivia	
	CUMAT - La Paz
Chile	
Coespa - Santiago	JMO International Ltda. Engineering and Automation - Santiago
Columbia	
Instituto Geografico Agustin Codazzi (IGAC) - Bogota	PROSIS, Ltda. - Bogota
Peru	
	TELEMATICA S.A. - Lima
Venezuela	
	Fundacion Instituto de Ingenicria (FII) - Caracas
Europe	
Austria	
Geospace - Bad Ischl	Austrian Space Agency (ASA) - Vienna Geospace GmbH - Salzberg

SPOT	Landsat
Belgium	
Services de la Politique de la Programmation Scientifique (SPPS) - Brussels Cicade - namur Eurosense Belfotop - Wemmel	Institute Geographique National (IGN) - Brussels
Croatia	
	GISDATA - Zagreb
Czech Republic	
	GISAT - Prague
Denmark	
Geomasters - Odense	Electromagnetic Institute - Vedback Kampsax Geoplan - Hvidovre
Finland	
National Board of Survey (NBS) - Helsinki	National Board of Survey (NBS) - Helsinki
France	
Spot Image - Toulouse	GDTA - Toulouse
Germany	
Dornier GmbH - Friedrichshafen Gesellschaft für Angewandte Fernerkundung (GAF) - Munich Geospace Germany - Bonn Agrotechnik - Frankfurt	Dornier GmbH - Friedrichshafen Gesellschaft für Angewandte Fernerkundung (GAF) - Munich
Greece	
Geomet Ltd - Athens	Geomet Ltd - Athens Integrated Information Systems (IIS) - Athens
Hungary	
Folmeresi Intezet (FOMI) - Budapest	Folmeresi Intezet (FOMI) - Budapest
Iceland	
	Iceland Geodetic Survey - Reykjavik
Ireland	
Environmental Resources Analysis Ltd (ERA) - Dublin	ERA - MAPTEC - Dublin
Italy	
Telespazio - Rome	Telespazio - Rome
Netherlands	
National Lecht - En Ruimtevaartlaboratorium (NLR)- Amsterdam Euroconsult - Arnhem	DHV Consultants BV - Amerstoort National Lecht - En Ruimtevaartlaboratorium (NLR)- Amsterdam
Norway	
Fjellander Wideroe A/S - Oslo	Tromsø Satellite Station - Tromsø

SPOT	Landsat
Poland	
Geokart - Warsaw	Institute of Geodesy and Cartography - Warsaw
Portugal	
Geometral - Amadora	Geometral - Amadora
Romania	
	Geosystems Romania S.r.l. - Bucharest
Spain	
Auxiliar de Recoursos y Energia S.A. (AURENSA) - Madrid	IBERSAT S.A. - Madrid INTA - Madrid Infocarto S.A. - Madrid
Sweden	
Satimage - Kiruna	SSC Satellitbild - Kiruna
Switzerland	
	Institut für Landestopographie (BFL) - Wabern Institut für Kommunikationstechnik (BTH) - Zurich RST Raumfahrt Systemtechnik AG - Gallen
Turkey	
Endustriel Ürunler - Istanbul	Endüstriyel Ürünler - Ankara ISLEM Geographic Information Systems and Engineering Co. Ltd. - Ankara
United Kingdom	
National Remote Sensing Centre (NRSC) - Farnborough Nigel Press Associates Ltd. - Edenbridge	National Remote Sensing Centre (NRSC) - Farnborough

Middle East	
Egypt	
Totsico - Cairo	Environmental and Remote Sensing Services (ERSS)- Cairo
Israel	
Interdisciplinary Centre for Technological Analysis and Forecasting (ICTAF) - Tel Aviv	Interdisciplinary Centre for Technological Analysis and Forecasting (ICTAF) - Tel Aviv
Jordan	
	AUTOGRAPHICS - Amman
Oman	
	Arabian Mapping Company - Medinat Oaboos
Saudi Arabia	
King Abdoulaziz City for Science and Technology (KACST) - Riyadh	

SPOT	Landsat
United Arab Emirates	
Maps - Sharjah	
Africa	
Benin	
Cenatel - Cotonou	
Chad	
C.R.A. Ministère du Plan et de la Coopération (BP 1228) - N'Djamena	
Ghana	
	Sambus Company Ltd. - Accra
Ivory Coast	
Société Générale de Topographie - Abidjan	
Kenya	
	Aerospace Surveys Kenya Ltd (ASK) - Nairobi Capricorn Consultants Ltd. - Nairobi
Morocco	
	Centre Royal de Teledetection Spatiale - Agdal-Rabat
Nigeria	
	Delta Systematics - Port Harcourt
Senegal	
E.A.D. (BP 11090) - Dakar	
South Africa	
Council for Scientific and Industrial Research (CSIR) Satellite Remote Sensing Centre - Johannesburg 2000	
Zimbabwe	
	Realtime Computers Ltd. - Harare
Far East	
China	
Research Institute for Science and Mapping - Beijing Tradeglobe Beijing Service Centre - Beijing	
India	
National Remote Sensing Agency (NRSA) Department of Space, Government of India - Hyderabad	
Japan	
Remote Sensing Technology Centre (RESTEC) - Tokyo Nissho Iwai - Tokyo	Remote Sensing Technology Centre (RESTEC) - Tokyo Nissho Iwai - Tokyo Sanko Tsusho Co. Ltd. - Tokyo

SPOT	Landsat
Mongolia	
	MonMap Engineering Services Co. Ltd. - Ulaanbaatar
Nepal	
Shrestha - Kathmandu	
Pakistan	
Pakistan Space and Upper Atmosphere Research Commission (SUPARCO) - Karachi	
South Korea	
Chang Woo Inc. - Seoul	Chang Woo, Inc. - Seoul
Taiwan	
Centre for Space and Remote Sensing Research (CSRSR) National Central University - Taiwan	Hermes-Epitek Corp - Hsin-Chu
Thailand	
National Research Council of Thailand (NRCT) - Bangkok	
Oceania	
Australia	
Australian Centre for Remote Sensing (ACRES) - Belconnen	Australian Centre for Remote Sensing (ACRES) - Belconnen
SPOT Imaging Services - St. Leonards, Sydney	
Indonesia	
P.T. Bhumi Prajasa - Bandung	
Malasia	
Terra Control Technologies (TCT) - Kuala Lumpur	
New Zealand	
Department of Scientific and Industrial Research (DSIR) - Ltd. Palmerston North	manaaki Whenua Landcare Research New Zealand (MWLR) - Aokautere, Palmerston North
Philippines	
CERTEZA Surveying & Aerophoto Systems - Quezon City	

5.5.1 LISTING OF SATELLITE OPERATORS

SPOT Image

The two master receiving stations are located at Aussaguel-Issus (Toulouse) in France and Kiruna in Sweden. Canadian and international SPOT data can be acquired from RADARSAT International and SPOT IMAGE. Data listings for a particular area of interest, world coverage index maps, current price lists and order forms are available from these organizations free of charge. The user can acquire specific data with specific time scheduling. Single frames or stereo pairs are available.
Organizations providing SPOT satellite data are listed as follows:

RADARSAT International Inc.
Building D, Suite 200
3851 Shell Road
Richmond, British Columbia
Canada V6X 2W2
Telephone: (604) 244-0400
FAX: (604) 244-0404

SPOT IMAGE
16 Bis, Avenue Edouard Belin BP
31005 Toulouse
Cedex, France
Telephone: 33 61539976
FAX: 33 61281354
Telex: 531081

SPOT IMAGE Corporation
1987 Preston White Drive
Reston, Virginia USA
22091-4326
Telephone: (703) 620-2200

Indian Remote Sensing Satellite-1A (IRS-1A)

Digital and photographic products are disseminated through the Space Application Centre, Ahmedabad, India. Data reception and processing and distribution of standard and special products are provided by the National Remote Sensing Agency (NRSA). The IRS Data Products System provides for the operational generation of data products and their dissemination to users. Catalogues of the data are generated according to the IRS-1A image reference system. The address is as follows:

National Remote Sensing Agency (NRSA)
Balanagar, Hyderabad 500037
Andhra Pradesh, India
Telephone: 262572 (ext. 67)
Telex: 0155-522

Marine Observation Satellite (MOS-1) and Japanese Earth Resources Satellite-1 (JERS-1)

The World Reference System similar to that of Landsat is used as an index for MOS data. Data from both satellites is received at the Earth Observation Centre, National Space Development Agency of Japan (NASDA). Digital and photographic products are available through the Data Service Department, Remote Sensing and Technology Centre (RESTEC) located at the following address.

Remote Sensing and Technology Centre (RESTEC)
University-Roppongi Building,
7-15-17, Roppongi
Minati-Ku
Tokyo 106, Japan
Telephone: 03 403 1761
FAX: (81) 3-403-1766
Telex: 2426780 RESTEC J

ESRIN, EARTHNET User Services
Via Galileo Galilei
C.P. 64
I-00044 Frascati, Italy
Telephone: (39) 6-94180478
FAX: (39) 6-9426285
Telex: 610637 ESRIN I

RADARSAT International is currently in negotiations with Japan in order to obtain the distribution rights for JERS-1 data coverage of Canada and the United States. MOS-1 data over Canada can be obtained from the Canada Centre for Remote Sensing (CCRS) at:

Canada Centre for Remote Sensing
580 Booth Street
Ottawa, Ontario, Canada
K1A 0Y7
Telephone: (613) 990-8033
FAX: (613) 991-5539

European Remote Sensing Satellite-1 (ERS-1)
Digital and photographic products covering North America are obtained through RADARSAT's Ottawa office; coverage of Europe, North Africa and the Middle East is obtained from ESRIN, and data from the remaining parts of the world can be obtained from SPOT IMAGE. Addresses are as follows:

RADARSAT International Inc.
Ottawa Branch
Telephone: (613) 238-5424
FAX: (613) 238-5425

ESRIN, EARTHNET User Services
Via Galileo Galilei
C.P. 64
I-00044 Frascati, Italy
Telephone: (39) 6-94180478
FAX: (39) 6-9426285
Telex: 610637 ESRIN I

SPOT IMAGE
16 Bis, Avenue Edouard Belin BP
31005 Toulouse
Cedex, France
Telephone: 33 61539976
FAX: 33 61281354
Telex: 531081

Radarsat

Radarsat is a Canadian satellite scheduled for launch in January 1995. Data will be distributed by RADARSAT International.

RESOURCE F-1 and F-2 (Soyuzkarta)

JEBCO Information Services, from it's offices in London and Houston, has signed a wide-ranging contract with Russian agencies State Centre Priroda and Rosvneshegeo to make Russian high resolution satellite imagery, covering most regions of the world, commercially available in digital form.

In Canada:
Fons Dekker & Associates
80 Canyon Drive NW
Calgary
Alberta, T2L 0R3.
Telephone: 403-289-5441
FAX: 403-289-5441

5.5.2 AIRBORNE DATA ACQUISITION

MEIS II

The MEIS II is currently with CCRS (the Canada Centre for Remote Sensing) and is not mounted on a platform. The MEIS is unavailable for commercial or research applications at the time of writing and will not be available for use until arrangements can be made with an operator who will offer the MEIS for general use.

CASI

The CASI is available for purchase or operational service can be arranged from a number of operators worldwide. To locate an operator near your area of concern you should contact Itres Research in Calgary, Alberta.

Itres Research Ltd.
Suite 155
2635 37th Avenue N.E.
Calgary
Alberta, T1Y 5Z6
Canada
Telephone: 403-250-9944
FAX: 403-250-9916

Daedalus

Daedalus are the manufacturer of a broad range of airborne imaging devices with operators worldwide. To purchase a system or locate an operator in your vicinity contact Daedalus' head office.

Daedalus Enterprises Inc.
P.O. Box 1869
Ann Arbor
Michigan, 48106-1869
USA
Telephone: 313-769-5649
FAX: 313-769-0429

Geoscan

Geoscan is an Australian airborne imaging spectrometer manufactured by Geoscan Pty. Ltd. from Perth, West Australia. Geoscan is currently unavailable for commercial or research applications at the time of writing and will not be available for use until the company can be restructured.

GER63

The GER63 airborne imaging spectrometer can be purchased or GER will conduct surveys and data analysis. They can be contacted at the following address:

Geophysical and Environmental Research Corp.
1 Bennett Common
Millbrook, NY
USA 12545
Telephone: 914-677-6100
Fax: 914-677-6106

STAR-1 Radar

Star-1 is owned and operated by Intera Information Technologies who provide world-wide service for this system as well as a series of other services.

Intera Information Technologies
Remote Sensing Division
1000, 645 - 7th Avenue S.W.
Calgary
Alberta, T2P 4G8
Canada
Telephone: 403-266-0900
FAX: 403-265-0499

Airborne Multispectral Digital Frame Camera (AMDFC)

The AMDFC is under development and testing at Carlton University. Additional information and the availability of the camera for testing can be obtained from Dr. Doug King.

Carlton University
Faculty of Social Sciences
Department of Geography
B-349 Loeb Building
1125 Colonel By Drive
Ottawa
Ontario K1S 5B6
Telephone: 613-788-2561
Fax: 613-788-4301

Ag-Recon

The Ag-Recon airborne frame camera owned and operated by Mr. David Olsen, Geomatics International Inc.

Geomatics International Inc.
12527, 130th Lane N.E.
Kirkland
Washington
USA 98034-7716
Telephone: 206-821-5354
Fax: 206-820-9399

5.5.3 SPECTRO-RADIOMETERS

Portable spectroradiometers for the acquisition of ground spectral signature information are as follows:

Spectron SE-590
Spectron Engineering Inc.
225 Yuma Court
Denver, CO
USA 80223
Telephone: 303-733-1060

FieldSpec
Analytical Spectral Devices, Inc.
4760 Walnut Street, Suite 105
Boulder, CO
USA 80301
Telephone: 303-444-6522
Fax: 303-444-6825

PIMA
North American Distributor:
Spectral International
208 West Clevland
Lafayette, CO
USA 80026
Telephone/Fax: 303-666-5517

GER
Geophysical and Environmental Research Corp.
1 Bennett Common
Millbrook, NY
USA 12545
Telephone: 914-677-6100
Fax: 914-677-6106

Chapter 6

6.0 INFORMATION SOURCES

The sources of information for this document come from a direct survey (Appendix A) of the geological and geophysical and related industries as mentioned in Chapter 1. In addition there was direct contact with a range of operations/research personnel directly or indirectly involved in one or more of the referenced papers. The RESORS remote sensing database and the Laurentian University Acid Mine Drainage databases were searched and papers related to the monitoring of remotely sensed data were acquired and used in the writing of this handbook.

A List of cited references is provided below.

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Hodcroft, A.J.T. and Moore, J. McM., 1988. Remote Sensing of Vegetation: a promising exploration tool. Mining Magazine, Oct. 1988. pp. 274-279.

Horler, D.H.H., Dockray, M. and Barber, J. 1983. The Red Edge Of Plant Reflectance. International Journal of Remote Sensing, Vol. 4, No. 2, pp. 273-288.

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Chapter 7

7.0 NEW METHODS AND APPLICATIONS

The previous sections cover the current state-of-the-art with respect to AMD applica tions. The only new development on the horizon is the airborne digital frame camera. Although this system is still in the developmental stages, if it can deliver image frames with multispectral, thermal and stereo capabilities, it will represent a new low cost means of acquiring digital information that can be used for a variety of applications, including AMD, on a local scale.

The development of existing technologies/methodologies in the field of airborne imaging represents the best possibility for improved methodologies as related to AMD. These technologies are only just starting to become an effective tool for monitoring AMD. Noteworthy issues include:

1. Practical methods of correcting for attitude and positioning airborne imaging data are just now starting to hit the market. This alone will make a significant difference in the applicability airborne imagery.

2. The processing systems to handle both the volumes of data and the intricacies of mosaicking are now reasonably available.

3. Trained personnel and a wide range of qualified and available services in these methodologies are now at the disposal of the user.

4. Inexpensive and portable imaging devices are starting to reach the market reducing the investment costs for imagers consequently providing increased cost effectiveness for these types of services - bringing them in line with more traditional alternatives.

5. Instruments capable of being configured with many user selectable bands (both in position and bandwidth) will improve the quality of analysis that can be expected in the future.

The collection of reference spectral signatures using portable spectroradiometers is quickly becoming an important component of site characterization for environmental remediation. The use of spectroradiometers is rapidly growing within the mining industry and they will be used in connection with airborne and satellite remote sensing studies for monitoring acid mine drainage.

These are the issues that will shape the near future of AMD applications. While there has been a reasonable amount of research work done on parallel types of applications there is only an extremely small body of work that is invested in remote sensing for actual AMD monitoring. The tools are available to greatly improve the quality of AMD monitoring using remote sensing and what is needed is not to look for a single instrument as the panacea for all of the inadequacies of the current methodologies but to look at the applicability of the various instruments as they relate to different components of an integrated solution. As it is improbable that the organization concerned with AMD monitoring will have the internal resources and skills to implement an integrated solution we recommend that the interested party join forces with one the available and qualified remote sensing service operations to implement such a project.

Of any developments in the sensor area we would believe that continuing research in radar methodologies might have the best chance of providing new and novel approaches to AMD monitoring beyond what we are dealing with to-day.

In the area of active optical devices, such as airborne fluorosensors, we believe that the current instruments are not sufficiently mature to hazard a proper guess. While there is reason to believe, theoretically, that active devices are capable of detecting more specific indicators than passive devices there is a long history of difficulties in the development of practical operational devices and the research that can be related to AMD is not sufficient to encourage an educated guess.

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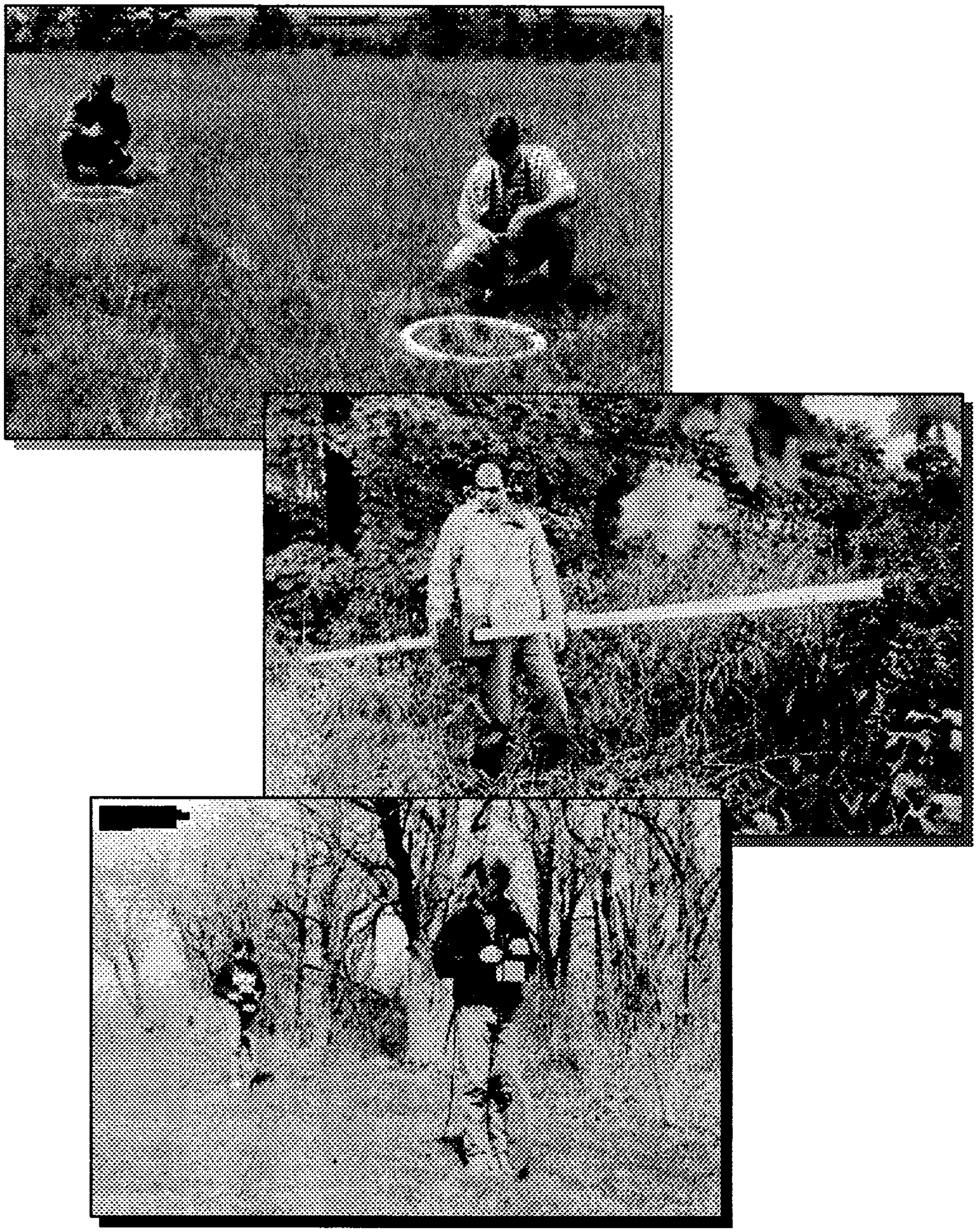
Part II
Geophysics



Chapter 8

8.0 STATE OF THE ART

Geophysical methods have been applied to mineral exploration problems for more than six decades. In the 1940's and 1950's reference is made to civil engineering and environmental applications, including ground water studies, dam site investigations and transportation/pipeline planning. The earliest published references to AMD applications seem to be in the late 1960's and early 1970's, including Chewning and Merkel (1972) and Merkel (1972) on the use of resistivity techniques to delineate AMD. Review papers by McNeill (1989, 1990), Monier-Williams et al (1990), Greenhouse et al (1989), Henderson (1992), King and Pesowski (1993) and Mwenifumbo (1993) describe a variety of geophysical techniques that have been applied effectively on problems similar to AMD. After a fairly thorough literature search the authors could only find 17 published (including university theses) references to the direct application of geophysics to AMD. These are included in the Selected References in Chapter 13. Evidentally, on the basis of questionnaires received from international mining companies, a considerable amount of geophysical work is being conducted that does not reach publication. King (1994) points out that AMD has been identified since 1990 as the "largest single environmental problem facing the Canadian mining industry", and his thorough study of acid seepage in the Sudbury area, commissioned under the MEND program, records a significant advance in the state of the art. King identifies three areas where geophysics can be used effectively on AMD problems:

1. sulphides, which are the source of AMD
2. areas of active chemical oxidation
3. acid mine drainage itself

Possibly a fourth category should have been added, namely the movement of contaminated groundwater, which has been shown by Corwin (1990) and others, to be detectable by the self-potential (SP) method. In addition, there are many indirect applications of geophysics that can benefit AMD remedial programs by mapping the 3-dimensional stratigraphy and structure in the vicinity of mine waste disposal sites. Dave and Siwik (1986), Pehme (1981), Roberts (1989), Hanson et al (1993), Snodgrass and Lepper (1993) and Clark (1993) describe geophysical surveys with a variety of methods aimed at solving the architecture of the ground as opposed to directly locating acid drainage. This information, which might include thickness of a tailings pile, the location and relief of buried river channels, the existence and depth of an aquitard such as a clay layer, or a bedrock ridge that might effect seepage flow, can very definitely benefit both the AMD assessment and an appropriate program of monitoring and remedial action.

Information received from the questionnaire mailing confirms the results of the literature search in terms of both scale and scope of the current state of the art. Approximately 60 respondents appear to be currently using geophysics for mine-related problems although only 26 claim to be working on AMD. Of these 26 probably 25 percent can be eliminated as several respondents appear to be working on the same projects. For example, an instrument manufacturer, a contractor, a university and two mining companies all report work on AMD that appears to be the MEND project described by King (1994). Eliminating overlap between the published work on AMD geophysics and the questionnaire results, it would seem that somewhere between 30 and 50 AMD-related geophysical studies are being or have been carried out in recent years. The number of individual organizations involved in these studies is, of course, considerably greater.

The methods reported on in the questionnaires agree reasonably well with those described in the literature though there is clearly some wishful thinking in some of the answers provided. The authors, in designing the questionnaire, attempted to draw on the available experience by asking what methods/techniques the respondents are using and "are planning to use in the future". As a result several responents ticked all the available methods, including magneto-tellurics (MT). Despite these distortions, it is apparent that the favourite methods for mine-related problems are electromagnetic (EM), DC resistivity and magnetics. The most popular techniques within these methodologies are:

EM: ground conductivity meters EM31 and EM34-3

DC Resistivity: dipole-dipole profiling/sounding and Schlumberger sounding

Magnetics: total intensity and vertical gradient measurements by proton precession or Overhauser magnetometer

In the following chapters methods and applications will be examined in more detail and areas will be identified that fall outside the current state of the art but where the authors feel that geophysics can play a useful role in detecting and monitoring AMD.

Chapter 9

9.0 WHO USES GEOPHYSICS?

In order to obtain some measure of the extent to which geophysics is being used for various applications, a mailing list of approximately 940 potential users was compiled from a variety of sources. A questionnaire was designed, a copy of which is included in Appendix A of this handbook.

As mentioned in Chapter 2, the response to the mailing was surprisingly good, with a total of 259 responses (28%). 170 responded to Part II - Geophysics and, of these, 148 reported using geophysics for one or more applications, 147 employ ground geophysical methods and 91 employ airborne geophysical methods.

A breakdown of respondents by discipline is given in Table 9.1:

TABLE 9.1

Breakdown of Respondents to Questionnaire

Mining Corporations	77	45%
Service Organizations	41	24%
Government Agencies	32	18%
Universities	20	12%

The preponderance of mining company users is not surprising, considering the history of geophysical methods development. What is interesting is the fact (see Table 10.1) that such a large percentage (67% of respondents) employ geophysics for engineering, environmental or groundwater purposes.

Bearing in mind the incomplete nature of the survey, particularly the regional distribution of respondents which heavily favours North America, it is difficult to extrapolate and arrive at an estimate of the extent to which geophysics is being used globally. Nor is it particularly relevant to the present study. Undoubtedly the survey failed to reach many organizations in Europe, Asia and Africa, where other geophysical activity statistics (e.g. The Leading Edge: Riley, 1993) show a considerable amount of ground and airborne geophysical activity. However, bearing in mind the concentration of geophysical manufacturing and service organizations in Canada, the USA and Australia, and the fact that these organizations are active worldwide, it might not be unreasonable to estimate that between 400 and 600 organizations currently employ geophysical methods worldwide for one purpose or another. Of these, it is estimated that roughly 2/3 or between 270 and 400 employ geophysical methods for environmental, engineering or groundwater purposes.

Chapter 10

10.0 APPLICATIONS OF GEOPHYSICS

Question 2 of Part II of the questionnaire (Appendix A) asks the question "does your organization currently use or have used geophysical technology? If yes indicate applications:". Answers to these questions were as follows:

TABLE 10.1

Applications of Geophysical Methods (Questionnaire)

Mineral Exploration	120	80%
Geological Mapping	120	80%
Mine Tailings	32	21%
Industrial Waste Management	29	19%
Acid Mine Drainage	26	17%
Construction/Engineering	41	27%
Permafrost	11	7%
Groundwater Exploration	68	45%
Salt Mapping	19	13%
Ice Thickness	11	7%
Bathymetry	15	10%
Contaminant Plumes	59	39%
Buried Artifacts	37	25%
Other	16	11%
Total Respondents using geophysics	150	80%

"Other" applications include soil thickness, geothermal, teaching, coal exploration, archaeology, petroleum exploration, soil/wetland studies, Karst research, detecting open mine workings, mine fires in abandoned mines and studies related to leaching applications in in-situ mining.

In the construction of this question, and in order to make sure that the scope was as broad as possible, categories are to some extent overlapping. In particular, the mine tailings, acid mine drainage and contaminant plume categories might all apply to studies of acid seepage from mine waste. In fact, however, only 16 respondents indicated all three categories, while 20 indicated AMD and one of the other two categories.

From this analysis it would seem that about 13% of geophysics users are involved in mine-related seepage problems, probably related to tailings. Extrapolating that to the estimated number of geophysics users worldwide, one obtains a range of 52-78 organizations worldwide that are using geophysics for AMD problems. This is surprisingly close to the estimate arrived at by a survey of the literature as discussed in Chapter 8 above. Certainly, it is not a high level of activity considering the huge number of active and abandoned mines that must be leaking acid into the environment.

The literature search conducted as part of this study generally confirms the above results in terms of applications, but provides greater detail on the specific problems being solved. Benson (1993) distinguishes between mine discharge waters and tailings leakage, a distinction that the questionnaire failed to address. He reports success in mapping acid contamination at 88 sites in Utah, including 14 mining operations. Several authors report studies of acid contamination around abandoned coal mines, some of which originates from mine spoil (e.g. Ebraheem et al, 1990 and Brooks et al, 1991), whereas others (e.g. Ladwig, 1982 and Watzlaf and Ladwig, 1987) refer to actively oxidizing in-situ coal seams. In the studies on tailings piles there is a diversity of specific applications in the literature. Dave et al (1986), and Clark (1991) concentrate on mapping the architecture of the tailings deposit in order to locate the fluid migration pathways. Pehme (1981), Geomar (1991 and 1992) and King and Pesowski (1993) specifically addressed the problems of leakage and contaminant plumes surrounding tailings piles. Snodgrass and Lepper (1993) and King (1994) describe studies both on and around tailings piles, aimed at studying the actively oxidizing zone, the fluid pathways and the external contamination as a single system. King (1993) and Clark (1991) both address the problem of the actively oxidizing layer, which King attempts to map with induced polarization (IP) and Clark by magnetometer survey.

Mwenifumbo (1993) discusses various applications of borehole geophysics both within tailings piles and in the contamination zones outside. One of the more interesting is the detection of fluid flow by combined self potential (SP) and temperature measurements. The application of SP to the detection of fluid movement is also addressed by Corwin (1990) as applied to leakage through dams and reservoir floors. Mwenifumbo (1993) demonstrates the application of gamma-ray logging to the detection of acid leakage beneath and surrounding uranium tailings ponds. He also shows the utility of other borehole measurements in determining stratigraphy, porosity, fracturing etc., all of which can assist in an AMD monitoring and remedial programs.

As part of the literature study, and included in the Selected References, Chapter 12 of this handbook, are a number of articles and theses dealing with other forms of acid contamination than AMD. The methods of addressing these problems show such similarity and face such similar obstacles that the information learned can be applied directly to AMD problems.

Excellent review papers on contamination studies given in Barber et al (1991), Butler and Llopis (1990), McNeill (1990), Greenhouse et al (1989), Henderson (1992), Monier-Williams et al (1990), Roberts (1989) and Stierman and Ruedisili (1988) describe the application of a large variety of geophysical techniques to industrial, municipal and groundwater problems with strong similarities to the AMD problem. Further reference is made to these and other non-AMD applications under the Methods and Techniques sections of this handbook, in Chapters 11 and 12.

The subject of monitoring is addressed, as well as detection, in several of these references. Monitoring can involve repeated surveying along the same profile or grid at various intervals on a seasonal or temporal basis. The purpose is to observe temporal variations in the distribution of physical properties in the ground. Some of these may be related to active and variable seepage. The most common approach to geophysical monitoring is the installation of geophysical sensors in boreholes, usually drilled for geochemical and/or piezometric measurements. The geophysical sensors measure different parameters and sample different volumes than the chemical and piezometric devices. Mwenifumbo (1993) and Frimpter and Maevsky (1979) describe a variety of borehole geophysical sensors and their application to physical property monitoring.

Of increasing importance in AMD studies is the use of airborne geophysics, particularly fixed-wing and helicopter electromagnetics (EM). King (1994) demonstrates the utility of helicopter EM in accurately delineating AMD contamination around producing and abandoned mines near Sudbury, Ontario. He also strongly recommends the use of existing airborne EM for baseline studies of conditions prior to mining operations, followed by repeat surveys during and after. Airborne EM has excellent depth penetration and 1-dimensional sounding capability.

Among other applications mentioned in the literature is the detection of cyanide contamination from a landfill in East Bohemia, Czechoslovakia (Cahyna et al, 1990) using induced polarization (IP). Why cyanide-contaminated sludge should produce an IP response is not explained, but the example illustrates the wide range of possible applications of geophysics that need to be examined either theoretically or empirically.

Chapter 11

11.0 GEOPHYSICAL METHODS

A useful compendium of geophysical methods and their applicability to environmental problems is given by Roberts (1989) and is reproduced as Table 11.1 below. The applications listed include the detection of electrically conductive zones similar to those associated with the sulphate-rich zones of tailings piles and acid seepage plumes. A similar table, dealing specifically with AMD applications, has been constructed as part of the present study and is shown in Table 11.2. The range of methods has been extended to include airborne as well as ground. Waterborne and borehole methods are not included.

TABLE 11.1

Applications/Concerns	GPR	Magnetic	Gravity	Resistivity	EM 34-3 H. Dipole	EM 34-3 V. Dipole	VLF EM
Detection of electrically conductive zones							
Vertical resolution	1	NA	NA	5	2	4	1
<2m depth	2	NA	NA	5	4	3	1
>2m depth	1	NA	NA	5	3	4	1
Lateral resolution	2	NA	NA	5	3	4	1
Detection of non-magnetic objects							
<2m depth	5	NA	1	NA	NA	NA	NA
>2m depth	3	NA	1	NA	NA	NA	NA
Detection of magnetic objects							
<2m depth	4	5	1	1	2	2	2
>2m depth	3	5	1	1	2	2	2
Determination of landfill thickness	1	3	5	2	2	2	1
Determination of lateral landfill surface contacts	5	4	3	2	2	2	2
Quantitative interpretation capabilities	1	4	5	3	2	2	1
Average signal-to-noise ratio	3	4	5	4	3	3	2
Confidence in forward and inverse interpretation	NA	4	4	4	3	3	NA
Surveying efficiency	5	4	1	2	3	3	4
Initial qualitative interpretation capabilities	2	5	1	3	4	4	2

5 = HIGH DEGREE
1 = Low Degree
NA = Not Applicable

(After Roberts, 1989)

TABLE 11.2

Effectiveness of Methods for a Variety of AMD Detection Applications

Rate 1-5; poor-good	Active oxidation	Acid seepage	Sulphide boundary	Stratigraphy & structure	Radioactive seepage	Fluid movement
Airborne EM						
Fixed-wing	3	3	1	1	NA	NA
Helicopter	4	5	1	2	NA	NA
VLF	1	2	NA	NA	NA	NA
Ground EM						
TEM	5	5	2	2	NA	NA
FEM	2-4	2-4	1-2	1-2	NA	NA
VLF EM	2	3	1	1	NA	NA
VLF resistivity	3-5	2-4	1-2	1-2	NA	NA
Airborne Mag	1*	NA	2*	1-3	NA	NA
Ground Mag	2*	NA	3*	2-4	NA	NA
Airborne Gamma Ray Spec.	NA	NA	NA	NA	4	NA
Ground Gamma Ray Spec.	NA	NA	NA	NA	4	NA
DC Resistivity	4	4	3	2	NA	NA
IP/Resistivity	5	4	5	2	NA	NA
SP	3	3	2	1	NA	3
Seismic refraction	NA	1	1	2-4	NA	NA
Seismic reflection	NA	NA	NA	2-4	NA	NA
Seismic tomography	NA	1-3	NA	2-4	NA	NA
GPR	NA	1-3	2-4	5	NA	NA
Gravity	NA	NA	1-3	2-5	NA	NA

*Assumes sulphide zone contains appreciable pyrrhotite or magnetite.

In this table, effectiveness is rated on a scale of 1 to 5, the higher numbers being the more effective. A range of numbers is given in cases where there is either a range of capabilities in the geophysical instruments or a range in the physical property contrasts of the target or geological structure. A more detailed breakdown is given in the following section (Chaper 12) of this handbook.

The results of the information survey conducted by questionnaire were of some help in compiling the above table. Table 11.3 is a list of answers to the question "if you are using or plan to use" geophysics for acid mine drainage, mine tailings or contaminant plume studies, which of the following techniques have you employed (or do you plan to employ)?". The 81 respondents to this question provided the following answers, arranged in decreasing order of popularity:

TABLE 11.3

Popularity of Various Methods for AMD-Related Applications (Questionnaire)

Electromagnetics	71	88%
DC Resistivity	49	60%
Magnetics	45	55%
I.P.	39	48%
Seismics	49	49%
VLF	32	39%
GPR	31	38%
Gamma-ray Spectrometry	30	37%
SP	29	36%
Gravity	23	28%
Other	16	20%
Magneto-tellurics	12	15%
Total Respondents	81	54%

It is immediately evident that respondents have taken some liberty with the words shown in parentheses in the question that was posed. It is tempting when asked what technique you "plan to use" to check all of the available boxes. This is what several respondents have done, as evidenced by the twelve who indicated that they would use magneto-tellurics, a technique that is limited to depths normally well in excess of 1 km. Notwithstanding these distortions, one can obtain some measure of what is perceived to be the effectiveness or cost-effectiveness of the various methods by examining their relative popularities. The three leading methods are not surprising and are entirely consistent with the literature study. Induced polarization (IP) is puzzling in view of the fact that only two references to IP studies (King, 1994 and Clark, 1992) have been found in the literature. It is possible that respondents are of the opinion that IP/resistivity can be carried out in lieu of DC resistivity at minor additional cost and with possible benefits. Unfortunately, the questionnaire did not separate VLF EM from VLF Resistivity, which requires ground electrodes and measures apparent resistivity as well as the phase angle between the magnetic and electrical fields. Both the literature and the experience of the authors suggest that the latter technique is much more effective for AMD-type problems than VLF EM.

Chapter 12

12.0 INSTRUMENTATION AND TECHNIQUES

12.1 ELECTROMAGNETIC

An impressive 87% of respondents using geophysics employ or plan to employ electromagnetic methods for AMD, mine tailings or contaminant plume studies. As explained in Chapter 11 above, these figures are probably distorted by the "plan to use" qualification, but they provide useful information on what users perceive to be the most effective techniques for their particular problems.

TABLE 12.1

Popularity of Various EM Techniques for AMD-Related Applications

Fixed-wing airborne transient (FWTR)	12	17%
Fixed-wing frequency domain (fwfd)	6	8%
Helicopter airborne transient (HAT)	6	8%
Helicopter airborne frequency domain (HAFD)	17	24%
Ground fixed loop transient (GFLT)	23	32%
Ground fixed loop frequency domain (gflfd)	17	24%
Ground moving coil transient (GMCT)	21	29%
Ground moving coil frequency domain (GMCFD)	36	50%
EM31	39	54%
EM34	35	49%
MAXMIN	14	19%
Other	9	12%
Borehole (BH)	23	32%
One or more EM techniques	71	87%

12.1.1 GROUND FREQUENCY DOMAIN EM

It is evident that ground moving coil frequency domain EM (FEM) is by far the most popular technique. This is clear also from the literature study. At least 45% of the articles and theses included in the Selected References at the end of Chapter 13 discuss the application of frequency EM (FEM).

Within this category of techniques, the ground conductivity meters EM31 and EM34, manufactured by Geonics Limited are by far the most popular. Thirty respondents (42%) report that they use or plan to use both of these instruments, as compared with 14 respondents (19%) for the horizontal-loop or Slingram type instrument MAXMIN manufactured by APEX Parametrics. This popularity undoubtedly stems from the fact that the conductivity meters have been designed (McNeill, 1980, 1990) specifically for environmental applications, whereas MAXMIN was intended originally for mining exploration. The recently introduced MAXMIN I series, particularly the MAXMIN 1-8S and MAXMIN 1-10, with coil separations as little as 5 m and frequencies up to 56 KHz, has been designed primarily for "geoengineering" applications.

Recently introduced in the market are two Androtex EM instruments, the EZM-1, which is quite similar to the EM31, and the RUSCAN KCR-7, a Russian instrument designed to map in the low conductivity range. Both instruments measure in-phase and quadrature components. No case histories are so far available for these instruments, and the EZM-1 is still in the prototype stage.

A desirable feature of the ground conductivity meters is the direct readout in conductivity units as distinct from the in-phase and quadrature field ratios measured by instruments such as MAXMIN. While geophysicists may be comfortable with the latter units, engineers and geologists prefer units more directly related to the physical properties of the ground. Speed, portability and cost are factors that also tend to favour the ground conductivity meter, particularly the EM31 which can be operated by one individual. On the other hand, as pointed out by McNeill (1980, 1990), Watzlaf and Ladwig (1987), Roberts (1989) and others, the conductivity meters have both small depth penetration and limited sounding ability. The latter restriction is important in layered-earth environments; the apparent conductivity values obtained from the EM31 and EM34 are only correct under perfectly homogeneous ground conditions. The importance of sounding (i.e. determining the vertical variations in conductivity as well as the lateral variations) in solving contaminant plume problems was pointed out by Roberts (1989) and Stierman and Ruedisili (1988). Jansen et al (1993) compares parametric (multi-frequency) sounding with a MAXMIN I-10 instrument and single spacing conductivity measurements with an EM31 at a number of landfill sites. One-dimensional inversions of the MAXMIN data with the Interpex EMIX-MM software package provided excellent conductivity cross-sections that pointed directly to the horizontal and vertical locations of the contaminant plumes.

A potential limitation of the conductivity meters is the limited conductivity aperature (McNeill, 1980) which for the Geonics units is approximately 1,000 ms/m (milliSiemens/meter) at surface and possibly as low as 100 ms/m at depth. The authors did not find in their literature search or conversations with users that this has proved to be a practical limitation. Where acidity is so high that conductivity exceeds the threshhold of accuracy, there is no need to know the exact value in ms/m. The RUSCAN KCR-7 appears to be limited, for effective operation, to conductivities below about 100 ms/m.

Attempts have been made to apply other FEM systems than MAXMIN to AMD-type problems. Greenfield and Stoyer (1976) apply a tilt-angle and ellipticity measuring instrument operating in the frequency range 10-103 KHz to map acid drainage from a coal mine in Pennsylvania. With a coil separation of 60 m, conductivity cross-sections were obtained to a depth of about 20 m. Experiments have been carried out with fixed-transmitter systems such as Turam (e.g. Poddar, 1983), demonstrating the advantages of added depth penetration and the convenience of a single transmitter location as compared with moving coil systems. This has also been demonstrated by the success of fixed-source transient EM (TEM) systems, as discussed in 12.1.2 below. A new wide-band version of the Androtex ELFAST FEM system is expected on the market shortly, designed specifically for environmental applications.

Deep penetration FEM systems such as the Zonge and Phoenix CSAMT would appear to have limited application to AMD problems, partly because the galvanic current response makes interpretation difficult. Deep mine acid leakage plumes might however call for instruments with this sort of capability.

While not denying the practical advantages of the ground conductivity meters, particularly in terms of speed and convenience, the authors believe that there will be a growing demand for multi-frequency moving coil and fixed-source systems capable of parametric soundings to greater depths, coupled with on-line apparent conductivity readouts and off-line 1-D inversion capabilities. Several inversion programs are available commercially, including Interpex EMIX-MM and GIPSI GEMINV.

Electromagnetic measurements are particularly relevant to AMD problems because, as numerous authors have pointed out (e.g. McNeill, 1980, 1989, 1990, Greenhouse et al, 1989, Greenfield and Stoyer, 1976, Benson, 1993, King, 1994 and many others) only minor changes in acidity can, through the release of H^+ and SO_4^- ions produce major changes in electrical conductivity. The problems associated with AMD are therefore closely conductivity-related. Even the layer of active oxidation may be detectable by virtue of the higher conductivity associated with the sulphide zone as compared with the overlying zone of oxides, though this boundary has been shown by King (1994) and Clark (1991) to be more easily distinguishable by induced polarization (IP). Significant advantages of EM over DC resistivity have been pointed out by King and Pezowski (1993), Greenfield and Stoyer (1976) and others, pointing to the better capability of EM to resolve electrical conductors, particularly at depth. On the other hand Jansen et al (1993) and Stierman (1984) stress the advantages of DC resistivity, particularly for defining shallow, resistive layers. Stierman and Ruedisili (1988) claim better lateral resolution for DC resistivity though the authors fail to see how this can be supported by either theory or experience.

The debate between the effectiveness of EM and DC resistivity will continue since both methods have their advantages and disadvantages. Between the various EM techniques, however, it is easier to select an appropriate technique for a particular problem. Undoubtedly the ground conductivity meters are the clear winners for rapid, shallow reconnaissance. At the other end of the scale, fixed-source TEM (or FEM) instruments probably lead. In between, there is room for moving coil and fixed-source FEM instruments and possibly moving coil TEM instruments designed specifically for environmental applications (see 12.1.2).

In Table 12.2 the authors have summarized the main characteristics of the most commonly used ground FEM instruments. An effectiveness rating of 1 to 5, based on all of the information received, has been provided to guide users in the choice of instruments for their particular applications.

TABLE 12.2

Effectiveness of Ground Frequency Domain EM Techniques for AMD Related Applications

Supplier/ Manufacturer	Instrument	Depth Penetration	Resolution	Speed & Portability	Capital Cost	Profiling	Sounding	Conductivity Aperture	Interpret -ability	Software Support
MOVING - COIL										
Androtex	EZM - 1 (Prototype)	2	5	5	4	4	0	3	2	N
	Ruscan KCR-7	2 - 3	4	4	4	5	1	1	1	N
Apex Parametrics	MAXMIN 1 6...10	4	4	3 -4	2 -3	5	4 - 5	3 - 4	4 - 5	Y
Crone	CEM	3	3	3	4	5	1	3	2	N
Geonics	EM 31	1	5	5	4	5	0 - 1	3	2	Y
	EM 34-3	2 - 3	4	3	3	4	2	3	3	Y
	EM 38	1	5	5	5	5	0 - 1	2	1	Y
Instrumentation GDD	BM-II-94 (Beep Mat)	1	5	5	4	-	0	-	1	-
Scintrex	IGS-2/EM-4 Genie TM-2	3	3	3 - 4	3	4	1	2	2	Y
FIXED - SOURCE										
Androtex	ELFAST RTX/HL-3D	4	3	3	3	3	4	3	3	N
Electromagnetic Instruments	IMAGEM 1/1MTx	4 - 5	2 - 3	1 - 2	1 - 2	3	4	3 - 4	3 - 4	Y
Phoenix	V5 CSAMT/T-3	5	2	1	1	3	4	3	3	Y
Scintrex	IGS-2/EM-4/TF-2	4 - 5	3	4	2 - 3	4	3	3	3	Y
Terraplus	Melis/Tx 1000	5	3	2 - 3	1 - 2	2 - 3	4 - 5	4	3 - 4	Y
Zonge	GDP 16 - 32 CSAMT GGT 3 - 30	5	2 - 3	1 - 2	1 - 2	2 - 3	4 - 5	3 - 4	3 - 4	Y

Effectiveness Rating (1-5; poor - good)

Y - Yes
N - No

12.1.2 Ground Transient EM (TEM)

Transient EM (TEM) methods are being used increasingly for environmental applications. Twenty percent of the articles and theses included in the Selected References describe applications of TEM to problems similar to AMD. Discussions with a number of geophysicists working actively on AMD indicated a growing preference for having both sounding and profiling data at the start of an AMD mapping program. Unlike many environmental applications, AMD can seldom be solved simply by locating surface seepage. TEM, as well as multi-frequency FEM, can provide the required data in the vertical direction.

The questionnaire results indicate a 32% popularity for fixed loop TEM and 29% for moving-coil TEM. This is a bit misleading because, in fact, almost 50% of the respondents who use (or plan to use) one technique, also use (or plan to use) the other. In fact, the question was not very carefully posed, and some respondents may perceive a moving receiver as a moving coil system, in comparison with center-loop measurements where both the transmitter and receiver are fixed. Indeed, the authors are unaware of any strictly moving-coil TEM systems, although the Geonics TEM47, used with the Protem receiver, as well as the Zonge GDP/NT-20, the Crone PEM and the SIROTEM Mk3, can all be employed in the moving transmitter mode for profiling.

The majority of references to TEM for environmental applications, and all of the references to AMD applications have been with the Geonics TEM47. This instrument has developed from the TEM37, a transient EM system developed mainly for mineral exploration, with a turn-off time of 20-750 μsec. Early attempts to use this system for environmental work were unsuccessful because of its inability to sound to shallow depths. The TEM47, with a turn-off time of less than 2.5 μsec (in a 40 m x 40 m loop) and greater portability was designed specifically for "shallow geoelectric sounding looking for conductive contaminant plumes, saline intrusion or general stratigraphic mapping". It can be used with a 5 m x 5 m transmitting loop to sound in the top 40 m. This is the instrument that is referred to by Geomar (1991, 1992), Sinha (1993) and King (1994), relating to work in the Sudbury area, Ontario. Hanson et al (1993) refer to fixed-source TEM and surface-to-borehole TEM on an experimental program at the San Xavier Experimental Mine near Tucson, Arizona, using a Zonge GDP-32 FEM system. The objective was to monitor a buried plume during the injection of saline water at the mine.

TEM applications in Australia have been mainly with an early-time (Mark 3) version of the sirotem (Buselli et al, 1990), a system developed by the CSIRO division of Exploration Geoscience, North Ryde, NSW. The center-loop sounding technique is favoured for most of these applications. No reference can be found to any work directly for AMD. Zonge Engineering & Research Organization, Tucson, AZ, offers NanoTEM, an early-time version of its versatile GDP 16/32 TEM systems using the GGT fast turn-off (<10 μsec in a 100 m x 100 m loop) transmitter. For very shallow sounding a 1.5 μsec turnoff time can be obtained with a 20 m x 20 m loop. The Lamontagne UTEM has an effective start to its recording window of between 10 and 20 μsec with a 50 m x 50 m loop. Crone PEM allows for user-defined windows as short as 4.5 μsec anywhere in the transmitted wave form. With all of these instruments the main limitation is shallow resolution, favouring problems such as deep leakage plumes and multi-layer stratigraphic or groundwater studies.

Table 12.3 summarizes the effectiveness of the most commonly used ground TEM systems, as determined from information supplied and conversations with users. Readers are reminded that a high rating for certain categories (e.g. depth penetration) does not necessarily translate to a high effectiveness for AMD applications.

TABLE 12.3

Effectiveness of Ground Transient EM Techniques for AMD Related Applications

Supplier/ Manufacturer	Instrument	Depth Penetration	Resolution	Speed & Portability	Capital Cost	Profiling	Sounding	Conductivity Aperture	Interpret-ability	Software Support
Crone	PEM	5	2 - 3	4	1 - 2	3 - 4	5	4	4	Y
Geonics	PROTEM 47	4	4	4	3	4	5	5	4	Y
	PROTEM 37-3D	5	2 - 3	2	1 - 2	2	5	4	4	Y
	PROTEM 57-3D	5	2 - 3	3	2	2	5	4	4	Y
Lamontagne	UTEM-3D	5	2 - 3	3	1 - 2	2	5	5	4	Y
Sirotem	Mk3	5	4	4	-	1	5	5	4	Y
Zonge	GDP-16-32 with GGT-3-30	5	3 - 4	4	3	3 - 4	5	4 - 5	4	Y
	GDP-16-32 NanoTEM with NT-20	5	4 - 5	4	2	4	5	5	4	Y

Effectiveness Rating (1-5; poor - good)   Y - Yes   N - No

The relative merits of TEM and FEM have been debated in the scientific literature and both techniques appear to have their advantages and disadvantages. In electromagnetically "noisy" environments, such as around mines, FEM systems may have some advantage. Also, these systems tend to be lighter and more portable. On the other hand, proponents of TEM point to greater versatility and flexibility, greater conductivity apperature, few if any topographic corrections, and an ability to survey under highly conductive surface conditions. For practical purposes, it would seem that the question reduces to one primarily of depth and application:

1. For studies in the 0-10 m depth range where sounding is not essential, the FEM conductivity meters are the most cost-effective.

2. In the 10-50 m depth range where sounding as well as profiling is required, either the FEM Maxmin I, the TEM Protem47, or NanoTEM would seem to satisfy the requirement, with a slight edge to the TEM systems because better resolution can be obtained through a shorter coil separation.

3. For studies below about 50 m, and for shallower problems where resolution is very critical, TEM systems would appear to be favoured. In the vicinity of active mines or other industrial plants, FEM systems may be the only ones capable of operating.

Inversion of TEM sounding data can be done by a variety of commercially available software programs, including Interpex TEMIX, and CSIRO Grendl (Barber et al, 1991). The advantage of inversions rather than apparent resistivity or conductivity pseudo sections has been pointed out widely in the literature and has been demonstrated effectively by Barber et al (1991).

12.2 AIRBORNE SYSTEMS

Since most airborne geophysical surveys for AMD are done for the primary purpose of conductivity mapping, they belong in this section of the chapter, together with other electromagnetic methods. As mentioned earlier in the handbook, airborne EM is assuming a more and more important role in conductivity mapping for a number of environmental applications. King (1994) describes its specific application to AMD detection in the Sudbury area, but expands on its potential role in other environments. Cook and Kilty (1992) refer to a number of environmental applications of the Dighem system in Australia, some of them closely related to AMD. A symposium dedicated to airborne electromagnetics (including environmental applications) was held at the University of Arizona in September, 1993, in which a number of case histories were presented on applications very similar to AMD. It is evident that with the large bandwidth, multiple frequencies/coil pairs, and fast sampling rates available in state of the art helicopter EM (HEM) systems, there is very little that can be done on the ground that cannot be done equally or almost as well from a helicopter platform. The ability to record VLF EM, magnetometer and, if necessary, gamma-ray spectrometer, simultaneously, adds to the efficiency of these systems.

Table 12.4 lists five HEM systems and two fixed-wing time domain (TEM) systems that are currently available for airborne conductivity mapping. The fixed-wing systems differ mainly from the helicopter systems in their coil configurations and height. Because of the relatively large coil separations and survey heights (usually greater than 100 m), the resolution of these systems is subtantially less than that of the HEM systems which have coil separations in the 3-8 meter range and operate with a bird-height of about 30 m. Accordingly, fixed-wing EM applications have been limited to date to mapping conductivity on a fairly large scale. Duncan (1993/1) and Wolfgram (1993) describe some of these applications. The QUESTEM System in the SALTMAP configuration is capable of adequate resolution for problems such as reconnaissance mapping of leakage plumes or mapping groundwater conductivity, but probably only at depths greater than about 5 m. The GEOTEM system utilizes on-time measurements which enable mapping of conductivities in the range 0.07 to 10^4 mS/m. This should be suitable for detecting weak AMD in a very resistive background.

TABLE 12.4

Airborne Geophysical Systems Suitable for AMD Related Applications

Contractor/ System	FEM	TEM	VLF	Magnetometer	Gamma-Ray Spectrometer	Overall Effectiveness For AMD-Related Applications	No. of Frequencies/Channels No. of Coil Configurations
Helicopter							
Dighem	Y	N	TOTEM IIA	Scintrex CS-2	Exploranium GR-820	5	5 freq/coil pairs (220 Hz - 137.5 KHz)
Geonex - Aerodat	Y	N	TOTEM IIA	Scintrex CS-2	Exploranium GR-820	5	5 freq/coil pairs (45 Hz - 33 KHz; 4 KHz-120 KHz)
Geotech (HUMMINGBIRD)	Y	N	EH Multi-Spectral	Scintrex CS-2	Picodas	5	4 freq/coil pairs (400 Hz-60 KHz) (Miniature bird)
High-Sense Geophysics	Y	N	TOTEM IIA	Scintrex CS-2	Exploranium GR-820	5	5 freq/coil pairs (900 Hz-36 KHz)
SIAL	Y	N	TOTEM IIA	Scintrex CS-2	Exploranium GR-820	5	5 freq/coil pairs (900Hz-35KHz)
Fixed Wing							
Geoterrex GEOTEM	N	Y	N	Scintrex CS-2	Exploranium GR-820	2	128 windows in 4 channels (75 Hz-10 KHz), single coil pair
World Geoscience QUESTEM	N	Y	TOTEM IIA	Scintrex CS-2	N	3	SALTMAP: 4 channels (100 Hz-50 KHz), 3 coil pairs

Effectiveness Rating (1-5; poor - good)

Y - Yes
N - No

The HEM systems listed in Table 12.4 have roughly similar capabilities though some have been stretched in bandwidth to include special applications such as bathymetry and ice thickness mapping. For example, the Geonex-Aerodat system (Gamey and Holladay, 1993) is available in a low frequency configuration (45 Hz-33 KHz) for conductive environments and in a high frequency configuration (4 KHz - 120 KHz) for resistive environments. The Geotech Hummingbird (Morrison & Thuma, 1993) is a newly introduced, miniature system designed for small helicopter operations with a bandwidth sufficient to cover most operating environments. The spatial resolution of all of these systems is probably of the order of 10 m. Penetration depends upon the ground conductivity and for most environments will vary between 75 m and 250 m below ground. Changes will be visible from the ground surface downward. This range effectively covers most of the situations common to AMD.

Standard with the HEM systems is a cesium magnetometer (Scintrex CS-2) and a 2-channel VLF EM system (the Herz Totem IIA). Standard products include apparent resistivity maps, EM anomaly maps and profiles, VLF EM profiles and filtered contours, total magnetic field contours and a map of processed magnetic fields such as first vertical derivative. Some contractors (e.g. Fraser, 1993) offer further processing such as conductivity-depth sections and enhanced profiles designed to do such things as discriminate between flat lying and steeply dipping conductors. Multi-layer HEM inversion software is available in the marketplace (e.g. GIPSI AEMINV) and is also available through several of the contractors. As mentioned earlier in this handbook, inverted cross sections are an extremely valuable end product for problems such as AMD where it is important to know not only that a conductive plume exists but where in the section it is situated.

The magnetometer and processed magnetic products are useful in recognising geologic events such as intrusions (e.g. dykes) and faults in crystalline rocks that may affect the groundwater flow. The VLF EM data to some degree duplicates the higher frequency HEM data but differs in that it favours the larger and less conductive features that may not respond well to the HEM system.

No references have been found in the literature to the application of gamma-ray spectrometry to the mapping of radioactive mind effluents, though it seems likely that mining companies have conducted surveys for this purpose. Daughter products, principally radon, of the decay and leaching of primary radioelements in the mine wastes are known to produce measurable gamma-ray anomalies in the surface drainage to considerable distances from active and abandoned mines. The method is, in general, limited to surface drainage, rather than contaminated groundwater at depth. Since most uranium mines produce sulphides as a component of their wastes, any leakage is probably both conductive and radioactive. The relative merits of the airborne EM and gamma-ray spectrometry must be judged in each individual case.

The authors are of the opinion that airborne geophysical methods in general and HEM in particular will find increasing use in AMD-related problems in the coming years.

12.3 DC RESISTIVITY

DC resistivity is probably the earliest geophysical technique to be applied to environmental problems, references in the literature dating back to 1910 and earlier. Instrumentation is relatively simple, the basic configuration consisting of a battery, a switching device and a high impedence volt-ammeter. Today, a wide range of instruments are available, some designed specifically for shallow engineering and environmental purposes and others adapted from more deep-penetration mining and groundwater systems. The most common of these currently available are listed in Table 12.5. In addition, the IP/resistivity systems listed in Table 12.7 can also be used for shallow DC resistivity surveys.

TABLE 12.5

DC Resistivity Systems Suitable for AMD Related Applications

Supplier/ Manufacturer	Instrument	Depth Penetration	Separate Tx and Rx	Internal Memory	Speed & Portability	Capital Cost	SP Capability	Software Support
Bison	2350B	2 - 3	N	N	5	5	-	N
	2390	3 - 5	Y	N	3 - 4	3	Y	N
Geostudi	GRM 1000	3 - 4	Y	N	2 - 4	4 - 5	N	Y
	GRM 3000	4 - 5	Y	N	2 - 4	3 - 4	N	Y
Oyo	McOHM-2115A	3 - 4	N	Y	4 - 5	4	Y	N
	McOHM-21	3 - 4	N	Y	3	2	Y	Y
Phoenix	RV - 1/2 with RT - 1	3 - 4	Y	Y	3 - 4	2 - 3	Y	N
	RV - 1/2 with IPT - 1	5	Y	Y	3	2	Y	N
SAGA Geophysics	Sting R1	3 - 4	N	Y	5	4	Y	Y
Scintrex/ Campus	Geopulse/Square - 4	3 - 4	N	N	5	3	Y	Y
Soiltest	Strata-Scout W/R-27A	2 - 3	N	N	4 - 5	5	N	N
Terraplus	Terrameter SAS 300c	3	N	-	5	3 - 4	Y	N
	Syscal R1 & R2	4 - 5	N	Y	3 - 4	2 - 3	Y	N
Urtec/ Geoscan	RM-15 4000 (Frequency domain)	2 - 3	N	Y	5	4 - 5	-	Y

Effectiveness Rating (1-5; poor - good)

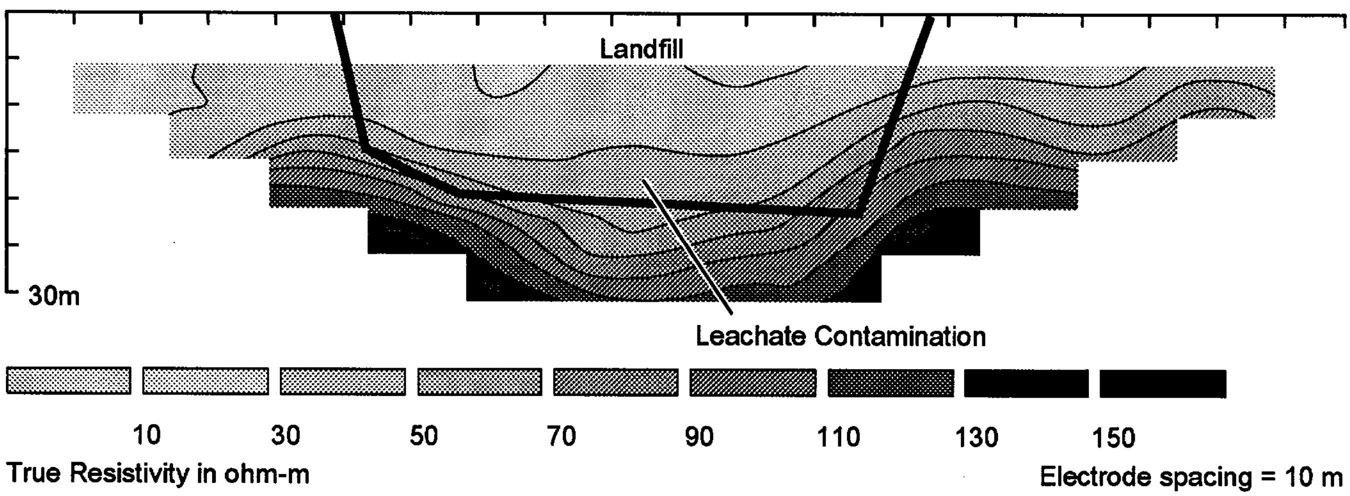
Y - Yes
N - No

The main difference between the systems currently in use lies in the current source or transmitter. Most of the instruments listed in Table 12.5 use a 12 v battery source, although several can be upgraded in power by the use of an auxillary engine-powered generator. Increasing power increases both the depth penetration and the measurement accuracy. In conductive environments more power is needed than in resistive environments. Manufacturers have gone to considerable pains to make their instruments user-friendly, with multi-channel capabilities enabling several electrode spacings to be measured at the same time, internal digital data storage and computer interfaces, adjustable averaging or stacking capabilities and so on. Some instruments have the ability to record self potential (SP) whereas others provide only for SP buckout. For AMD problems shallow penetration is satisfactory but, as demonstrated by Ebraheem et al (1990), in some cases large electrode spacings are necessary, requiring much higher power. Vertical electrical soundings (VES) generally require greater electrode spacings and correspondingly higher power than resistivity profiling, which is normally carried out at spacings just sufficient to penetrate to the depth of greatest interest. In selecting a resistivity system considerations should be given to the electrode configuration to be used. For Wenner or Schlumberger profiling or soundings a combined transmitter-receiver is convenient, whereas for dipole-dipole or gradient array profiling it may be more efficient to have a receiver that is not directly linked to the transmiter. The Bison 2390, SAGA and Geostudi intruments are of the latter type. The Phoenix RV-1/2 receivers are also used in this mode.

Multi-separation resistivity profiles are used to create pseudo-sections of apparent resistivity, based on simple approximations and plotting routines. These are usually adequate for locating conductive sources but fail to provide the spatial integrity needed for interpreting fluid pathways or planning monitoring drillholes. Inversion techniques such as the RES 2 DIM-2 program of Campus Geophysics and distributed by Scintrex Limited, Toronto (Diagram 12.1) produce cross-sections of true resistivity which come close to approximating the sub-surface stratigraphy/hydrology. DC resistivity instruments with internal memory and PC interfaces are essential to take advantage of available data enhancement, plotting and interpretation tools.

DIAGRAM 12.1

Landfill Site



This is a processed resistivity-depth section of a landfill site in an old sandstone quarry, the survey having been carried out to check for leakage of leachate from the fill. The section shows an area of low resistivity in the sandstone below 20 metres, the known depth to the quarry floor, clearly showing seepage of the low resistivity leachate.

DC resistivity can be used both for the direct detection of AMD (e.g. Ebraheem et al, 1990) or indirectly, as explained by Pehme, 1981, to determine the structure or architecture of the leakage area by virtue of the variations in conductivity of the underlying strata. For the latter purpose it would seem that DC resistivity has a distinct advantage over the EM ground conductivity meters and possibly (Stierman, 1984) some advantage over the multi-channel FEM and TEM fixed-source EM systems. The debate over the relative advantages of DC resistivity and EM will no doubt continue. The authors believe that there is a role for both methods.

12.4 GROUND MAGNETICS

As described by Roberts (1989), ground magnetometer data can be used for a variety of purposes in environmental applications. The most common is the direct detection of metal objects in the ground, which is not of concern in AMD. Indirect applications include the mapping of geologic boundaries and faults in crystalline bedrock that may affect groundwater flow. Clark (1991) describes the direct application of magnetics to the mapping of fluid migration pathways in high sulphide tailings ponds through the oxidation of pyrrhotite. Precise and detailed magnetic profiles can be modelled to provide information on depth as well as plan location, thereby assisting in the understanding of the active oxidizing regime.

Ground magnetometers are by far the most widely used ground geophysical instruments, having applications in all areas of exploration as well as engineering and archeology. Table 12.6 lists the more common instruments currently on the market together with some of their important characteristics. All of the instruments listed are based on proton-precession, Overhauser, or optical pumping (cesium) principles. These instruments have few mechanical parts and are generally light weight, rugged, automatic and easy to use. The main difference between one instrument and another lies in its resolution or sensitivity. These terms are confusing because they are used in different ways by different manufacturers. In general, sensitivity is taken to mean the smallest variation that the instruments will accurately record, leaving aside temporal variations in the earth's magnetic field. Sensitivities of today's magnetometers vary from 0.01 to 1.0 nT. For AMD purposes it would seem that a 0.1 nT sensitivity is appropriate, bearing in mind the type of variations one may expect from shallow pyrrhotite-rich wastes and the magnitude of geological anomalies in most crystalline rocks. This sensitivity is available in a wide range of inexpensive and user-friendly magnetometers.

Some of the instruments listed in Table 12.6 have the capability of measuring the vertical magnetic gradient, comprising the difference in total magnetic field between two sensors, usually spaced about 1 m apart on a hand-held staff. The vertical magnetic gradient emphasizes shallow sources and suppresses the broader effects from the underlying strata. For reconnaissance purposes, when looking specifically for shallow magnetic bodies, such instruments may have some advantage. For AMD, however, where magnetic surveys will probably be carried out on a closely spaced grid of stations, accurate measurements of total magnetic field are probably sufficient. The vertical magnetic gradient can be easily calculated off-line by a variety of computer software packages, most of which are available through the instrument manufacturers.

Magnetometers with internal memory are recommended since the data can be easily corrected for temporal variations by the use of a simultaneously recording magnetic base station. All of the magnetometers with internal memory have interface provisions for PC-based processing and interpretation packages such as the Geosoft Mapping System. Field-based PC and plotting hardware enable the surveyor to produce contour maps or colour images concurrently with the survey, thus facilitating fill-in or detail profiles over critical areas.

TABLE 12.6

Ground Magnetometers Suitable for AMD Related Applications

Supplier/ Manufacturer	Instrument nT	Total Field Resolution nT	Relative Sensitivity	Vertical Gradient Capability Portability	Speed &	Capital Cost	Software Support	Internal Memory
Bison	MMP-203	1.0	-	N	5	5	N	N
EG&G Geometrics	G-822L (Cesium)	0.1	-	N	5	3	Y	N
	G-856 (Proton)	0.1	-	Y	5	5	Y	Y
Geotech	M-1000 (Proton)	-	0.1	N	5	5	Y	Y
Scintrex	ENVI-MAG (Proton)	0.1	0.1	Y	5	5	Y	Y
	IGS-2/MP-4 (Proton)	0.1	0.1	Y	5	3 - 4	Y	Y
	OMNI MAG (Proton)	0.1	0.1	Y	5	4	Y	Y
	SMARTMAG (Cesium)	0.1	0.01	N	5	3	Y	Y
	M-200 (Proton)	-	0.5	N	4	5	N	N
Terraplus/ GEM Systems	GSM-8 (Proton)	0.5 - 1.0	1.0	N	5	5	N	N
	GSM-19 (Overhauser)	0.01	0.02	Y	5	3 - 4	N	Y
	GSM-19 (Proton)	0.01	0.2	Y	5	5	N	Y
Urtec/ Geoscan Research	FM-9	0.01	0.02	N	4	5	N	N
	FM-18	0.01	0.02	Y	5	4	Y	Y
	FM-36 (vertical component fluxgates)	0.01	0.02	Y	5	3	Y	Y

Effectiveness Rating (1-5; poor - good)   Y - Yes   N - No

The ground magnetometer has not seen widespread use in AMD studies to date, probably because its direct application is limited to pyrrhotite- or magnetite-rich mine wastes. Even then, it can only be applied to the actively oxidizing area rather than to the detection of leakage plumes. Nevertheless, it has much to offer in an indirect sense and should be considered on all AMD ground geophysical programs.

12.5 IP/RESISTIVITY

The induced polarization (IP) method has not been widely used for AMD or, for that matter, for any other environmental applications. Developed in the 1950's for base-metal exploration, the method responds primarily to disseminations of metallic particles in a medium of ionic current flow. This is not a target of much concern in most AMD problems though it has been shown recently (King, 1994 and Clark, 1991) that IP surveys over actively oxidized sulphide-rich tailings ponds can be helpful in determining the location and extent of acid-rich waste. The method also records electrical resistivity which is used to help interpret the IP source configuration but, in addition, provides some useful information, both direct and indirect, as explained in 12.3 above.

IP/resistivity instrumentation (Table 12.7) consists of two separate units: transmitters and receivers. Transmitters vary from small battery-powered instruments with an output of 1 or 2 amps to truck-mounted motor-generators with outputs of 20-30 kw. Most of the newer transmitters can provide a variety of wave forms, suitable for both time-domain and frequency-domain operations. The choice of transmitter is based largely on the depth of investigation, the lowest powered instruments being restricted, in most environments, to depths of the order of 30-50 m. Receivers, on the other hand, vary according to the complexity of the problem being studied. If the purpose of the survey is to map an IP boundary, without serious consideration of the nature of the IP source or its geometry, simple integrating or 2-frequency receivers may be adequate. Multi-channel or multi-frequency "spectral" receivers can be used to differentiate between different types of IP source, and also to assist in removing EM effects on deep-penetration surveys in conductive environments. These sophistications would not seem to be appropriate on AMD surveys. Other capabilities of the top-end receivers include provision for simultaneous recording of multiple electrode setups, and other features that are unlikely to be necessary on AMD surveys.

For most AMD problems, essentially dealing with mapping of tailings ponds, suitable instrumentation would probably consist of a transmitter in the power range 1000-3000 watts and a receiver with an internal memory and minor spectral capability. The Phoenix V-4, Zonge GDP-16 with GGT transmitter, Scintrex IGS-2/IP-4, Androtex TDR-4 and Terraplus ELREC 6 all appear to fall in this category.

IP/resistivity results are normally presented as pseudo-sections of apparent resistivity and IP effect (chargeability, percent frequency effect or phase) using simple approximations and diagramatic plotting techniques. These serve well for localising discrete IP sources but fail to provide the kind of information that an engineer requires for an assessment of a potential leakage problem under a tailings pond. One-dimensional inversion techniques have been used for resistivity for some time, and progress has been made in interfacing these with field-base data processing and mapping systems. The RES 2 DIM-Z package by Campus Geophysics is an example. More recently, inversion techniques have been extended to include IP. A very powerful software package DC IP 2D is currently being marketed by the Geophysical Inversion Facility of the University of British Columbia. This program generates cross sections of true resistivity and true IP effect based on readings taken with the dipole-dipole or pole-dipole electrode arrays. These cross sections, which can be sliced horizontally to produce contour plans or images at any depth, are ideal for engineering assessments of tailings pond conditions.

TABLE 12.7

IP/Resistivity Systems Suitable for AMD Related Applications

Supplier/ Manufacturer	Instrument Tx	Instrument Rx	Speed & Portability	Capital Cost	Spectral Capability	SP Capability	Software Support	Frequency or Time Domain
Androtex	STX-300	TDR-3	5	5	N	Y	N	FD & TD
	STX-10/15/20	TDR-4	3 - 4	3 - 4	Y	Y	N	FD & TD
	STX-7.5/15.0	TDR-6	2 - 3	2 - 3	Y	Y	Y	FD & TD
Phoenix	IPT-1	IPV-1	5	5	N	-	N	-
	300-3000W	V-2 (phase)	4 - 5	4 - 5	N	Y	Y	FD & TD
		V-4 (phase)	3 - 4	3 - 4	Y	Y	Y	FD & TD
		V-5 (phase)	2 - 3	2 - 3	Y	Y	Y	FD & TD
Scintrex	IPC-9	IPR-10A	5	4	N	N	Y	TD
	TSQ-2E	IGS-2/IP-4	3 - 4	2 - 3	Y	Y	Y	TD
	TSQ-3/4	IPR-12	2 - 3	2 - 4	Y	Y	Y	TD
Terraplus	VIP 3000	ELREC 6	5	2 - 3	Y	Y	N	FD & TD
Zonge	GGT-3/10	GDP-16-32	3 - 4	2 - 3	Y	Y	Y	FD & TD
	GGT-30	GDP-16-32	2	2	Y	Y	Y	FD & TD

Effectiveness Rating (1-5; poor - good)

Y - Yes
N - No

The IP method also responds to sources other than disseminated metallic particles. When ions pass through constricted passageways or at the boundaries of granular and clay-rich sediments polarization takes place that may be measurable in some cases on the ground surface. Referred to as "electro-osmosis" and "membrane polarization" these effects are normally smaller than those from metallic sources, but are often detectable in the absence of metallics. No reference has been found in the literature to the use of IP to detect conditions of this sort for the purpose of understanding the local geology/hydrology, though its potential application is outlined by Bisdorf (1985). It is not impossible, however, that the method will be used for this purpose at some time in the future.

Finally, an unusual mine-related application of IP has been described by Cahyna et al (1990) based on the discovery that cyanide contaminated sludge from a gold mining operation in East Bohemia produced strong IP effects. The discovery was made empirically on laboratory samples and no explanation is given for the effect. It raises the possibility, however, that IP may respond to other materials than sulphides in mine wastes. If these materials accompany acid drainage they could be used to trace drainage pathways.

12.6 SEISMICS

The seismic refraction method has been very popular for environmental and engineering studies since the 1930's. There are very few references, however, in the literature, to the application of seismic refraction or reflection to AMD problems. In this application, as pointed out by Dave et al (1986) the method is used indirectly to determine the structure or architecture of the ground in order to determine the pathways of fluid migration. Dave et al applied the method successfully at the Waite Amulet Mine, Noranda, Quebec, to identify four strata of different seismic velocity. Uppermost was an unsaturated, poorly consolidated layer of tailings; the second layer consisted of saturated tailings; the third was an impervious clay layer; the fourth was crystalline bedrock. In conjunction with ground conductivity and DC resistivity measurements the seismic data were able to define, with some accuracy, the hydraulic gradients prevailing in the area, indicating that the maximum fluid flow would be at the exits from the sides of the tailings dam. Snodgrass and Lepper (1993) describe similar studies at several mine sites in Western U.S.A.

In most respects the studies differ very little from the thousands of engineering studies conducted with seismic refraction and reflection over the past fifty or so years for designing dam sites, bridges, major foundations, excavations etc. all over the world. These studies have become more sophisticated in recent years with the advent of very high resolution, wide-band instrumentation capable of both refraction and reflection, together with newly developed techniques for 2-dimensional and 3-dimensional subsurface mapping. Borehole to surface seismic tomography (e.g. King et al, 1989) is also being used for environmental purposes but does not appear to have a direct application to AMD.

The limiting factor in applying seismics to AMD problems is the apparent lack of seismic velocity difference between contaminated waste and uncomtaminated waste. Unlike electromagnetics and DC resistivity, the seismic method would appear to be restricted to a supporting or indirect role. In this role, however, it has some advantages over electromagnetic and DC resistivity methods. Firstly, there are boundaries that exhibit seismic contrasts but no variations in electrical conductivity. More importantly, the seismic method is capable of considerably better resolution than either the electromagnetic or DC resistivity. Whether in the refraction or reflection mode, high resolution (16-24 bit) seismic instruments are capable of roughly 1 m vertical and 5 m horizontal resolution to depths of the order of 100 m. Even under favourable conditions neither the electromagnetic nor the DC resistivity method can approach this order of resolution.

Seismic performance, particularly on shallow surveys, play a very important role in both speed/cost and performance. Common sources include the shot-gun, the hammer, the weight drop and the standard explosive charge. Of these the shot-gun has become very popular because of its versatility (almost any ground conditions) and portability. Used in the stacking mode, its repeatability is not as good as the weight drop, but it can be used in many conditions where the hammer and the weight drop are ineffective. Explosive charges are not popular for most environmental applications since the survey areas tend to be built-up and there are often governmental restrictions on their use.

Table 12.8 lists the more common engineering seismographs but excludes the above-mentioned sources. The seismographs differ greatly in resolution and recording channel capability. There is a corresponding variation in cost. To achieve the resolution necessary for AMD studies an A/D resolution of at least 16 bits is probably necessary. For most applications, however, the recording channels may be as few as 12-24 without serious loss of efficiency. Seismographs are relatively complicated, electro-mechanical instruments, and prone to problems of cold-weather performance and damage through rough handling, moisture etc. The only reliable way to determine performance in these areas is experience.

All of the state-of-the-art seismographs provide internal or on-line computing support, enabling the user to obtain relatively quick visual verification of results. However, data enhancement, which may be necessary, depending upon the problem and the environment, must be carried out off-line. A variety of software packages are available for this task, including the Interpex Viewseis and Seistrix 3. Standard refraction processing software is included with most of the systems listed in Table 12.8.

12.7 VLF EM AND VLF RESISTIVITY

The VLF EM method is a rapid and inexpensive means of locating conductivity variations in the ground, using distant US naval radio transmitting stations as the electromagnetic source. These signals, in the frequency range 15-25 kHz, through both current channelling and inductive means, cause secondary electromagnetic fields that are measurable by relatively simple, portable EM receivers. Developed in the 1960's for mineral exploration purposes, the method has been used widely for reconnaissance exploration and geological mapping. Few references to VLF EM have been found in the literature, though the authors are familiar with programs that have been carried out for ground water exploration where the role of VLF EM was to map boundaries of intrusions and to locate faults. VLF EM instruments do not record the apparent resistivity of the ground. It is possible to obtain a pseudo-resistivity by horizontal integration of the inclination of the tilt angle of the measured VLF EM field (one of the parameters commonly recorded). This is a qualitative approach at best.

In the 1970's Geonics Limited introduced the EM-16R, a modification of the EM-16 electromagnetic receiver, utilizing two ground electrodes to provide a measure of the electrical field as well as the magnetic. With these two quantities an apparent resistivity (or conductivity) can be determined, together with the phase angle between the electric and magnetic fields. Using these parameters it is possiblel to obtain not only an approximation to the resistivity of the ground in the vicinity of the measuring station, but also an indication of whether the resistivity increases or decreases with depth. Charts are supplied to provide a semi-quantitative estimate of depth to the resistivity increase or decrease.

The VLF resistivity method, as it is now known, has been adopted by most of the other manufacturers, and has changed significantly the effectiveness of the method for environmental applications. Greenhouse et al, 1989, describe an application to the mapping of acid effluent from a refinery site in Breslau, Ontario. An excellent case history by Pehme, 1981, describes the application of the EM-16R to the mapping of a contam-

TABLE 12.8

Engineering Seismographs Suitable for AMD Related Applications

Supplier/ Manufacturer	Instrument	No. of Channels	A/D Resolution	Onboard PC and Internal Data Storage	Speed & Portability	Capital Cost	Software Support
Bison	24000 Series	12-120	24 bit	Y	5	2 - 4	Y
	9000-A DIFP Series	12-120	21 bit	Y	5	2 - 4	Y
	9000 DIFP Series	1-48	16 bit	Data storage only	4	4	Y
	7000 DIFP Series	1-24	14 bit	Data storage only	4	5	Y
	5000 DIFP Series	2-12	8 bit	Data storage only	4	5	Y
	1570C	1	-	N	5	-	Y
Geometrics	SmartSeis	12 - 24	16 bit	Y	5	4 - 5	Y
	StrataView	12 - 60	24 bit	Y	5	2 - 3	Y
	ES2401 Series	24 - 96	15 bit	Y	5	2 - 3	Y
	ES1225	1 - 12	8 bit	N	5	5	Y
Oyo Geospace Canada Inc.	Mc Seis - 170 F	12 - 24	20 bit	-	5	5	Y
	DAS-1	24 - 144	24 bit	Y	5	2 - 4	Y
Scintrex	S-2 Echo	12 or 24	12 bit	Y	5	5	Y
Terraplus	TERRALOC MK3	2 - 24	8 bit	Y	5	4	Y
	TERRALOC MK6	4 - 48	18 bit	Y	5	4	Y

Effectiveness Rating
(1-5; poor - good)

Y - Yes
N - No

ination plume from the Nordic tailings basin at Elliot Lake, Ontario. Pehme not only outlines the plume but calculates, with some accuracy, the specific conductance of the effluent. He concludes that the method, used in conjunction with DC resistivity and piezometric and geochemical studies, can be very effective in directing the monitoring of problem areas.

Among the difficulties of using VLF EM and VLF resistivity is the uncertainty of the primary signal. US naval transmitting stations have their own protocal for interrupting, scrambling and shutting off transmissions for maintenance etc. These interruptions can be troublesome if they occur during a survey. To help overcome this problem it is common to record two or more stations, if they are measureable in the survey area. Most of the instruments listed in Table 12.9 have this capability. A second approach is to supplement or replace the military transmitters with a transmitter dedicated to the particular receiver or receivers. Androtex and Geonics market such devices. This approach would appear to have significant advantages where the survey area is small (typical of AMD studies) and where the ability to move the transmitter for preferential coupling of structure may be important.

The newer VLF EM and VLF resistivity instruments have internal memory and lend themselves to both on-line and off-line data processing and compilation. A number of software programs are available to calculate filtered products such as the Fraser and Hjelt filters of the VLF EM field inclination for making plan maps or pseudo-sections. VLF resistivity data lends itself to immediate contouring and imaging of apparent resistivity. No software appears to be available at the present time for doing quantitative interpretation.

12.8 GROUND PENETRATING RADAR

Ground penetrating radar (GPR) is an electromagnetic technique useful for mapping layering in soils and rocks and for detecting underground objects due to changes in the electrical properties of materials. The frequencies employed are in the 10-1000 MHz range, which allows for higher resolution than other geophysical methods. The technique has been in existance since the late 1970's, but most of the major developments have taken place since about 1986. A good review of the method is given by Davis and Annan (1992), including several case histories of applications to mapping bedrock topography and stratigraphy. This function it can do with great precision (about 0.1 m) to depths in excess of 50 m in soils with low conductivity (less than 1 ms/m) in the frequency range 25-50 MHz. At lower frequencies and resolutions penetration can be increased correspondingly. In higher conductivity environments such as marine clays and saline soils penetration may be limited to 10 m or less. The method is very rapid, a profile at a 1 m station interval taking only 3-4 hrs per km to survey. Instruments are interfaced with PC's and mapping software, providing rapid verification and on-site enhancement and mapping facilities.

As a tool for mapping stratigraphy in the vicinity of AMD problem sites the GPR method would appear to be ideal though only one direct reference is found in the literature. Snodgrass and Lepper (1993) described GPR profiling at the Midnite Mine, Washington State, in conjunction with electromagnetic and DC resistivity surveys for the characterization of subsurface geology and hydrology. Apart from emphasizing the importance of an integrated approach, the authors give little information on the results. It seems likely that more work will be done with GPR on AMD applications in the future. There is also a direct application for GPR in AMD studies. Davis and Annan (1992) show an example of the direct detection and mapping of acid leachate (Diagram 12.2) at a landfill site where the soil is a fine sand of eolian and fluvial origins. The reflection at the top of the contaminant plume is believed to coincide with the sharp increase of electrical conductivity of the groundwater which strongly attenuates the radar signals. If this type of result can be obtained in other environments the GPR method would seem to have tremendous potential.

TABLE 12.9

VLF-EM Systems Suitable for AMD Related Applications

RECEIVERS

Suppliers/ Manufacturer	Instrument	Number of Frequencies	Self Orienting	Speed & Portability	Capital Cost	Software Support	Resistivity Mode	Memory
Geonics	EM16/EM16R	2	N	3	5	N	Y	N
Scintrex (EDA)	OMNI-VLF	3	Y	5	3	Y	Y	Y
Scintrex	VLF3/4	3	Y	5	3	Y	Y	Y
Terraplus	T-VLF	2	Y	5	3	Y	Y	Y
	WADI	1	Y	5	3	N	N	Y

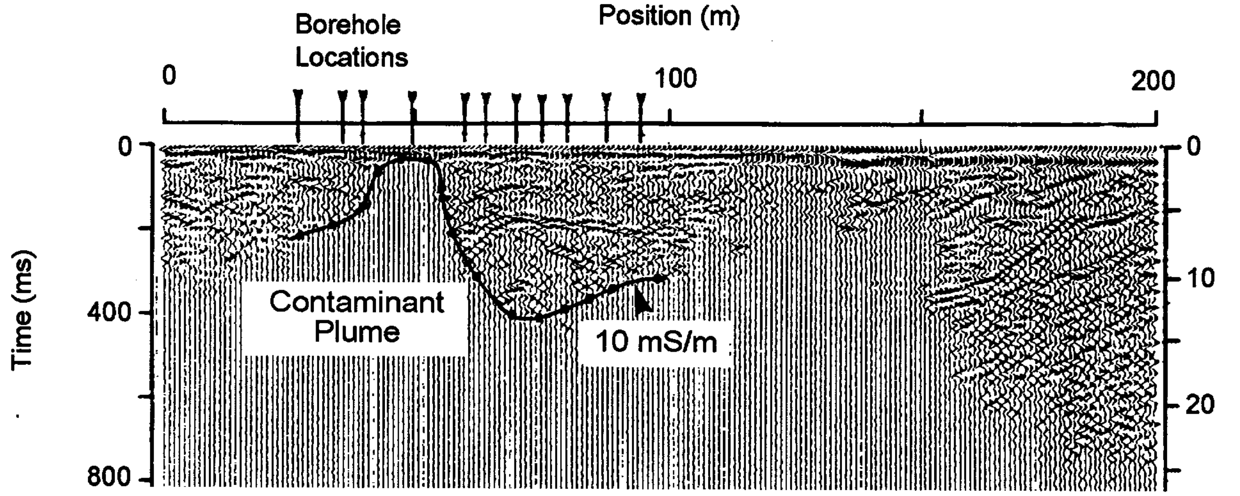
TRANSMITTERS

Suppliers/ Manufacturer	Instrument	Current	Multi Frequency	Speed & Portability	Capital Cost	Motor Generator Rq'd
Androtex	RTX-6D	7.5 A	Y	4	4	Y
Geonics	TX27	0-2 A	18.6 KHz only	4	4	Y

Effectiveness Rating (1-5; poor - good)

Y - Yes
N- No

DIAGRAM 12.2



Radar record along a survey line near a waste disposal site. The area below the 10 ms/m line is interpreted to be in the contaminant plume

Instrumentation for ground penetrating radar is obtainable from at least four suppliers, as shown in Table 12.10. Factors upon which to base the selection of equipment include portability, storage capability, real-time monitoring and on-site verification and processing. The choice of frequency range will depend upon the problem and the environment.

12.9 GAMMA-RAY SPECTROMETRY

Most uranium mines, as well as mines with uranium or thorium as accessory minerals, produce wastes that are to a greater or lesser extent radioactive. The daughter products from the decay of these radioelements migrate in the groundwater system, producing plumes with measureable radioactive content under the ground and in the surface drainage. Readers who are familiar with gamma-ray spectrometer maps of the Elliot Lake and Beaverlodge areas will be familiar with the anomalies recorded over the tailings piles and in the low-lying ground in their vicinity. Mapping these effluents by gamma-ray spectrometer would seem to be a simple and direct way of tracing the migration of solutes. As stated above in section 12.2, this may well be a role for airborne gamma-ray spectrometry, particularly in a repetative monitoring role. Such surveys are not in themselves aimed at AMD, but at the acid leachate that is produced by the sulphide-rich waste, a common by-product of uranium and thorium mining. It remains to be determined whether detecting the acid component by EM or DC resistivity methods is more effective than carrying out gamma-ray spectrometer surveys. Against the use of spectrometry is the fact that gamma-radiation can be masked by as little as 0.5 m of wet soil whereas conductivity changes may be detectable to 100 m or more. On the other hand, radon gas, a common daughter product in the radioactive decay chain, can migrate through both water and soil and produce measurable gamma-ray anomalies over buried radioactive sources. It is questionable, however, whether such a chain of migration paths would produce a reliable signature of a buried radioactive plume.

It is not surprising, therefore, that few references have been found to the use of gamma-ray spectrometry for AMD in the published literature. King and Pesowski (1993) show the results of a ground, total-count gamma-ray survey carried out in the vicinity of the Stanleigh uranium mine near Elliot Lake, Ontario, showing anomalies exceeding 5 micro-Rems/hr over a significant area around the Stanleigh Mine and in low ground 1-2 km to the east. These anomalies are not correlated in the report with groundwater conductivity.

TABLE 12.10

Ground Penetrating Radar Systems Suitable for AMD Related Applications

Supplier/ Manufacturer	Instrument	Frequency Range	Depth Penetration	Resolution	Speed & Portability	Capital Cost	Software Support
GeoRadar Inc.	Stepped FM GPR	100-1000 MHz	10m	4	4 - 5	5	N
Geophysical Survey Systems Inc.	SIR System 2, 2-M, 3	15-2500 MHz	50m+	5	4 - 5	3 - 5	Y
	SIR System 10, 10A, 10H	15-2500 MHz	50m+	5 (selectable)	4 - 5	2 - 4	Y
Sensors & Software Inc.	pulse EKKO IV	12.5-200 MHz	to 100m	5	5	3 - 4	Y
	pulse EKKO 1000	200-1000 MHz	10m	5	5	3 - 4	Y
Terraplus	Spectra - Mac	20-500 MHz	to 100m	5	4	3 - 5	Y

Effectiveness Rating
(1-5; poor - good)

Y - Yes
N - No

The instruments listed in Table 12.11 vary significantly in capability, both in sensitivity (crystal size) and in spectral capability (number of channels). For the purpose of reliably mapping radioactive mine effluent one should probably have some spectral capability, as demonstrated by the normalized gamma spectrum for uranium tailings presented by King and Pesowski (1993). It would not seem necessary, however, to have the full spectral capability of the GR-256/320 or the Vistaspec. On the other hand, internal data storage is an advantage.

The authors are of the opinion that more work needs to be done before the efficacy of gamma-ray spectrometry to AMD studies around radioactive tailings sites can be assessed.

12.10 SELF POTENTIAL

A Self Potential (SP) survey measures the DC potential between pairs of evenly spaced points on a survey grid (gradient mode) or between a stationary electrode and a single moving electrode (pole-pole array). In either case the result is a map showing the variations in electrical potential on the ground surface. These are caused by three natural geological conditions:

1. An actively oxidizing source such as a sulphide body.
2. A conductive body linking areas of different pH.
3. Movement of ionized groundwater.

Developed primarily for the first purpose, the SP method is extremely simple, consisting basically of a high-impedence voltmeter. Non-polarizing electrodes are also required, as they are in DC resistivity and IP/resistivity. SP can also be measured by most DC resistivity receivers and some IP/resistivity receivers (see Tables 12.5 and 12.7). Most of the surveys referred to in the literature, however, have been carried out with high impedance laboratory-type voltmeters. No table is included in this section since there do not appear to be any commercially available SP meters.

Corwin (1990) describes in detail the application of the SP method to environmental and engineering problems. He emphasizes the "streaming potential" or "electro kinetic" source of SP anomalies, which are of greatest interest for these applications. It should be noted that the SP method is the only geophysical method that responds to fluid flow and can point directly to a dynamic leakage problem as distinct from a static condition. Several authors have described the application of SP to detect leaks in reservoirs and dams. Bisdorf (1985) gives a good description of its application to the monitoring of reservoir leakage. Butler and Llopis (1990) give further detail on seepage detection at the Mill Creek Dam, Washington, the Clearwater Dam, Missouri and the Beaver Dam, Arkansas. Fixed SP electrode arrays were used to monitor temporal changes. The polarity of the anomalies indicated the direction of fluid flow, and distinguished them from geological effects.

Most authors agree that the SP method is under-used in environmental applications and has a definite role to play in studies involving fluid migration. It would seem to be a highly effective method for monitoring leakage around sulphide-rich tailings ponds.

12.11 GRAVITY

Gravity anomalies are produced by lateral variations in density in the subsurface or, putting it differently, lateral variations in depth to a boundary between strata of different density. Roberts (1989) reviewed applications of the gravity method to environmental and engineering studies and found that they had been almost exclusively for the the purpose of mapping bedrock topography. He applied the method at two landfill sites in Indiana and was able to map the thickness of the landfill by virtue of its density contrast with the underlying bedrock.

TABLE 12.11

Gamma Ray Spectrometers/Scintillometers Suitable for AMD Related Applications

Supplier/ Manufacturer	Instrument	Number of Channels	Detector Crystal Sizes	Internal Data Storage	Speed & Portability	Capital Cost	Spectrometer (Sp) or Scintillometer (Sc)	Software Support
Terraplus/ Exploranium	GR-256	256	0.35L	Y	4	3	Sp	Y
	GR-320 ENVISPEC	256/512	0.35L-8.4L	Y	4	2	Sp	Y
	GR-110	2	4.5 cu. in	N	5	5	Sc	N
Scintrex	BGS-4	1	-	N	5	5	Sc	N
	GRS-500	4	7.5 cu in	N	5	4	Sp	N
	GAD-6/GSP-45	4	22 cu in	N	4	3	Sp	N
	VistaSPEC	1024	3"x3", 2"x3"	Y	4	2	Sp	N

Effectiveness Rating (1-5; poor - good)   Y - Yes N - No

In other environmental applications gravity has been used to locate sinkholes in karst limestone, and shallow workings in abandoned coal mines.

It is difficult to visualize a direct application to AMD problems but several indirect applications are evident. Firstly, buried bedrock channels or paleochannels often serve as favoured pathways for groundwater flow. The presence of such channels under tailings ponds can act as leakage paths for acid drainage. Geomar (1992) carried out electromagnetic soundings at Fault Lake, Falconbridge, Ontario to detect such channels. Watzlaf and Ladwig (1987) carried out ground conductivity and DC resistivity surveys around six abandoned coal mines in west Virginia for the same purpose. Wolfe and Richard (1990) performed gravity and seismic surveys at the Cedar Bog wastesite in Ohio for 3-dimensional bedrock mapping.

For most of the gravity surveys mentioned above, standard gravity meters with a resolution of 10 microgal were used. Higher resolution meters (1-5 microgal) are available and have found some application in the so-called "micro gravity" mode for mapping sinkholes and buried cavities etc. The limiting factor in the use of instruments with the precision is the interference provided by density changes at or close to the ground surface. Transported overburden, in particular, is prone to strong lateral and vertical density variations. In steep topography the problem is still more serious. To effectively remove these near-surface gravity anomalies in order to see the horizon or target of interest is very difficult and may, in some instances, require simultaneous shallow seismics or GPR. In most cases this would negate the advantage of the low-cost gravity survey.

Table 12.12 lists the more commonly used gravity meters and some of the characteristics of significance in AMD-related applications. One parameter not listed is the operating range of the instrument, which is of not much importance in environmental studies. For most applications the Sodin Prospector 100-100T, the Scintrex CG-2 and the Lacoste and Romberg Model D/U would appear to be roughly equivalent. The automatic recording facility of the Scintrex CG-3 and its extra resolution, would be the next level up for more extensive and/or more precise surveys.

12.12 BOREHOLE GEOPHYSICAL SYSTEMS

As mentioned in the Preface to this handbook, borehole methods do not fall under the definition of "non-intrusive" methods, and are therefore outside the scope of the present study.

Borehole geophysical technology is well-advanced and a number of textbooks have been published on the subject. Since almost all surface geophysical methods can be applied in one form or another in boreholes, there is a correspondingly large number of instruments that perform both logging and exploration functions. A separate handbook would be required to do justice to these.

Readers interested in obtaining an overview of the application of borehole geophysics to environmental applications in general are referred to an excellent article by Mwenifumbo (1993) entitled "Borehole Geophysics in Environmental Applications". While he does not address specifically the AMD problem, he discusses methods of measuring such parameters as porosity, fracture intensity, density, water quality, fluid resistivity, Eh and pH and fluid flow. He discusses both the determination of the extent of contamination at existing sites and long-term monitoring of migration of contaminants. His article contains a brief but authoritative bibliography.

TABLE 12.12

Gravity Meters Suitable for AMD Related Applications

Supplier/ Manufacturer	Instrument	Resolution	Drift	Speed & Portability	Capital Cost	Software Support	Auto Levelling Option	Thermal Compensation Option
Terraplus/ LaCoste and Romberg	Model "U"	10 microgal	low	5	4	Y	Y	Y
	Model "G"	10 microgal	low	5	4	Y	N	Y
	Model "D"	1 microgal	low	5	4	Y	N	Y
Scintrex	CG - 2	10 microgal	low	3	5	N	N	N
	CG - 3 Autograv	5 microgal	low	5	3	Y	Y (std)	Y
	CG - 3M High Res.	1 microgal	low	5	3	Y	Y (std)	Y
W. Sodin (Gravity) Ltd.	Prospector 100, 200, Geodetic 100	10 microgal	low	3	5	N	N	N
	Prospector 100T, 200T	10 microgal	low	3	5	N	N	Y
	Geodetic 100-GT	5 microgal	low	5	5	N	N	Y

Effectiveness Rating (1-5; poor - good)

Y - Yes
N - No

Chapter 13

13.0 INFORMATION SOURCES

13.1 DATABASES

In order to conduct the literature search which resulted in the Selected References and General Bibliography in this handbook a number of databases were interrogated. Table 13.1 lists the library, the database and the contact person who assisted in the search.

Key words used in searching the above databases included most of the geophysical techniques and parameters as well as words such as acid, drainage, contaminant, and other words such as tailings relating specifically to AMD.

Published indexes of several professional societies were also reviewed in depth.

13.2 GENERAL BIBLIOGRAPHY

The above database search resulted in many hundreds of references, some dealing with geophysical methods with little or no relevance to AMD and others relating to AMD with no particular reference to geophysics. Some of these papers, however, provide useful background on AMD or geophysics and have been included in the General Bibliography following Chapter 14. A great many of the references in this bibliography deal with environmental applications of geophysics that are pertinent to AMD problems although they may have been applied to industrial waste seepage, saline fluid migration or other similar problems.

A number of the references in the general bibliography are from the Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP). These proceedings are published by the Environmental and Engineering Geophysical Society and do not appear to be referenced in any of the both databases. The SAGEEP Symposia take place every year and a Proceedings volume is published simultaneously. Copies can be obtained by contacting the Environmental and Engineering Geophysical Society, PO Box 4475, Englewood, CO, USA, 80155, (telephone 303-771-6101, FAX 303-843-6232).

13.3 LIST OF SELECTED REFERENCES

Most of the references quoted in the handbook were selected as being particularly pertinent to the present study and were reviewed individually by the authors. A list of these was compiled separately from the General Bibliography and is included in this chapter for convenient reference. A few references quoted in the text were obtained too late to be properly reviewed and are listed in the General Bibliography following Chapter 14.

Obtaining copies of some of the Selected References may be difficult as some of the publications are hard to locate. To assist readers in accessing the the Selected References, arrangements have been made by the MEND Secretariat, CANMET, for those articles dealing specifically with the mine environment to be included in the Laurentian University database, Laurentian University, Sudbury, Ontario. For copies readers may contact: Mr. Ron Slater, Laurentian University Library, Ramsey Lake Road, Sudbury, Ontario P3E 2C6, telephone 705-675-1151 (Ext. 3329), FAX 705-673-6524.

13.4 SUPPLIERS/ MANUFACTURERS/ CONTRACTORS

To assist readers in obtaining further information on instruments and services, a complete list of addresses and contact persons is included in this chapter following the Selected References.

TABLE 13.1

Summary Of Database Search

Library	Name of Database	Contact
Canada Centre for Remote Sensing operated by Horler Information Inc. Suite 1006, 131 Albert St. Ottawa, Ontario K1P 5G4	RESORS	Louis Marcotte Manager RESORS (613) 594-5155 Fax (613) 594-8679
Canadian Geocience Information Centre Energy, Mines and Resources Canada Geological Survey Of Canada Sector 350 - 601 Booth St. Ottawa, Ontario K1A 0E8	INSPEC COMPENDEX GEOSCAN GEOREF GEOARCHIVE	Sari Burgoyne Subject Specialist (613) 996-5259 Fax (613) 943-8742
CANMET Library Natural Resources Canada 555 Booth St. Ottawa, Ontario K1A 0G1	MINTEC MINPROC	Marg Ahearn Reference Librarian (613) 943-8773 Fax (613) 995-8730
Laurentian University J.N. Desmarais Library Ramsey Lake Road Sudbury, Ontario P3E 2C6	MINING ENVIRONMENT DATABASE	Ronald Slater Assist. Librarian, Technical Services (705) 675-1151 ext3329 Fax (705) 673-6524
State of California Department of Conservation Office of Mine Reclamation Reclamation Unit 801 K Street, MS 09-06 Sacramento, California 95814-3529	EPA AMD-GEOPHYSICS	Kit Custis Assoc. Engineering Geologist (916) 323-9976 Fax (916) 322-4862

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Chapter 14

14.0 CONCLUSIONS AND FUTURE DIRECTIONS

The present study describes ten ground geophysical methods, reviews briefly the pertinent airborne geophysical methods and mentions, but does not discuss in detail, borehole geophysical methods. Under each method the authors have attempted to identify the plus and minus factors for both direct and indirect AMD applications. In all cases, except self potential (SP), a table is given listing the more commonly used instruments in each category. Some measure of affectiveness for AMD applications can be obtained from the columns of these tables. An overall summary of applicability can be found in Table 11.2.

It would appear that EM methods will continue to be the most widely used for AMD studies, with future developments falling in two areas:

1. Increasing use of multi-frequency (FEM) or multi-channel (TEM) profiling and sounding techniques.

2. Greater use of available EM inversion techniques and the development of PC-based methods for producing true conductivity cross sections in the field.

Airborne electromagnetics, particularly helicopter EM (HEM), has been shown (King, 1994 and others) to be a very powerful technique for mapping both surface and underground acid leachate plumes. Ancillary devices on the helicopter platform produce useful information of an indirect nature. HEM surveys cover large areas at a relatively low unit cost and are therefore well suited to the primary identification of contaminated areas around existing mines. Ground studies will be required to pinpoint sites for borehole testing. An increase in use of HEM in AMD studies is almost certain.

DC resistivity methods will continue to play a useful role but will probably decrease in popularity at the expense of multi-frequency and multi-channel EM. Inferior lateral resolution, particularly at depth, appears to offset a somewhat better vertical resolution, particularly of resistive layers, near surface. Increase in the use of inversion techniques is forecast, with PC-based software making this possible in the field.

Ground magnetics has been shown to provide useful information on the boundaray between oxidized and unoxidized pyrrhotite-rich tailings. This application is worthy of further investigation.

The IP/resistivity method has seen little use in AMD studies but has shown itself to be capable of mapping fluid pathways in sulphide-rich tailings. There is a possible future application outside the tailings areas in the measurement of soil parameters that may be related to hydraulic conductivity. Further research is needed of these effects.

The seismic method plays a useful supporting role in determining the structure or architecture of the ground, particularly the location of buried bedrock channels and paleochannels.

VLF resistivity has been demonstrated to provide quick and accurate information on ground conductivity, with some sounding capability. An increasing use of dedicated transmitters is forecast. The method is unlikely to replace other types of EM.

A major increase in the use of ground penetrating radar (GPR) is forecast over the next few years. This extremely rapid (1-2 km/day) method is capable of very high resolution profiling of the subsurface to depths generally in the order of 20-60 m. In addition, it has been shown that the contaminant interface may be detectable where it occurs in contact with lower conductivity groundwater or unsaturated strata. This method would seem to be applicable to almost all AMD problems.

Gamma-ray spectrometry may be useful in some cases for mapping radioactive mine effluent with associated acidity. It is debatable whether the method can be as cost-effective as the ground conductivity meters.

The SP method is a much-maligned geophysical method, because of a somewhat checkered history in mining exploration. It does, however, have significant application to AMD studies, being the only geophysical method that will directly sense fluid movement. It has been used effectively to not only map active leakage paths but also to monitor the changes in fluid flow over a period of time. Improvements in this technology may be expected.

The gravity method will continue to play a supporting role in mapping bedrock topography.

This handbook has not dealt specifically with borehole geophysical methods but some sources of information have been given. The subject is worthy of a separate study.

In conclusion, it is apparent that geophysical methods can play a very important role in AMD studies. This conclusion is supported by a significant body of information. It is hoped that corporations and agencies responsible for conducting the studies will have the vision and courage to supplement the traditional methods of drilling and piezometric/chemical monitoring with airborne, ground and borehole geophysical techniques. If there is one point of consensus in the literature reviewed in this study it is that integration of techniques is essential for a well-rounded and efficient program. Wisdom and experience will be required to put these together.

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Appendix A

QUESTIONNAIRE

Review of State of the Art Methods for the Remote Detection of Acid Mine Drainage

PART 1: REMOTE SENSING

Name: ______________________________

Job Title: ______________________________

Organization: ______________________________

Address: ______________________________

____

____

Telephone: ______________

Fax: ______________

1. Are you familiar with the use of remote sensing for:

- ❑ Mineral exploration
- ❑ Geologic mapping
- ❑ Mapping and identification of waste rock piles and tailing ponds
- ❑ Geobotany
- ❑ Monitoring and change detection

2. Does your organization currently use or have used remote sensing technology

❑ Yes ❑ No

If yes, indicate which data source(s) you are using:

Satellite Data:	Airborne Scanner Data:
❑ MSS (Multispectral)	❑ CASI
❑ TM (Thematic Mapper)	❑ MEIS II
❑ SPOT (Multispectral)	❑ Daedalus
❑ SPOT (Panchromatic)	❑ AIS
❑ ERS-1 (Radar)	❑ TIMS
❑ NOAA AVHRR (Thermal)	❑ AVIRIS
❑ Other _______	❑ Other _______

Indicate Application(s):

- ❑ Mineral Exploration
- ❑ Geologic Mapping
- ❑ Mine Site Mapping
- ❑ Detection of Acid Mine Drainage
- ❑ Geobotany/Detection of Stressed Vegetation
- ❑ Land Reclamation
- ❑ Change Detection
- ❑ Planning
- ❑ Land Use/Land Cover Mapping
- ❑ Other ________________

Please provide additional application information if available:

____

____

____

____

If no, are you planning to investigate the potential of remote sensing technologies in the near future?

❑ Yes ❑ No

If yes please answer the following:

Data source(s) you would consider using:

Satellite Data:	Airborne Scanner Data:
❑ MSS (Multispectral)	❑ CASI
❑ TM (Thematic Mapper)	❑ MEIS II
❑ SPOT (Multispectral)	❑ Daedalus
❑ SPOT (Panchromatic)	❑ AIS
❑ ERS-1 (Radar)	❑ TIMS
❑ NOAA AVHRR (Thermal)	❑ AVIRIS
❑ Other _______	❑ Other _______

Possible Application(s):

❑ Mineral Exploration
❑ Geologic Mapping
❑ Mine Site Mapping
❑ Detection of Acid Mine Drainage
❑ Geobotany/Detection of Stressed Vegetation
❑ Land Reclamation
❑ Change Detection
❑ Planning
❑ Land Use/Land Cover Mapping
❑ Other ________________

Please provide potential application details if available:

____
____
____

3. Is your organization currently using satellite and/or airborne remote sensing for environmental monitoring at operational and/or abandoned mine sites

❑ Yes ❑ No

If yes, please provide details

____
____
____
____

If no, are you interested in remote sensing techniques that could be used to detect and monitor acid mine drainage?

❑ Yes ❑ No

4. Would you be prepared to supply an example from a case history that could be included in the Acid Mine Drainage Monitoring Handbook?

____
____
____
____

5. Has your organization produced any published or unpublished literature on methods or applications relevant to Acid Mine Drainage detection?

❑ Yes ❑ No

If yes, please provide references or return reprints with your questionnaire.

If literature is extensive, who may we contact in your organization for further information?

PART II: GEOPHYSICS

Review of State of the Art in Methods for the Remote Detection of Acid Mine Drainage

Name: ______________________________

Job Title: ______________________________

Organization: ______________________________

Address: ______________________________

____

Telephone: ____________________

Fax: ____________________

1. Are you familiar with the use of geophysics for:

- ❑ Mineral exploration ÷ ❑ Geotechnical applications
- ❑ Geological mapping ÷ ❑ Contamination studies
- ❑ Hydrogeology ÷ ❑ Ice thickness or bathymetry

2. Does your organization currently use or have used geophysical technology?

❑ Yes ❑ No

If yes, indicate which method(s) you are using:

Ground

- ❑ Magnetics
- ❑ Gravity
- ❑ IP/resistivity
- ❑ Resistivity
- ❑ Seismics
- ❑ Magnetotellurics
- ❑ Electromagnetics
- ❑ Gamma-ray spectrometry (radiometrics)
- ❑ VLF EM
- ❑ Self Potential
- ❑ Ground Probing Radar
- ❑ Other__________________

Airborne

- ❑ Magnetics
- ❑ Electromagnetics
- ❑ Gamma-ray spectrometry
- ❑ VLF EM
- ❑ Other______________________

Indicate Applications:

- ❑ Mineral exploration
- ❑ Geological mapping
- ❑ Mine tailings
- ❑ Industrial waste management
- ❑ Acid mine drainage
- ❑ Construction/engineering
- ❑ Permafrost
- ❑ Groundwater exploration
- ❑ Salt mapping
- ❑ Ice thickness
- ❑ Bathymetry
- ❑ Contaminant plumes
- ❑ Buried artifacts
- ❑ Other __________________

If you are using (or plan to use) geophysics for Acid Mine Drainage, Mine Tailings or Contaminant Plume studies, which of the following techniques have you employed (or do you plan to employ):

Magnetics
- ❑ Airborne total field
- ❑ Airborne vertical gradient
- ❑ Ground total field
- ❑ Ground vertical gradient
- ❑ Borehole

Electromagnetics
- ❑ Fixed-wing airborne
- ❑ Transient
- ❑ Frequency domain
- ❑ Helicopter airborne
- ❑ Transient
- ❑ Frequency domain
- ❑ Ground
- ❑ Fixed loop transient
- ❑ Fixed loop frequency domain
- ❑ Moving coil transient
- ❑ Moving coil frequency domain
- ❑ EM 31
- ❑ EM 34
- ❑ MAXMIN
- ❑ Other____________________
- ❑ Borehole

Gamma-Ray Spectrometry
- ❑ Fixed-wing airborne
- ❑ Helicopter airborne
- ❑ Ground
- ❑ Marine
- ❑ Borehole

Gravity
- ❑ Standard precision (0.01 mgal)
- ❑ Micro-gravity (<0.005 mgal)

VLF EM
- ❑ Fixed-wing airborne
- ❑ Helicopter airborne
- ❑ Ground
- ❑ Other____________________

IP/Resistivity
- ❑ Soundings
- ❑ Profiling
- ❑ Dipole-dipole
- ❑ Pole-dipole
- ❑ Wenner
- ❑ Borehole

Resistivity
- ❑ Soundings
- ❑ Profiling
- ❑ Dipole-dipole
- ❑ Pole-dipole
- ❑ Wenner
- ❑ Borehole

Self-potential
❑ Moving pole
❑ Moving dipole
❑ Borehole

Ground Probing Radar
❑ Surface
❑ Borehole
Specify model and bandwidth________________________

Seismics
❑ Reflection
❑ Refraction
❑ Continuous wave (e.g. Vibroseis)
❑ Underwater profiling
❑ Borehole
❑ Tomography
❑ Other________________________

Magnetotellurics
❑ MT
❑ AMT
❑ CSAMT

List any other techiques that you are using or plan to use in the near future:

____
____
____

3. Is your organization currently using geophysical methods for environmental monitoring at operational and/or abandoned mine sites.

❑ Yes ❑ No

If yes, please provide details.

____
____
____

If no, are you interested in geophysical techniques that could be used to detect and monitor acid mine drainage?

❑ Yes ❑ No

4. Would you be prepared to supply an example from a case history that could be included in the AMD Monitoring Handbook?

____
____
____

5. Has your organization produced any published or unpublished literature on methods or applications relevant to AMD detection?

❏ Yes ❏ No

If yes, please provide references or return reprints with your questionnaire.

____

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____

If literature is extensive, who may we contact in your organization for further information?

____

____

____