A Survey of Electromagnetic Characteristics of Soils in the Donbass Region (Ukraine) for Evaluation of the Applicability of GPR and MD for Landmine Detection

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***Abstract*— In order to design holographic and impulse GPRs, as well as metal detector (MD) sensors for humanitarian demining in the Donbass conflict zone, we have compiled a listing of the AP and AT mines that have been confirmed in use in Donbass, and their dimensions and construction. Just as importantly, we have attempted, from existing literature (since it is an active war zone), to characterize the specific soils in this region in order to understand the physical property contrasts between mine casings/components and the soils in which they may be buried, as well as the propagation characteristics of radar signals in these soils. We conclude that MD should be generally effective for locating Donbass mines, and GPRs operating near the frequency of 2GHz should provide sufficient penetration for detection and, simultaneously, sufficient resolution to assist with discrimination of mines from clutter. As is common in GPR applications, the main limiting factor may be soil moisture content, so operations may be restricted to dry periods or seasons. Field measurements are scheduled to confirm the values from the literature.**

***Index Terms*—holographic, impulse, metal detector, landmines, chernozem.**

I. INTRODUCTION

People are killed or dismembered every day by stepping on landmines – often in peaceful but post-conflict countries. In these countries, the majority (79%) of casualties are civilians and almost half (46%) are children [1]. This violence continues despite the decades-old Mine Ban Convention, which has been ratified by nearly three-quarters of the world's nations. The convention has virtually halted the global production of anti-personnel mines, and has drastically reduced their deployment. Due to herculean efforts by many organizations, myriad mined or suspected hazardous areas have been declared safe and released for productive use, attended by a coincident steep decline in casualties in recent years. However, well over 10 million stockpiled mines await destruction [Ibid.], and vast expanses of land remain potentially dangerous – impeding peaceful social and economic development.

The latest trouble spot is southeastern Ukraine in the Oblasts of Donetsk and Luhansk ("Donbass"), where protests by pro-Russian and anti-Ukraine Government organizations escalated into war in April, 2014 [2]. As of January 2016, Mine Action Review stated that "Ukraine is contaminated with anti-personnel mines and cluster munition remnants" [3], which have killed over 3000 persons, including 49 children [4]. According to news photos [5], [6], Mine Action Review [3], Human Rights Watch [7], reports by the State Emergency Service of Ukraine [4], and personal communications with Jörg Lobert of the Geneva International Center for Humanitarian Demining (January, 2016) and Colin King, Editor of Jane's Mines (February 2016), mines in Donbass probably include Russian-made PMN-2 and PMN-4 antipersonnel (AP) mines, plus TM-62M, TM-62P3 and PTM-1G anti-tank (AT) mines. There are also many allegations (mainly on social media) of PFM-1 or "butterfly" mines, but these remain either unconfirmed, or have been proven incorrect - involving obviously-inert training mines [C. King pers.

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Comm.]. While most of the mines listed above can be located by metal detection (MD), clutter rejection is critically important as evidenced by the recent work of HALO and others in Cambodia [8], [9]. In one case [8], for 1.4 million MD identifications over a two-year period, the ratio of clutter to mines was 250:1. However, combining GPR with MD provided rejection of 95% of clutter items.

While the Donbass conflict is still active, in preparation for post-conflict humanitarian demining, we are in the process of evaluating the suitability of GPR and other sensors for use in the particular soils characteristic of Donbass, and in relation to the specific mines and their physical characteristics, with the ultimate goal of designing GPRs with signal characteristics appropriate for this region.

II. MINES IN DONBASS

In addition to the AP blast mines PMN-2 and PMN-4 reported in Ukraine, directional fragmentation AP mines MON-50 and MON-90 have been documented in Donbass [4, 7, Lobert, King]. These will not be considered further since they are not buried, and can be detected visually. The PMN-2 and PMN-4 (Fig. 1) are both plastic-cased, but with enough metal content to be located by MD in most conditions [10], [11]. They have diameters of 121mm and 95mm respectively [Ibid].

The TM-62M and TM62-P3 are both 320 mm in diameter, and have an internal booster charge in a metal canister, but the casing and all exterior fittings on the TM-62P3 are plastic, while the TM-62M casing is steel [12], [13].

Fig. 1. PMN-2 (left) and PMN-4 (right) AP blast mines. Photos from [9], [10].

Fig. 2. TM-62M (left) and TM-62P3 (right) AT blast mines. Photos from [12], [13].

The PTM-1G AT blast mine is a large (337mm by 69mm) rectangular plastic prism. Since it is scatterable and has a large metal fitting, it is generally locatable visually or with MD [14].

Fig. 3. PTM-1G scatterable AT blast mine. Photo from [14].

None of these mines should present difficulties for simple detection – particularly with a metal detector. However, except for the TM-62M, the metal detector will respond to various springs, rods and other hardware - not to the casing. Therefore discrimination of these mines from metallic clutter will require plan-view GPR imaging, using either continuous wave holographic radar, or time-slices of impulse radar C-scans [e.g. 15] with adequate lateral resolution of 9cm or less for the smaller AP mines.

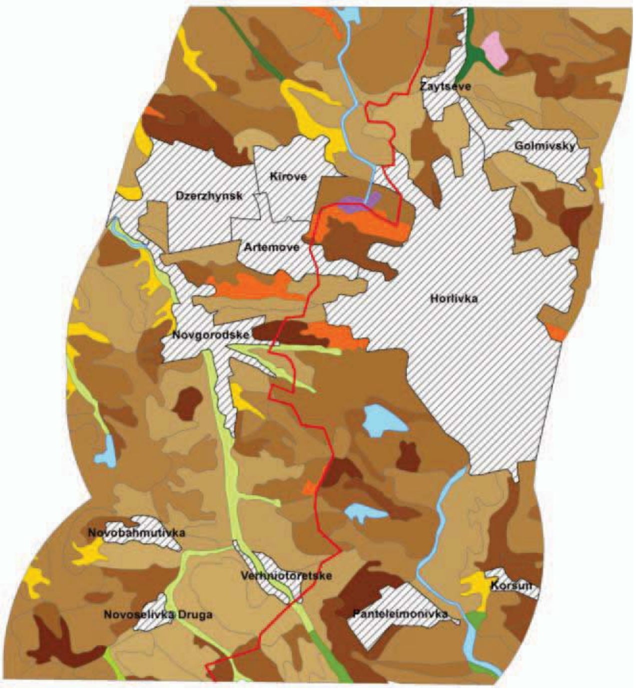

Fig. 4. Soils map of a representative portion of the front line (red) of the Donbass conflict (as of January, 2016). Chernozemic soils in shades of brown.

III. SOILS IN DONBASS

Since it is an active war zone, direct field testing in this region will require careful planning, scheduling, and security. Therefore, for this preliminary study, the Ukraine National Scientific Center «Institute for Soil Science and Agrochemistry Research named after O.N. Sokolovsky» compiled already-existing physico-chemical data for soils extending 25 km to either side of the front-line of the conflict as of January, 2016 (Fig. 4). Based on this detailed mapping, approximately 71% of the soils are Haplic (Calcic) Chernozems, another 12% are Luvic Chernozems, and 27% are other different types of soils. Chernozems (shades of brown on Fig. 4) in general are organic-rich soils that develop on relatively flat surfaces under thick grass vegetation of the Steppe Zone in climates with cold winters and hot summers [16], [17], [18].

The surficial layer (plow zone) in these chernozemic soils will be the most relevant for evaluating GPR and MD performance for detecting and discriminating the mines described in the previous section. This surficial layer can be very roughly characterized (in a highly generalized fashion) by the ranges of parameters in Table I.

Index & Depth (cm)	Photograph
Hk 0-30 0-15 plowing 15-30	
Hpk 30-45	
Phk 45-67	
Pk below 67	

Fig. 5. Photograph of soil profile P4.

The Soil Science Institute has previously excavated test pits through many of these soil types, and selected example photographs are provided in Figs. 5 and 6. Note the dark, organic, homogeneous, near-surface plow zone horizon.

Table I

Parameter	**Value (%)**	
	Lo	***Hig***
Clay	45	65
Porosity	50	56
Organic Matter	3.3	5.5
Min. Water	17	32
Ionic Content	0.0	0.07
Fe_2O_3	3.7	5.8

Index & Depth (cm)	Photograph
H plowing 0-34	
Hpk 34-50	
Phk 50-77	
P1k	

Fig. 6. Photograph of soil profile R3.

IV. PRELIMINARY IMPLICATIONS FOR MD AND GPR

According to the “CEN Workshop Agreement – Part 1”, [19], the most important soil properties influencing MD performance are magnetic susceptibility and electrical conductivity. Soil moisture content also plays a secondary role since it can influence the conductivity, particularly in clay-rich soils. For GPR, the important parameters are electrical conductivity as well as electrical permittivity [20]. Magnetic susceptibilities within normal ranges for soils have no effect on GPR[21].

Magnetic susceptibility is frequency-dependent, and difficult to characterize with any single soil parameter. It is dependent on soil mineralogy and grain size, plus temperature and temperature history. For the Donbass soils characterized in Table 1 and depicted in Figs. 5 and 6, there are several clues that might indicate potential magnetic difficulties for MD. These include the high content of organic matter plus Fe_2O_3, and the reddish color of the subsoils. The Fe_2O_3 could be present as haematite, which is second in importance only to magnetite as a common mineral contributing to soil and rock magnetism and susceptibility, and may convert to highly magnetic maghaemite in the presence of organic matter [22]. The reddish color may potentially be only a mild concern because magnetic soils are often reddish, but not all reddish soils are magnetic [20]. In any case, there are sufficient warning signs such that field geophysical testing of magnetic susceptibility on in-situ Donbass soils is planned.

The electrical properties (conductivity and permittivity) are controlled primarily by clay content, clay mineralogy, salt content, and water content. Chernozems are generally well drained and so are generally free of excess soluble salts [23]. This is also evident in Table I. However, Table I indicates that the clay content is quite high. The very high-CEC clay mineral smectite is typically less common in chernozemic soils than in the loess parent material [Ibid], but at high clay contents, there is probably enough to significantly affect soil electrical conductivity in the presence of moisture. In general, soils with clay content >35% are considered restrictive for GPR [24]. However, for landmine detection where penetration of 20cm is often sufficient, even typically "restrictive" soils can transmit a sufficient signal [25]. Instead, there will be a trade-off between 1) selection of a low-enough frequency for the transmitted signal to provide sufficient penetration, and 2) the preference for a higher frequency signal to maximize resolution [26]. For the plastic-cased mines of Donbass, there may even be an advantage to working in otherwise "restrictive" soils, since they will provide a larger permittivity contrast between casing and mine than would be present in dry sand or other "preferred" GPR media [25].

Spatial variations in soil properties and localized anomalies, such as clasts, also commonly interfere with MD and GPR mine detection [20]. However, the soils information we have reviewed so far indicates a relatively homogenous plow zone at the small depths that will be of interest.

Of course, actual soil moisture content will vary with seasons, and even shorter-term variations will track weather. Previously, this complication might render this type of a-priori evaluation of sensor suitability meaningless. However, recent work on GPR as a tool for analyzing the moisture content of soils has led to the development of robust empirical formulae called "geophysical pedo-transfer functions" (GPTF's), relating soil moisture content to both soil electrical conductivity and permittivity – including for chernozemic soils [27]. These were intended to obtain soil moisture content measurements from GPR scanning, but can also work in reverse, and predict GPR performance based on soil moisture content.

Based on this preliminary review and analysis of Donbass soil properties, we propose to work with holographic and impulse radars with frequencies centered near 2GHz. Based on direct measurements of radar propagation in chernozemic soils over a wide range of frequencies [28], we can estimate the propagation behavior of 2GHz signals as a function of water content as depicted in Fig. 7.

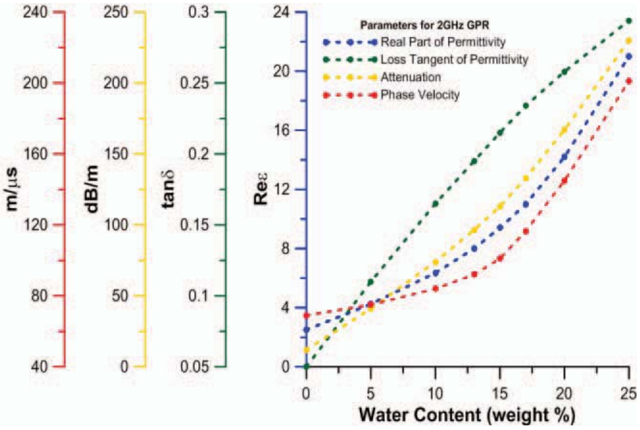

Fig. 7. Estimated propagation characteristics of 2GHz radar based on direct testing of chernozemic soil by others [28].

The direct testing [28] of the electromagnetic properties of this type of soil reveals that above 1 GHz the real part of the complex permittivity and the loss tangent (imaginary part) are quite constant and smaller than the values at frequencies below 1 GHz. So the chosen frequency range for GPR can be above 1 GHz without suffering dispersive effects.

Note that the moisture content effects are dramatic and must be taken into account, especially at values above approximately 15%. At 2GHz, the attenuation factor (yellow in Fig. 7) can reach approximately 200dB/m in the worst case of 25% moisture. This means an attenuation of 50dB on a round trip of 0.25m, which is acceptable for a shallow buried AP mine.

The phase velocity, which dictates the axial resolution, goes from 0.6 to 1.7 x10^8m/s, which implies increasing wavelength (and declining resolution) with increasing moisture. Although for demining the lateral resolution may be most important for determining the dimensions of targets such as plastic-cased mines, the axial resolution may also be important for targets with lesser metal content. Good initial estimates of these parameters will also be very important in developing focusing algorithms for GPR B- or C-scans for optimal clutter rejection.

As with MD, geophysical testing of electrical conductivity and permittivity as it affects GPR is planned for in situ Donbass soils. This will allow at least qualitative a priori prediction of the performance of MD and GPR sensors [21].

V. CONCLUSIONS

Mines in Donbass are mainly plastic-cased, but generally contain sufficient metal for MD location. However, GPR may be critical for the discrimination of mines from clutter. The dominant soils in Donbass seem generally suitable for MD and for shallow GPR. Elevated electrical conductivity due to clay content may be a GPR advantage rather than a restriction for shallow plastic (low conductivity) casings. Direct testing (by others [28]) of GPR signal propagation characteristics for chernozemic soils suggest that frequencies near 2GHz may be optimum for shallow signal penetration, as well as vertical and lateral resolution. Elevated soil moisture content may represent the greatest limitation, and may require careful scheduling of survey work for relatively dry days and seasons. The effects of varying moisture content on soil electrical conductivity and permittivity will be modelled using newly-developed GPTFs, and scheduled geophysical testing of in situ Donbass soils will allow for prediction of the efficacy of MD and GPR for landmine detection.

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