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A small discussion on microwave application for groundwater exploration: A review

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ABSTRACT

This review article presents the electromagnetic (EM) technique are the most common implemented methods by geophysicist for mineral exploration. The use of EM technique in environmental and engineering application is also established, especially in detection of contaminant plumes and exploration of waste sites in recent. Throughout the globe, the EM is used for groundwater related studies along with its mother work in mineral exploration. Airborne EM is appropriate for large scale and efficient groundwater surveying. Due to dependency of the electric conductivity on different material present (as clay, rock, water, sand) in the host body and the mineralization of the water. EM system are suitable for providing information of the aquifer structure, and water quality respectively.

Keywords: Electromagnetic technique, ecology, geology, oceanography.

1. Introduction

This review article presents the current status of Electromagnetic (EM) parameters for various key issues within the disciplines of ecology, geology, hydrology, and oceanography. The electromagnetic (EM) technique are the most common implemented methods by geophysicist for mineral exploration. The use of EM technique in environmental and engineering application is also established, especially in detection of contaminant plumes and exploration of waste sites in recent as well in groundwater exploration. There are space-borne and ground based EM system as well. Radars (SAR-synthetic aperture radar) work on C and X band of microwave region are first multi frequency and multi polarization system launched into space with the advancement of technology in Radar remote sensing and verification of earlier findings with NASA/CSA-SAR missions.

The limitation present in resolution and penetration depth of frequencies in present time frame of knowledge will be ruled out in future. GPR (ground penetrating radar) is a surface geophysical technique that can provide high resolution images of the dielectric properties of the top few tens of meters of earth. Radar data can be used to detect contaminants in application field of hydrology. The presence of liquid organic contamination, due to dielectric property differences from the other solid and fluid components in subsurface. The resolution of radar imaging methods is such that it might be used for development of hydrogeological models of subsurface, required to predict the fate and transport of contaminants. GPR images are interpreted to obtain a model of the large scale design of the undersurface and assist in estimating hydrologic properties, like water content, porosity, permeability etc. It’s non-surgical capacity make GPR alternative to the traditional methods used for subsurface characterization.

1.1 Space-borne microwave

The Spaceborne Imaging Radar-C, X-Band Synthetic Aperture Radar (SIR-C/XSAR) was the first multi-frequency and multi-polarization SAR system to be launched into space. Two-frequency radar SIR-C, which simultaneously acquires polarimetric C-band (5.8 cm wavelength/5.1GHz) and polarimetric L-band (23.5 cm wavelength/1.27GHz), X-SAR operates at X-band (3.1 cm wavelength/9.67GHz) and vertical polarization (VV). SIRC/ X-SAR, the most advanced imaging radar system flowing in Earth orbit, was carried in the cargo bay of the Space Shuttle Endeavour in April and October 1994, imaging over 300 sites around the Earth and returning 143 terabits of data (Evans et al. 1996). The advancement of knowledge in the field of radar remote sensing accomplished in the last eight years, as well as the verification of earlier findings since the two successful SIR-C/X-SAR missions have been tremendous. Results clearly show the increased value of using multi-parameter and interferometric capabilities to characterize the Earth's surface and vegetation cover, and to generate geophysical products, compared with optical sensors or single-channel radars alone.

1.2 Ground-borne microwave

Another advancement that technology had made in microware is a portable system GPR. Ground penetrating radar (GPR) is a geophysical tool that can provide high resolution three-dimensional images of the subsurface of the earth. Advances in radar technology over the past 10 to 15 years have led to its widespread use for imaging the top tens of meters of the earth. Digital radar systems are now available with a range of capabilities and are used for many varied applications including the assessment of groundwater resources, mineral exploration, archaeological studies and environmental applications. The GPR is most likely to lead a role of leader in the field of contamination and hydrology .With any direct sampling method only a limited volume of the subsurface is sampled, and there is always the inherent risk of contacting or further spreading the contaminant. GPR thus has tremendous appeal as a noninvasive means of imaging the subsurface. In addition to the radar method that operates from the earth's surface, borehole radar systems are also available, where the subsurface is sampled using new or existing boreholes.

GPR is an imaging method that utilizes the transmission and reflection of high frequency (1 MHz to 1GHz) electromagnetic (EM) waves within the earth. Descriptions of the fundamental principles can be found in publications by Daniels et al (1988) and Davis & Annan (1989). A standard GPR survey is conducted by moving a transmitter and receiver antenna, separated by a fixed distance, along a survey line. The pair of antennas is moved to stations (measurement locations) with the spacing between stations determined by the survey objectives. At each station, a short pulse or "wavelet" of EM energy is sent into the earth by the transmitter antenna. The GPR wavelet contains a number of frequencies, but is usually referred to by the center frequency of the antennas, most typically 50, 100, 200, or 400 MHz. The reflected energy returned to the earth's surface is recorded at the receiver antenna. The GPR image is a representation of the interaction between the transmitted EM energy and the spatial variation in the complex, frequency-dependent EM properties of the earth: the dielectric permittivity, the electrical conductivity , and the magnetic permeability.

In the last decade there has been a tremendous revival of interest in the use of EM techniques for environmental applications due to their improved spatial resolution and low costs.

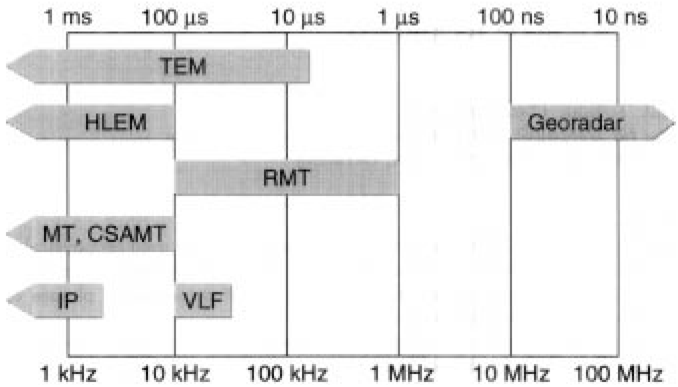

Figure 1: Frequency and time range of some EM-techniques

In figure 1 the frequency ranges of some EM methods are shown. Usually Controlled Source Audiomagnetotellurics (CSAMT) and Horizontal Loop EM (HLEM) systems operate below 10 kHz, but 'Stratagem' system (Geometrics) can observe transfer functions up to 70 kHz. The conventional VLF has a limited frequency range (10 kHz–30 kHz). RMT (10 kHz–1 MHz) is between VLF and conventional Georadar, but there still remains a gap (1–10 MHz) in the 1–10 MHz frequency band are available from existing radio transmitters or can easily be generated by using controlled sources, but placement currents cannot be neglected in this frequency range. Theoretical aspects and solutions for this case have been presented by Kaufman and Keller (1983), Zhdanov and Keller (1994) and recently by Song et al. (1997). Unfortunately, there is no instrument available to cover the whole frequency range. The transient EM (also known as time domain EM) instruments measure the decay of eddy current in the time range of 5µs to 100 ms depending on the type of instrument. This corresponds to an investigation depth between several meters to several hundred meters depending on the conductivity of the earth. The application of EM methods and other near surface (0–200 m) geophysical techniques for the solution of problems in archaeology, engineering science, groundwater exploration, detection of contaminant plumes, and buried unknown waste sites has three distinguishing characteristics not shared with regional geophysics (Butler et al., 1997).

The EM surveys carried on ground should have fulfilling these 3 conditions especially for the hydrological studies.

1. Very high resolution surveys.
2. Public health and safety concerns.
3. Near real time validation.

2. Air-borne Microwave

Helicopters are used than fixed-wing systems in airborne surveys esp. for the groundwater exploration projects. Helicopter-borne frequency-domain electromagnetic (HEM) systems use a towed rigid-boom. Helicopter-borne time-domain (HTEM) systems, which use a large transmitter loop and a small receiver within or above the transmitter, are generally designed for mineral exploration purposes but recent developments have made some of these systems usable for groundwater purposes as well. The quantity measured, the secondary magnetic field, depends on the subsurface conductivity distribution. Due to the skin-effect, the penetration depths of the AEM fields depend on the system characteristics used: high-frequency data/early-time channels describe the shallower parts of the conducting subsurface and the low-frequency data/late-time channels the deeper parts. Typical investigation depths range from some ten metres (conductive grounds) to several hundred metres (resistive grounds), where the HEM systems are appropriate for shallow to medium deep (about 1–100 m) and the HTEM systems for medium deep to deep (about 10–400 m) investigations. Generally, the secondary field values are inverted into resistivities and depths using homogeneous or layered half-space models. As the footprint of AEM systems is rather small, one-dimensional interpretation of AEM data is sufficient in most cases and single-site inversion procedures are widely used. Laterally constrained inversion of AEM data often improves the stability of the inversion models, particularly for noisy data. Based on typical field examples the advantages as well as the limitations of AEM surveys compared to long-established ground-based geophysical methods used in groundwater surveys are discussed. In a case history from a German island an airborne frequency-domain system is used to successfully locate freshwater lenses on top of saltwater. An example from Denmark shows how a time-domain system is used to locate large-scale buried structures forming ideal groundwater aquifers (Bulent,1999).

Large-scale groundwater surveys increasingly apply airborne geophysical methods in order to investigate huge areas in reasonable time and at relatively low costs. From the most common airborne methods currently utilized – magnetics, radiometrics and electromagnetics, which are generally used simultaneously – airborne electromagnetics (AEM) contributes most to groundwater exploration purposes due to the dependency of the electrical conductivity on (a) the salinity of the groundwater, i.e., the groundwater quality, and (b) the clay content of the subsurface, i.e., the aquifer conditions and protection level (Kirsch 2006). The application of geoelectrical and electromagnetic methods on ground (McNeill 1990; Binley and Kemna 2005; Everett and Meju 2005; Ernstson and Kirsch 2006) has a long tradition in groundwater exploration. AEM, however, was introduced for mineral exploration and as compared to this, the airborne groundwater exploration is very new. Although the first tests on the applicability of airborne systems for hydrogeological investigations date back to 1965 (Baudouin et al. 1967; Collett 1967), when airborne geophysics was not a sufficient tool for groundwater exploration at that time. One of the first successful groundwater investigation surveys was conducted on the island of Spiekeroog, Germany, in 1978 (Sengpiel and Meiser 1981) using an early HEM system (DIGHEM II, Fraser 1972) operated by the German Federal Institute for Geosciences and Natural Resources (BGR). Paterson and Bosschart (1987) and Sengpiel and Fluche (1992), showed examples of the early times of airborne groundwater exploration. Airborne EM data is also valuable for delineating special aquifer structures such as fault zones (e.g., Siemon and Greinwald 2004) or buried valleys (e.g., Eberle and Siemon 2006; Christiansen et al. 2006). Due to their mapping and sounding facilities AEM data are suitable for 3D modelling, not only for resistivity modelling but also for geological and hydrogeological modelling (e.g., Bakker et al. 2006; Rumpel et al. 2006; Scheer et al. 2006). Recently, airborne EM data have gained increasing importance for salinity mapping, spatial planning and land use management purposes strongly associated with groundwater resources.

2.1 Model on hydro geological and contamination

Using radar data to develop a model of the subsurface can be described as involving two stages of characterization. The first is to obtain a model of the three-dimensional architecture of the subsurface region of interest. This involves mapping out geologic units at a scale of meters to 10’s or 100’s of meters (Area of Interest) and identifying any large-scale features, such as the water table, faults, or fractures, that are critical to the fluid transport model. In order to use such a model to predict transport, hydrogeologic properties such as porosity, water content, and permeability etc need to be determined. The second stage in characterization is to use the radar data to assist in obtaining estimates of these properties that can then be assigned to regions within the large-scale model. Many EM methods /instruments used for mapping near surface geology exist and nowadays they play a central role in environmental geophysics.

Once the location of subsurface contamination has been identified, the transport model derived with above said methods is used to study the flow of contaminants from surface to subsurface region. The contamination would be verified using either direct sampling or geophysical methods, decisions must be made about the short term and long-term strategies for dealing with the contaminated region. The various options can include physically removing contaminated materials, treating the contaminant in situ, physically isolating the contaminant through the use of impermeable barriers, and electing to do nothing. (The "do nothing" option does not necessarily imply no positive change in the state of the contaminated region as natural processes of biological breakdown of the contaminant, referred to as bioremediation or natural attenuation, can occur.) Assessment of these various options generally involves the development of a model of the subsurface that can be used to predict the fate and transport of the contaminant. Given the large volume of data required to develop an accurate model of the subsurface, and the limitations of direct sampling, the use of geophysical methods can contribute significantly to the challenge of obtaining information about the subsurface.

3. Hydrology

The hydrological cycle is very crucial part as it is directly and indirectly the climate generator of Earth. It has two components

(1) the ocean- continent water and energy exchange due to the global circulation; and
(2) the continent-internal energy- water interactions, which change in response to land surface management practices.

Soil moisture is an environmental descriptor that integrates much of the land surface hydrology. Only microwave data have demonstrated the ability to measure soil moisture quantitatively, under a variety of topographic and vegetation cover conditions (Engman and Hall et al. 1995). Temporal changes in the distribution and volume of glaciers and ice sheets are good indicators of climate trends. Seasonal snow cover and alpine and himalyan glaciers are the largest contributors to the ground-water recharge in many parts of the world. Multiparameter radar data have shown sensitivity to snow wetness with an absolute error of 2.5 % by volume at a 95 % confidence interval (Shi and Dozier 1995). Good agreement was found for the mass balance estimated with SIR-C/XSAR data and the field measurements carried out at two Alpine glaciers (Rott et al. 1996).

Table 1 lists the current SAR requirements for hydrological and glaciological applications. The table illustrates the need for long wavelengths for soil moisture mapping. Polarimetric data are necessary for snow and ice volume estimations. Short wavelengths are required to map snow and ice extent. The requirements can be summarized as follows

(1) P-band is the best choice for soil moisture mapping, because of its penetration
(2) through the vegetation layer;
(3) Polarimetric L-band is needed to model the volumetric water content of snow;

(4) Polarimetric X- or C band are required to map the snowpack extent, best discrimination of mountain glaciers is cross polarized X- and L-band.
(5) Polarimetry and multifrequency are required for ice mapping.

Table 1: Optimal SAR parameters for hydrological, glaciological and geological applications

Discipline	Research topic/ operational application	X hh	X vv	X cr	C hh	C vv	C cr	L hh	L vv	L cr	P hh	P vv	P cr
HYDRO	Soil moisture/ Texture	—	—	—	▽	▽	▽	●	●	●	○	○	○
	Salinity mapping	—	—	—	—	—	—	●	●	—			
	Soil surface roughness	▽	▽	▽	▽	▽	▽	●	●	●	▽	▽	▽
	Land-water boundaries/ flooding	—	—	—	▽	▽	—	●	▽	—	●		
ICE	Snowpack extent	✧	✦	●	✧	✦	▽	▽	▽	▽	—	—	—
	Snow wetness/ water equivalent	●	●	●	●	●	●	●	●	●			
	Mountain glaciers	✧	✦	●	▽	▽	▽	✧	✧	✧	✦	✦	✦
	Sea ice discrimination	✧	✦	▽	✧	✦	▽	✧	✦	▽	—	—	—
	Ice sheets and shelves	✧	✧	✧	✦	✦	✦	✧	✦	●	✧	✦	●
	Iceberg monitoring	✧	✦	●	✧	✦	●	—	—	—	—	—	—
Geology	Lithological mapping	✧	✦	●	✧	✦	●	✧	✦	●	○	○	○
	Tectonics	●	▽	●	●	▽	●	●	▽	●	—	—	—
	Geomorphic process/roughness	●	●	●	●	●	●	●	●	●	○	○	○
	Sand dune morphology	●	●	—	●	●	—	—	—	—	—	—	—
	Arid land studies	▽	▽	●	▽	▽	●	●	—	●	●	▽	▽
	Sand penetration/subsurface mapping	✧	✦	▽	✧	✦	●	✧	✦	●	✧	✦	●
	Paleodrainages	—	—	—	▽	—	▽	●	▽	●	●	▽	●

Table 2: Symbols used in Table 1

● : Very Important	○ : important frequency, no specific polarization
✧ : Moderately Important ✦ : Less Important	⟠ :only one of the polarizations is required, ⊗ : polarimetry is required, but only One of the two frequencies
▽ : helpful, — : not mandatory	No symbol: No information

(Symbols used in tables: As noted above, superscript numbers refer to SIR-C/X-SAR investigators, superscripts are used in the text, hh and v v stand for horizontal and vertical co-polarization, cr for crosspolarization.)

On the Earth's surface, traces of its formation and clues to future geological processes can be found. Solid Earth sciences cover a broad range of applications, many of which are being investigated with SIR-C/X-SAR data, volcanic processes and hazards (summarized in Mouginis-Mark 1995), lithologic and structural mapping (Schaber et al. 1996, Abdelsalam and Stern 1996), and alluvial fans (Farr and Chadwick 1996). Previously unknown paleodrainage systems have been discovered (McCauley et al. 1996); and aerodynamic roughness, an important parameter in atmospheric circulation models, was correctly predicted using cross-polarized L-band data (Greeley and Blumberg 1995).

Table 1 also shows the current optimal SAR parameters for various geologic research topics. For surface morphology cross-polarization is more useful than co-polarization (Evans et al. 1995). Multi-frequency data are needed for most applications except sand dune morphology, where short wavelengths are sufficient, and paleodrainages, for which only the L- or P-bands are necessary.

The requirements can be summarized as follows

1. Multi frequency and cross-polarization for geological mapping;
2. Subsurface geological mapping requires multifrequency rather than polarimetry;
3. L- or P-bands are needed to detect paleodrainages;
4. The L-band is the best single frequency option.

4. Conclusion and discussion

Electromagnetic techniques can be applied successfully to environmental problems. They can, for example, delineate buried waste and characterize the surrounding geology. Some EM case histories of the detection of contaminant plumes give encouraging results. Sometimes a combination of different techniques (including DC resistivity) is necessary for a successful application. The interpretation of the impedance methods (RMT, CSAMT) is highly developed. However, due to the limited frequency range of existing EM instruments used for shallow applications (e.g., VLF-R, RMT), it is sometimes difficult to get information beneath a highly conductive target. The development of an instrument operating from several Hz to 100 MHz is a future task. Many efforts were made to interpret the observed EM data by multidimensional conductivity models and to derive depth information. The successful interpretation of RMT data by 2D inversion techniques and 3D modeling of VLF data are the best examples of these. The TEM measurements for the mapping of aquifers in Denmark show particularly the acceptance of geophysics (EM techniques) by local and regional authorities and enable confidence to be placed in future investigations. New EM instruments developed in the last years allow the surveying of a large area in short time periods necessary in environmental applications. The VLF instrument developed at the University of Neuchatel and the PATEM instrument developed in the University of Arhus allow measurements by car and by a towed system respectively. There is also a clear tendency to build EM systems for quick measurements.

There is a tremendous need for the development of noninvasive technologies that can be used to obtain quantitative information about contaminated regions of the subsurface. This need arises because of recognized limitations in the traditional methods of subsurface characterization. The ultimate goal in using GPR for applications in contamination and hydrology can be described as taking an image, such as that shown in Figure 2, and transforming it into a quantitative image of the relevant physical, chemical, and biological properties of the subsurface.

While it is possible at present to extract useful information about large-scale structure, we are still limited in our ability to obtain accurate, quantitative information about the subsurface properties of interest at the required scale. There is one fundamental problem that we face in attempting to interpret GPR data: The information provided by a GPR measurement is far too limited given the spatial complexity of the subsurface. This problem is not unique to GPR data. It is a general challenge in the interpretation of subsurface measurements—geophysical and other—and highlights the need to take a multifaceted approach to characterization and to combine various sources of data. Significant advances in the use of geophysical data for subsurface characterization are likely to be made if the geophysical data, rather than being acquired and interpreted in isolation, are closely integrated with other forms of subsurface measurement.

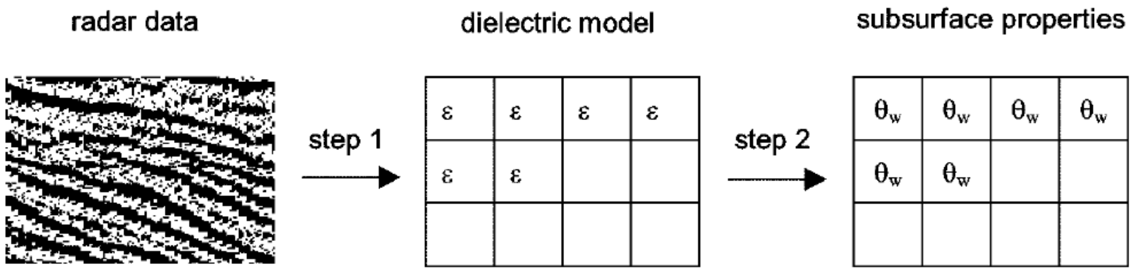

Figure 2: Schematic illustration of the methodology used for the quantitative interpretation of a radar image to obtain a model of subsurface properties. Step 1 involves extracting a dielectric model from the radar data, where each "έ-block" is assigned a single dielectric permittivity (έ) value. Step 2 involves using the appropriate rock physics relationship to transform έ in each block to the hydrogeologic property of interest, e.g. water content θw

Some researchers have proposed specific methodologies that can be used to integrate measurements obtained from radar data with those obtained from standard hydrogeologic testing (Poeter et al 1997; Hubbard et al 1997, 1999; Chen et al 1999; Hubbard & Rubin 2000). A recent example is the study by Chen et al (1999) in which surface radar data were used along with tomographic seismic and radar data to improve estimates of permeability at the Department of Energy Oyster Site in Virginia. GPR is a high resolution geophysical technique that can provide remarkable images of the subsurface of the earth. Contained in these images is a wealth of information; extracting this information is a focus of ongoing research. A GPR image represents the interaction between EM waves and the dielectric properties of the earth. It is deciphering the link between the resulting radar image and the subsurface properties and processes of interest that underlies the future usefulness of GPR for applications in hydrology.

Airborne electromagnetics is a very useful method for surveying large areas in order to support hydrogeological investigations. Due to the dependency of the geophysical parameter electrical conductivity on water content, water chemistry, pore volume and structure and the electrical properties of the host mineral grains (McNeill 1980), information about water quality and aquifer characteristics can be derived from AEM data. The results, however, are sometimes ambiguous: a clayey aquitard in a freshwater environment and a brackish, sandy aquifer, for example, are associated with similar conductivities. As a consequence, additional information, e.g., from drillings, are required for a solid hydrogeological interpretation of the AEM data. Airborne electromagnetic (AEM) surveys increasingly gain importance in groundwater exploration. Particularly in large-scale (> some 10 km2) surveys they are indispensable due to technical and economical reasons. Even at medium-scale (< some 10 km2) airborne systems may be more suitable for groundwater surveys than measurements on

ground, in hardly accessible areas. Compared to ground geophysical measurements AEM measurements are definitely faster, cover larger areas, provide generally a higher spatial density and are nearly everywhere applicable. Still the AEM cann't provide the capabilities of Borehole EM or Ground based surveys as a fact of recording at a distance above the ground.
Frequency-domain electromagnetic measurements are suitable for high-resolution surveys as long as the targets are seated not deeper than 100 m. For deeper targets ground-based or airborne time-domain measurements are more suitable. Helicopter-borne multi-frequency – and increasingly time-domain – systems are widely used in groundwater explorations due to their high-resolving properties and their applicability even in rough terrain. Fixed-wing systems are applicable for reconnaissance surveys in a flat terrain because these systems outrange helicopter-borne systems and they are less expensive but they are less flexible and have less-resolving properties. Still there is requirement for development of instruments that can help Ground water exploration team in looking down under the surface for 100m depth and even more.

5. Future recommendation

The spaceborne segment of EM in microwave region have the great power of resolution upto 1m of spatial resolution and the coarser is 250m-500m. The CSA is evaluating the high resolution data of Radarsat-2 in a very closed group. The microwave have the capacity of all time looking (as dense clouds also not interfere in information collection) but the problem that is understood is the higher the resolution , the scene area reduces and it increase the cost of data. So until the scene area is increased keeping the high resolution and the price compatible with other data product from space, Radarsat data may get some problems in acceptance in research community. There is need to reduce the price of data set and keep the resolution high.

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