Effects of soil water content and texture on radar and infrared landmine sensors: implications for sensor fusion

R.L. Van Dam[1], B. Borchers[1], J.M.H. Hendrickx[1], R.S. Harmon[2]

[1] New Mexico Tech, Socorro, USA, rvd@nmt.edu, borchers@nmt.edu, hendrick@nmt.edu
[2] U.S. Army Research Office, Durham, USA, russell.harmon@us.army.mil

Abstract

The performance of most, if not all, sensors for the detection of buried landmines is influenced by the properties of the soil that surrounds the mine. Most field soils are highly heterogeneous, in terms of texture, pore space quantity and distribution, composition, or water content. Soil heterogeneity can affect different modalities of landmine sensors and the temporal and spatial variability in soil properties accounts for a significant part of the detection uncertainty that is associated with sensors. In particular, ground-penetrating radar (GPR) and thermal infrared (TIR) sensors are affected by the water content and the texture of the soil. However, both of these sensor types react in their own way to variations in soil water content and soil texture. In this paper we show (i) how variations in physical state of the soil can affect GPR and TIR sensor performance, (ii) how soil databases can be used in early stages of planning landmine demining operations, and (iii) how these performance effects could impact sensor fusion.

1. Introduction

Landmines pose a serious threat to the society in around 90 countries in the world. In recent years, the case for a landmine free world has become stronger, and various efforts are ongoing to develop new and improve existing technologies that can help in identifying landmine fields, and in detecting and clearing landmines [1]. Currently, metal detectors are the only technology that is routinely used in humanitarian demining operations. However, low-metal landmines are very difficult to detect using metal detectors. Two promising techniques for the detection of low-metal landmines are ground-penetrating radar (GPR) and thermal infrared (TIR). The U.S. Army recently deployed a prototype handheld landmine detector system that combines a metal detector and ground-penetrating radar.

Earlier research has demonstrated the important effects of spatial and temporal variability in the soil-mine system. A significant part of the variability in landmine signatures can be attributed to the spatial heterogeneity and temporal variability that is characteristic of most soils. Soil data from a wide range of environmental settings show that soil water content varies widely and over distances of less than one meter [2]. This variability has important implications for sensors that are affected by soil water content, as their performance may be variable over quite short distances.

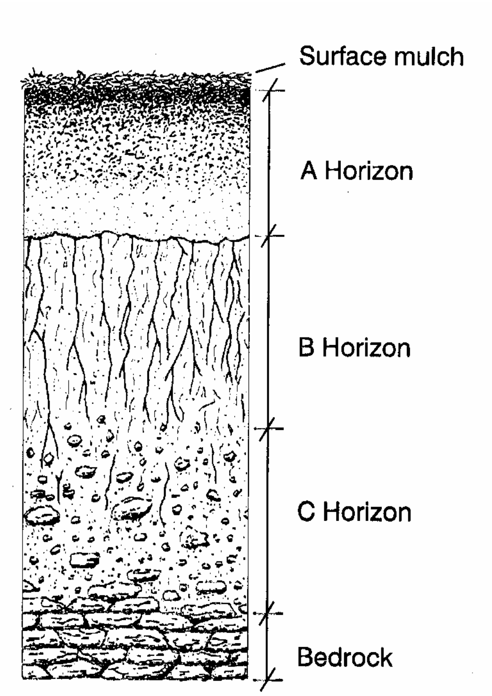
Sensor fusion operations combine different detection methodologies to reduce false alarm rates and to improve the probability of detection [3]. However, the performance of most landmine detection sensors is related to the same (e.g., soil water content) soil properties. Moreover, each sensor will react in its own way to variations in one or another soil property. The fact that the reliability of each sensing method may vary over time and distance in an unrelated manner has important implications for sensor fusion.

The goal of this paper is to show show (i) how variations in physical state of the soil can affect GPR and TIR sensor performance, (ii) how soil databases can be used in the early stages of planning landmine demining operations, and (iii) how these performance effects could impact sensor fusion.

2. Soil properties

Soils are complex natural bodies made up of a heterogeneous mixture of mineral particles, organic matter, fluids, and gases. Soils vary in character from location to location as a result of soil forming processes that depend on regional climate, local vegetation, soil organisms, bedrock composition, and time. Every soil consists of one to several horizons, which reflect the physical, chemical, and biological processes present at the location during the time over which the soil forms (Figure 1).

Figure 1. Schematic presentation of a soil profile [4].



The top layer, or A horizon, is the zone of major biological activity and is, therefore, generally enriched with organic matter and typically darker in color than the underlying horizons. Its thickness can vary from 1 to 30 cm. Beneath the A horizon a B horizon is often present in which leached materials (e.g., clay, carbonates, aluminum and iron hydroxides, or organic matter) from the A horizon have accumulated. The B horizon is generally thicker than the A horizon. Underlying the B horizon is the C horizon which consists of parental rock material in various stages of disruption and weathering. In arid regions, a K horizon characterized by the presence of calcium carbonate nodules and coatings on soil particles, is frequently present. Obviously, for landmine detection the composition of the A horizon and – for deeper mines – the B and K horizons are of most interest.

As noted above, soils are not the same from one place to another. In the United States, soil scientists have classified soils into 11 standard orders (Table 1). This classification is the basis upon which soil mapping typically occurs.

Table 1. Soil classification system of the USDA [5]

Order	Characteristics
Alfisol	Thin A horizon over a clay-rich B horizon, rich in iron and aluminum; typical of humid middle latitudes
Andisol	Soil developed on pyroclastic deposits, which is characterized by low-bulk density and high content of amorphous minerals
Aridsol	Thin A horizon above thin B horizons, often with carbonate accumulation in a K horizon; typical of dry climates
Entisol	Soil with an incipient A horizon, but generally lacking well-developed compositional horizons
Histosol	Peaty soil, rich in organic matter
Inceptisol	Weakly-developed soil with recognizable A horizon and incipient B horizon. No iron and aluminum enrichment
Mollisol	Grassland soil with thick, dark A-horizon rich in organic matter. B horizon may be enriched in clay
Oxisol	Relatively infertile soil with oxidized A horizon and frequently thick B horizon
Spodosol	Acidic soil characterized by highly-organic A horizon and iron / aluminum-rich B horizon
Ultisol	Strongly weathered. A horizon over clay-rich B horizon
Vertisol	Organic-rich soil with a high content of clays that swell and shrink with seasonal variations in soil moisture

2.1. Soil databases

Attention has been called to the need for the use of soil databases in humanitarian demining [6]. The development of Geographical Information Systems (GIS) over the past two decades has made it possible to easily store and retrieve soil data and to develop soil geospatial databases. In a GIS one can distinguish between point and area data.

Point data are detailed descriptions of representative soil profiles, often including chemical, physical, and mechanical analyses. Soil maps and mapping units are regarded as area data. Many national and international organizations and agencies have made soils databases accessible on the internet [7].

These soil databases and many other national databases provide much information about the composition of the top soil layer such as texture, organic matter content, bulk density, and salt content. However, no soil database will provide site specific information because the number of sampled representative profiles is only an infinitely small fraction of the entire soil volume. Yet, in many cases a database can give a clear picture of average soil conditions that are found in a region and the associated degree of local soil variability. It is recommended that soil scientists be consulted to extract relevant soil information from these databases for use in mine detection and removal.

Due to its temporal variability, soil water content cannot be obtained from soil data bases. Remote sensing from satellites can sometimes be used to determine soil water content in the top layer of the soil at large geospatial scales (e.g. >10km). In addition, soil water content, dielectric constant, and electrical conductivity can be determined in the field with time domain reflectrometry or neutron probes [8].

2.2. Soil variability

Soil texture, organic matter, and bulk density have a large impact on soil water content. These properties control the amount of water that soils can absorb, retain, and transmit. However, spatial variability in these properties also exacerbates the temporal and spatial variability of soil water content. Vertically, the water content gradationally varies due to capillary rise and downward redistribution after infiltration. Horizontally, the water content varies as a result of inhomogeneous soil properties. Over time, the water content is affected by precipitation, infiltration, runoff, and evapotranspiration.

Another factor that greatly increases soil water content variability is the occurrence of water repellent soils. These soils are found all over the world under a variety of climatic conditions [9]. Wetting patterns in these soils are irregular and incomplete and these soils exhibit a large spatial and temporal variability of soil water content.

2.3. Pedotransfer functions

A major problem with soil databases is that soil scientists typically measure the soil properties which are of greatest importance in agriculture. Parameters of direct interest in landmine detection, including the real and imaginary parts of the dielectric constant, magnetic susceptibility, electrical conductivity, thermal conductivity, and heat capacity are typically not measured. Fortunately, many of these properties depend in fairly direct ways on more basic properties such as soil texture, density, and water content. Simple models called "pedotransfer functions" have been developed to predict the unmeasured soil parameters from known parameters [7].

Dielectric properties − For the determination of the real and imaginary parts of the dielectric coefficient of a soil our research team has used the pedotransfer function of [10], which was calibrated by fitting the model to a set of experimental observations with a variety of soil textures and water contents, for frequencies from 0.3 to 1.3 GHz. For frequencies above 1.3 GHz we used the model by [11].

Empirically derived formulas give the effective soil conductivity for frequencies below [10] and above [11] 1.3 GHz, respectively:

$$\sigma_e = 0.047 + 0.220\rho_b - 0.411 m_s - 0.661 m_c \,, \tag{1}$$

$$\sigma_e = -1.645 + 1.939\rho_b - 2.013 m_s + 1.594 m_c \,. \tag{2}$$

In these equations, ρ_b is the bulk density of the soil, m_s is the clay mass fraction, and m_c is the clay mass fraction.

The real (ε') and imaginary (ε'') parts of the dielectric constant for the bulk soil are estimated by:

$$\varepsilon = \varepsilon' - \varepsilon'' i \,, \tag{3}$$

where

$$\varepsilon' = z\left[1 + \frac{\rho_b}{\rho_s}\left(\varepsilon_s{}^{\alpha} - 1\right) + \theta_v^{\beta''} \varepsilon'_{fw}{}^{\alpha} - \theta_v\right]^{1/\alpha} , \tag{4}$$

$$\varepsilon'' = \left[\theta_v^{\beta''} \varepsilon''_{fw}{}^{\alpha}\right]^{1/\alpha} . \tag{5}$$

In these formulas, ρ_s is the density of the soil particles, θ_v is the volumetric soil water content, ε_s is the dielectric constant of the soil particles, ε'_{fw} and ε''_{fw} are the real and imaginary parts of the dielectric constant of free water, respectively, and α is an empirically derived constant (0.65). The variable z in Equation (4) is 1.15 for frequencies below 1.3 GHz [10], and equals unity for higher frequencies [11]. β' and β'' are given by:

$$\beta' = 1.2748 - 0.519 m_s - 0.152 m_c , \qquad (6)$$

$$\beta'' = 1.33797 - 0.603 m_s - 0.166 m_c . \qquad (7)$$

Thermal properties − The soil properties needed to model soil surface temperatures are the volumetric heat capacity (C) and the thermal conductivity (λ) [12]. The volumetric heat capacity of soil is often expressed as the weighted sum of the heat capacities of the various soil constituents. Since the volumetric heat capacity of air is about three orders of magnitude less than that of the other soil constituents it can be neglected so that:

$$C = \rho_b \left(c_s + c_w \theta_g \right), \qquad (8)$$

where c_s and c_w are the specific heat of soil (0.73 kJ kg^{-1}K^{-1}) and water (4.18 kJ kg^{-1}K^{-1}), and θ_g is the gravimetric soil water content [13].

Soil thermal conductivity can be determined from an empirical equation [14]:

$$\lambda = a + b\theta_v - (a-d)\exp[-(c\theta_v)^4] , \qquad (9)$$

where a, b, c, and d are soil dependent coefficients which are related to fairly readily available soil properties. These relationships are:

$$a = \frac{0.57 + 1.73\varphi_q + 0.93\varphi_m}{1 - 0.74\varphi_q - 0.49\varphi_m} - 2.8\varphi_s (1 - \varphi_s) , \qquad (10)$$

$$b = 2.8\varphi_s , \qquad (11)$$

$$c = 1 + 2.6 \big/ \sqrt{m_c} , \qquad (12)$$

$$d = 0.03 + 0.7\varphi_s^2 . \qquad (13)$$

Here, φ is the volume fraction of a particular component, and subscripts "q", "m", and "s" indicate quartz, minerals other than quartz, and total solids. The thermal conductivity predicted by this equation is the total conductivity which includes the sensible and the latent heat components.

Using the above we can calculate (for homogeneous soils) the surface temperature amplitude (A_{Ts}) as a function of the amplitude of the heat flux density (A_H) [15]:

$$A_{Ts} = A_H \big/ \sqrt{\lambda C \omega} , \qquad (14)$$

which in turn allows for calculation of the soil surface temperature as a function of time:

$$T_s(t) = T_{avg} + A_{Ts} \sin \omega t , \qquad (15)$$

where ω is the radial frequency ($2\pi/86400$) and T_{avg} is the average soil temperature. For soils with buried landmines the equations are more complex [15,16].

3. Sensor types

3.1. Ground-penetrating radar

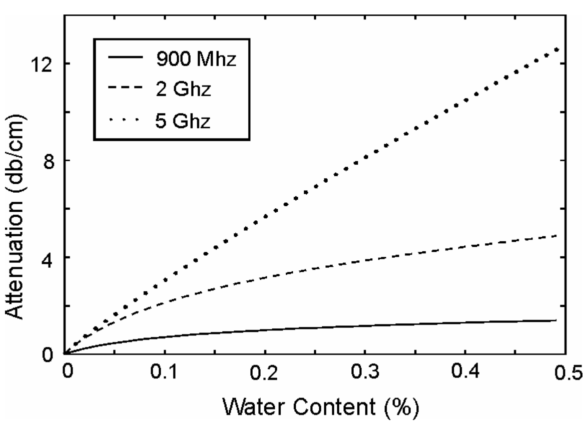
Ground-penetrating radar (GPR) has long been recognized as a powerful technique for the detection of underground objects and landmines. With most landmines typically buried in the top 30 cm of a soil, in many circumstances GPR offers a good tradeoff between resolution and penetration. Since the dielectric properties of the soil control the attenuation of the signal, and because the contrast between the landmine and the background medium controls the scattering and reflection strength, the dielectric properties of both mine and soil are crucial variables to understand radar signatures of landmines [17]. The temporal and spatial variability in soil properties is seldom incorporated into models for the prediction of landmine signatures. Even when the effects of soil properties are acknowledged, very little modeling and little or no experimental research on the specific problem of soil variability has been done.

Pulsed GPRs transmit a short electromagnetic pulse typically in the frequency range between 100's of MHz to several GHz. Due to the bandwidth of the signal and the shallow burial depth of many landmines, the reflection from the landmine is often incorporated in the ground bounce.

Soil water content − The dielectric properties of the soil are strongly influenced by the water content, as the dielectric constant of water (80) is significantly higher than that of air (1) and most soil constituents (~4). The relationship between soil water content (and other soil properties such as bulk density and particle size distribution) and bulk electromagnetic properties can be described by pedotransfer functions.

Various studies have numerically and experimentally shown the effects of soil water content and frequency dependence on landmine detection, e.g.,[18]. Most authors agree that at frequencies below 1 GHz the attenuation is relatively low and that attenuation and relaxation losses drastically increase over 1 GHz. Also, it is widely understood that GPR signal attenuation increases with water content. Figure 2 summarizes the effects of water content and frequency on the attenuation of GPR signals in a clay soil.

Figure 2. Attenuation of GPR signals in a clay soil, using the models by [10] and [11].



For low-metal landmines most studies have observed that the presence of soil water enhances the dielectric contrast. Based on this observation, some authors argue that artificial watering of dry soils may improve landmine detection, e.g.,[19]. Since larger water contents increase attenuation losses, there is a trade-off between enhancing dielectric contrast and increasing signal attenuation. The optimal soil water content also depends on burial depth and frequency. With increasing burial depth and higher frequencies the attenuation will become more significant.

A wetting or drying front at the surface due to precipitation or evapotranspiration will cause different dielectric properties for the top part of the soil. A layer with variable dielectric properties at the surface leads to changes in arrival time (apparent depth of the mine) and signature strength. Horizontal variability in soil water content due to water repellent soils or soil inhomogeneities will cause similar effects of variations in wave velocity, attenuation, and reflection strength.

Soil texture − Soil texture has a smaller effect on GPR signals than does water content. The imaginary part of the dielectric constant is slightly larger in clays and silts than in sand. Although it is recognized that signal attenuation is greater in clayey soils than sandy soils, thus limiting penetration depth, part of this difference in field soils can be attributed to the higher water content of clay soils.

Summary − The detectability of low-metal landmines using GPR mainly depends on the soil water content and radar frequency. Higher soil water contents lead to larger dielectric contrasts between the landmine and the soil in which it is buried. However, higher soil water contents also lead to a larger attenuation. With higher frequencies, the resolution is improved, but (notably above 1 GHz) attenuation and relaxation losses become more significant. Therefore, when using GPR for landmine detection, trade-offs are necessary between (i) increased dielectric contrasts between soil and mine by water, or (ii) increased attenuation due to higher soil water contents and higher frequencies. It is very important to keep in mind that soil moisture is never constant in time and space and can vary considerably over distances of <1m in many soil types.

3.2. Thermal infrared techniques

The potential of TIR for the detection of landmines has been recognized decades ago; nevertheless, only in recent years it has come in focus. The advantages of TIR sensing over other techniques are its ability to detect mines from longer ranges and to scan large areas at once. The driving process in thermal infrared imaging is the daily temperature fluctuations induced by solar radiation.

Several modeling studies have been done to understand the physics of heat propagation and the generation of thermal signatures at the surface above a buried mine, e.g.,[20,21]. The results of many of these studies are contradictory in terms of signal strength and phase shift. The reason for this is that the thermal properties of soil and landmine are often considered fixed variables and are different for each study. The important role of soil variability has not been systematically investigated.

Soil water content − Most studies agree on the fact that soil water content has a significant effect on the thermal signatures and signal phase shift of buried landmines. For example, Figure 3 shows the thermal signature (peak amplitude) in July for landmines in Kuwait. These data demonstrate that the thermal signature is largest under moist and lowest for dry conditions. However, it should be kept in mind that results such as these are highly dependent on landmine burial depth (Figure 4) and landmine thermal characteristics. The signal phase shift depends in a complex way on heat flux, water content and landmine properties [12,16]. The peak times that are shown in Figure 3 will vary strongly for different conditions.

Soil texture − Soil texture has only a small effect on the temperature signature at the surface [16]. However, variations in soil texture often influence the water content of the soil (clay has a higher water retention capacity than sand). As a result, soil texture may indirectly influence the thermal signatures.

Summary − The thermal signatures of buried landmines depend in a complex way on incoming heat flux, variation in soil water content, and the burial depth and composition of the landmine. These properties together control the strength of the thermal signature and the phase shift of the signal. Since it is very difficult to predict at what times the passive thermal signature of a buried landmine is strongest or weakest, thermal infrared techniques require continuous measurements during at least one day. This disqualifies TIR for mounting on a vehicle based (multi-sensor) platform. Instantaneous measurements might be viable where the thermal signature is caused by recent soil disturbance.

Figure 3. Landmine thermal signatures for different soil moisture conditions in July, Kuwait. The landmine consists of TNT and was buried at 15 cm depth (after [16]).

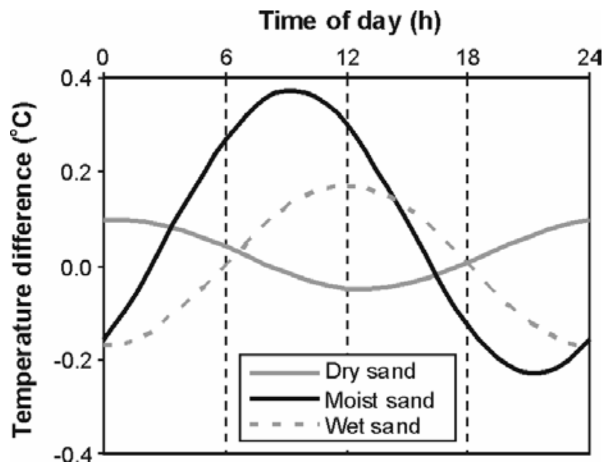
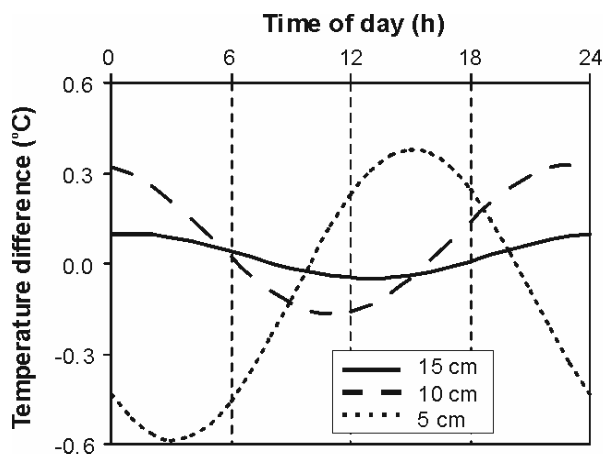


Figure 4. Landmine thermal signatures for different burial depths in July, Kuwait. The landmine consists of TNT and was buried in dry sand (after [16]).



4. Implications for sensor fusion

There is general agreement that no sensor can by itself be used to find landmines under all conditions. Data fusion techniques are used to combine the information from different sensors to increase the probability of detection and decrease the false alarm rate.

Most work on data fusion for landmine detection has involved data fusion at the decision level. That is, data from each sensor is processed to produce a "mine" or "no mine" prediction [22]. These individual predictions are then combined in a probabilistic manner to obtain an overall prediction of whether or not a mine is present at a suspect location. A variety of algorithms are available for combining the data including voting fusion, neural networks, Bayesian inference and Dempster-Shafer inference [22].

In implementing decision level data fusion, it's critical to know the probability of detection and the probability of a false alarm at each detection threshold for each of the sensors. Effectively, a receiver operator characteristic curve (ROC) is needed for each sensor. To date, most research on sensor fusion for landmine detection has assumed that this information can be gained by training the landmine detection system on field data, e.g.,[23]. Furthermore, if the performance of the individual sensors is strongly correlated, then the sensor fusion algorithm may also need the correlation coefficients. As a practical matter, models of sensor performance do not seem to be accurate enough to directly provide this information.

Given that soil properties potentially can have a very large influence on the ROC curve associated with a particular sensor, there are several ways to deal with variability of soil properties. One could simply retrain the data fusion algorithm for each new location and new day where we wish to use the system. Alternatively, it might be possible to train the algorithm on a very large set of data, representative of all the conditions under which the system would ever be used. However, the resulting data fusion algorithm might be much less effective under particular soil conditions than an algorithm trained on data gathered under those conditions. A third option would be to incorporate information about the soil properties in the area under investigation into the data fusion process.

For example, if a library of ROC curves was available for a GPR sensor under a variety of soil water content and soil texture conditions, then the operator could select the ROC curve from the library corresponding to soil conditions that were closest to the observed conditions. This would be done for each of the available sensors, and the data fusion algorithm would then be optimized for the prevailing conditions.

5. Conclusions

A large body of research has shown that soil physical properties can have important effects on various sensors used in landmine detection systems. Some basic soil properties include water content, texture, bulk density, and mineralogy. These properties in turn control properties such as electrical conductivity, dielectric constant, thermal conductivity, and heat capacity, which directly effect sensor performance. These properties can be highly variable in space and time.

Multisensor landmine detection systems using sensor fusion techniques are being developed to deal with the high false alarm rate and low probability of detection of systems based on a single sensor. Since the performance of individual sensors varies strongly with soil properties, sensor fusion algorithms should be designed to incorporate information about prevailing soil conditions. Incorporating information about soil properties into the sensor fusion process has the potential to greatly improve the performance of multisensor landmine detection systems.

References

[1] MacDonald, J., Lockwood, J.R., McFee, J.E., Altshuler, T., Broach, J.T., Carin, L., Harmon, R.S., Rappaport, C., Scott, W.R., and Weaver, R., Alternatives for Landmine Detection, RAND, 2003.
[2] Bauters, T.W.J., Steenhuis, T.S., DiCarlo, D.A., Nieber, J.L., Dekker, L.W., Ritsema, C.J., Parlange, J.Y., and Haverkamp, R., "*Physics of water repellent soils*," Journal of Hydrology, Vol. 231, pp. 233-243, 2000.

[3] Gunatilaka, A.H. and Baertlein, B.A., "*Feature-level and decision-level fusion of noncoincidently sampled sensors for land mine detection*," IEEE transactions on pattern analysis and machine intelligence, Vol. 23, pp. 577-589, 2001.
[4] Hillel, D., Environmental Soil Physics, Academic Press, 1998.
[5] Agriculture, U.D.o., Soil taxonomy, a basic system of soil classification for making and interpreting soil surveys, U.S. Government Printing Office, 1999.
[6] Das, Y., McFee, J.E., and Cross, G., "Soil properties database for humanitarian demining: a proposed initiative," in *17th World Congress of Soil Science*2002.
[7] Hendrickx, J.M.H., Van Dam, R.L., Borchers, B., Curtis, J.O., Lensen, H.A., and Harmon, R.S., "Worldwide distribution of soil dielectric and thermal properties," in *Detection and Remediation Technologies for Mines and Minelike Targets VIII*, R.S. Harmon, J.H. Holloway, and J.T. Broach, eds., 2003.
[8] Brisco, B., Pultz, T.J., Brown, R.J., Topp, G.C., Hares, M.A., and Zebchuck, W.D., "*Soil moisture measurement using portable dielectric probes and time domain reflectometry*," Water Resources Research, Vol. 28, pp. 1339-1346, 1992.
[9] Jaramillo, D.F., Dekker, L.W., Ritsema, C.J., and Hendrickx, J.M.H., "*Occurrence of soil water repellency in arid and humid climates*," Journal of Hydrology, Vol. 231/232, pp. 105-114, 2000.
[10] Peplinski, N.R., Ulaby, F.T., and Dobson, M.C., "*Dielectric properties of soils in the 0.3-1.3 GHz range*," IEEE Transactions on Geoscience and Remote Sensing, Vol. 33, pp. 803-807, 1995.
[11] Dobson, M.C., Ulaby, F.T., Hallikainen, M.T., and El-Rayes, M.A., "*Microwave dielectric behavior of wet soil - Part II: dielectric mixing models*," IEEE Transactions on Geoscience and Remote Sensing, Vol. GE-23, pp. 35-46, 1985.
[12] Simunek, J., Hendrickx, J.M.H., and Borchers, B., "Modeling transient temperature distributions around landmines in homogenous bare soils," in *Detection and Remediation Technologies for Mines and Minelike Targets VI*, A.C. Dubey, J.F. Harvey, J.T. Broach, and V. George, eds., Proceedings of the SPIE, Volume 4394, pp. 387-397, 2001.
[13] Kluitenberg, G.J., "Heat capacity and specific heat," in *Methods of Soil Analysis Part 4. Physical Methods*, J.H. Dane and G.C. Topp, eds., pp. 1201-1208, Soil Science Society of America, 2002.
[14] Bristow, K.L., "Thermal conductivity," in *Methods of Soil Analysis Part 4. Physical Methods*, J.H. Dane and G.C. Topp, eds., pp. 1209-1226, Soil Science Society of America, 2002.
[15] Van Wijk, W.R., Physics of plant environment, John Wiley & Sons, 1963.
[16] Van Dam, R.L., Borchers, B., Hendrickx, J.M.H., and Hong, S., "Soil effects on thermal signatures of buried nonmetallic landmines," in *Detection and Remediation Technologies for Mines and Minelike Targets VIII*, R.S. Harmon, J.H. Holloway, and J.T. Broach, eds., 2003.
[17] Hendrickx, J.M.H., Hong, S., Miller, T., Borchers, B., and Tobin, H., "Soil effects on ground penetrating radar detection of buried nonmetallic mines," in *Ground Penetrating Radar in Sediments*, C.S. Bristow and H.M. Jol, eds., pp., 2003.
[18] Carin, L., Geng, N., McClure, M., Sichina, J., and Nguyen, L., "*Ultra-wide-band synthetic-aperture radar for mine-field detection*," IEEE Antennas and Propagation Magazine, Vol. 41, pp. 18-33, 1999.
[19] Borchers, B., Hendrickx, J.M.H., Das, B.S., and Hong, S., "Enhancing dielectric contrast between land mines and the soil environment by watering: modeling, design, and experimental results," in *Detection and Remediation Technologies for Mines and Minelike Targets V*, A.C. Dubey, J.F. Harvey, J.T. Broach, and R.E. Dugan, eds., Proceedings of the SPIE, Volume 4038, pp. 993-1000, 2000.
[20] Sendur, I.K., Baertlein, B.A., and Vafai, K., "*Three-dimensional thermal modeling of land mine signatures over a diurnal cycle*," IEEE Transactions on Geoscience and Remote Sensing, 2001.
[21] Khanafer, K. and Vafai, K., "*Thermal analysis of buried land mines over a diurnal cycle*," IEEE Transactions on Geoscience and Remote Sensing, Vol. 40, pp. 461-473, 2002.
[22] Klein, L.A., Sensor and data fusion concepts and applications, SPIE, 1999.
[23] Baertlein, B.A., Liao, W.J., and Chen, D.H., "Fusion of acoustic LDV and GPR data," in *Detection and Remediation Technologies for Mines and Minelike Targets VI*, A.C. Dubey, J.F. Harvey, J.T. Broach, and V. George, eds., Proceedings of the SPIE, Volume 4394, pp. 970-978, 2001.