Journal of Applied Geophysics 132 (2016) 17–24

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Rolling ball algorithm as a multitask filter for terrain conductivity measurements

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ARTICLE INFO

Article history:
Received 15 January 2016
Received in revised form 4 June 2016
Accepted 30 June 2016
Available online 2 July 2016

Keywords:
Rolling ball algorithm
Electromagnetic
Frequency domain
Utility
Apparent conductivity

ABSTRACT

Portable frequency domain electromagnetic devices, commonly known as terrain conductivity meters, have become increasingly popular in recent years, especially in locating underground utilities. Data collected using these devices, however, usually suffer from major problems such as complexity and interference of apparent conductivity anomalies, near edge local spikes, and fading of conductivity contrast between a utility and the surrounding soil. This study presents the experience of adopting the rolling ball algorithm, originally designed to remove background from medical images, to treat these major problems in terrain conductivity measurements. Applying the proposed procedure to data collected using different terrain conductivity meters at different locations and conditions proves the capability of the rolling ball algorithm to treat these data both efficiently and quickly.

1. Introduction

Electromagnetic (EM) exploration is one of the oldest geophysical tools that comprises a wide variety of exploration methods and techniques. Recent years have witnessed significant rise of a particular EM technique, that is portable frequency domain electromagnetic (FDEM), or what is so called terrain conductivity measurements. Today, a large variety of terrain conductivity meters are available and successfully used in various disciplines. There are many reasons behind the fast and wide spread of these terrain conductivity meters. They are capable of providing useful information about the upper several meters of the subsurface in a short time and with relatively low cost. They are capable of providing almost real-time imaging of the subsurface. In addition, these instruments are rigid, light weight, one man-operable, easy to use, and environmentally benign investigation tools.

Because of their notable advantages, terrain conductivity meters have found a variety of applications, including soil characterization (Triantafilis et al., 2009), precision agriculture (Sudduth et al., 2001), archeological studies (Tong et al., 2013), ice sheets thickness estimation (Haas et al., 2011, Tateyama et al., 2004), contaminant plume mapping (Triantafilis et al., 2011; Gibson et al., 2013), unexploded ordnance detection and characterization (Huang et al., 2007), and forensic investigations (Dionne et al., 2011). However, the most popular application of terrain conductivity meters is detecting and mapping underground utilities (Jeong and Abraham, 2004, Rashed and Al-Garni, 2013; El-Qady et al., 2014; Rashed and Atef, 2015).

Data collected using terrain conductivity meters suffer from 3 major problems. The first problem is noise spikes. Because underground utilities mapping surveys are usually conducted in or near urban areas, the collected data usually contain high amplitude noise bursts especially near the edges of the survey area. Such noise bursts can be caused by cultural noise sources, instrument malfunction, but most commonly by surface objects near the periphery of the survey area. Such noise bursts sometimes have so high amplitude that they mask the genuine anomalies due to subsurface objects of interest. The second problem is the difficulty to pinpoint the exact position of the underground utilities because of the complexity and the interference of anomalies of both in-phase and quadrature components. The third problem is the disappearance of some anomalies due to fading of conductivity contrast between the causative underground utility and the surrounding soil. This problem occurs frequently when surveying large areas and where soil has significant variation in soil conductivity.

The rolling ball algorithm was proposed more than 3 decades ago to remove background intensity variations from medical images (Sternberg, 1983). This algorithm applied to the medical image plotted as a 3D surface, with the pixel value of the image being the surface height. A ball of a user-defined radius is rolled over the backside of the surface creating a background surface. Subtracting this background surface from the original image removes intensity variation at the image. This study presents the experience of applying a slightly modified form of the rolling ball background subtraction algorithm to treat terrain conductivity data from the 3 problems, mentioned above, in a single run. The rolling ball algorithm is applied to 3 data sets, having different types of signals and noises, and collected using different types of terrain conductivity meters at different locations.

http://dx.doi.org/10.1016/j.jappgeo.2016.06.016
0926-9851/

2. Theoretical context

Terrain conductivity meters are special types of the well-known Slingram electromagnetic setting. In terrain conductivity meters, both the transmitter (TX) and the receiver (RX) are mounted inside a boom in a coplanar setting that can be operated in either vertical- or horizontal-dipole mode. Different terrain conductivity meters have different TX-RX spacing that ranges from one meter to few meters. Some terrain conductivity meters have single operating frequency, while others can be operated at variable frequencies.

The basics of working mechanism of terrain conductivity meters are simple. The transmitter coil is energized with a time-harmonic current, creating a primary electromagnetic field having a frequency ranging between 1 and 100 kHz. This primary field imposes eddy currents into nearby subsurface conductors. These eddy currents give rise to a secondary field in the conductor that is sensed, along with the primary field of the transmitter, by the receiver. The primary field is compensated in the receiver coil through a connection between the transmitter and the receiver leaving only the secondary field. The secondary field is decomposed by the conductivity meter into in-phase and quadrature components. At low induction number constrain, the quadrature component of the secondary field, expressed as a percentage of the primary field, is linearly related to the subsurface apparent conductivity. Low induction number constrain assumes that the transmitter-receiver spacing is much less than the skin depth, the depth at which the amplitude of a frequency domain electromagnetic field falls to 1/e of its value at the surface of a homogeneous half space. At low induction number constrain, apparent conductivity can be given by the following equation:

$$\sigma_a = \frac{4}{\omega\mu_0 S^2}\left(\frac{H_S}{H_P}\right)_Q \quad (1)$$

where σ_a is the apparent electric conductivity, ω is the angular frequency, μ_0 is the magnetic permeability of free-space, S is the spacing between the transmitter and the receiver coils, and $\left(\frac{H_S}{H_P}\right)_Q$ is the ratio between the quadrature components of the secondary and the primary fields at the receiver coil (McNeill, 1980).

Due to the distinct TX-RX configuration of terrain conductivity meters, apparent conductivity anomalies resulting from these instruments have a complex asymmetrical M-shape pattern. This pattern is caused by the variable geometrical relationships between transmitter, the receiver, and the subsurface conductor. Fig. 1 shows how such a complex shape of anomaly is formed as a co-planner vertical dipole terrain conductivity meter is moved over a subsurface conductor. Fig. 1a shows the value of apparent conductivity measured by the meter at different positions (A to G), while Figs. 1b–f show the relationship between the primary fields, secondary field, transmitter, receiver, and conductor at different positions.

When the center of the instrument is positioned at point A, the transmitter coil is too far from the conductor for the primary field to generate eddy currents in the conductor. No secondary field is induced in the receiver coil by the conductor and the meter's reading represents only the apparent conductivity of the surrounding soil (Fig. 1). As the center of the meter is moved to point B, the secondary field induced in the conductor and the primary field generated by the transmitter, have the same direction at the receiver coil, and hence a positive peak is formed in the collected data. When the center of the meter is moved to point C and the transmitter coil is exactly over the conductor, the induced secondary field lines are parallel to the receiver coil plane, and no secondary field is sensed by the receiver. When the center of the meter is exactly over the conductor, at point D, the secondary field is in opposite direction to the primary field, and a strong negative anomaly is formed because at this point, the transmitter, the receiver, and the conductor are closer to each other than in any other position. As the meter is moved to point E, the transmitter becomes exactly over the conductor and the primary field is in plane with the conductor. Accordingly, no secondary field is induced in the conductor and only the primary field is sensed by the receiver coil. As the meter travels farther to the point F, the primary field and the secondary field, again, become in the same direction and a positive peak is formed. Because the transmitter is closer to the conductor at point F than it is at point B, the positive conductivity values at point F have higher amplitudes, and hence the asymmetrical anomaly shape. With the meter at point G, the transmitter is again too far from the conductor to induce any secondary field in it. This mechanism shows that the complex asymmetrical M-shape

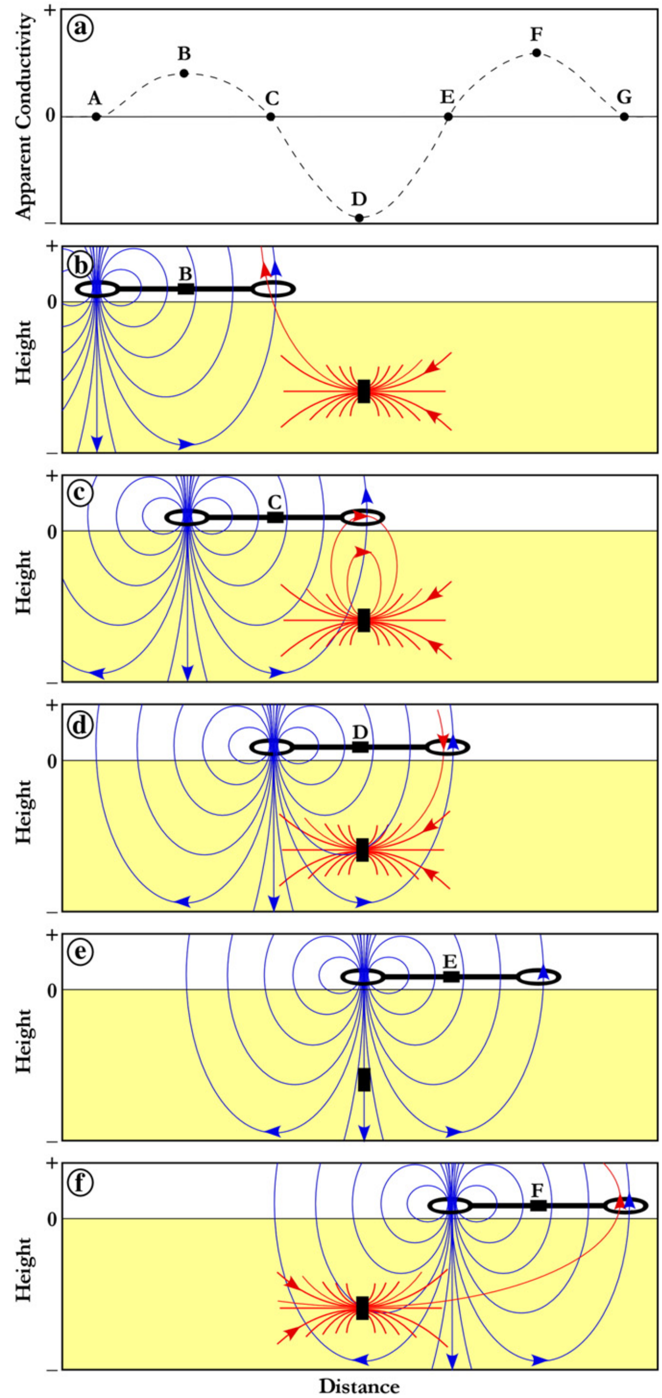

Fig. 1. Formation of the complex shape anomaly of apparent conductivity (a) as the terrain conductivity meter is moved over different positions relative to a subsurface conductor (b–f).