

Introduction

As a new aerial vehicle, drone technology has been developing fast in recent years, and has been used in various applications for scientific research thanks to its advantages of easy-controlled, low-cost etc. (Floreato and Wood, 2015; Coops et al., 2019). Soil properties characterization is essential for environment, hydrology, biology, agriculture etc. (Dominati et al., 2010; Corradini, 2014; Fatichi et al., 2020). In geophysical methods, ground-penetrating radar (GPR) is an efficient and promising tool for field-scale soil surveys like soil water content and hydraulic characterization (Minet et al., 2012; Tran et al., 2014; Zajíčová and Chuman, 2019; Got et al., 2020). In drone-GPR applications, several studies have proven the potential of the combination of drone and lightweight GPR system. These drone-GPRs are, respectively, used for shallow subsurface imaging, underground objects detection and soil moisture mapping (Colorado et al., 2017; Ludeno et al., 2018; Garcia-Fernandez et al., 2019; Wu et al., 2019; Noviello et al., 2020). In addition, soil electrical conductivity is also an important property for non-destructive soil characterization. Airborne electromagnetic induction has been used for a long time to measurement the electrical conductivity (Sattel, 2009). However, the soil conductivity measurement using GPR has remained a challenge in field conditions. Common midpoint data is used to generate the soil conductivity by updating the phase and amplitude of the source wavelet (Busch et al., 2012). Time-domain GPR with full-wave inversion is used to estimate the soil conductivity (Mourmeaux et al., 2014). Nevertheless, these methods require medium-coupled or on-ground measurements. To use with a drone, a lightweight and remote-controlled radar system is needed, and importantly, an off-ground configuration. Lambot et al. proposed an air-coupled GPR full-wave inversion method for the soil electromagnetic characterization (Lambot et al., 2004a; Lambot and André, 2014). In this method, a radar equation accounting for the antenna and its interactions with a planar layered medium is proposed, so that the antenna effects are filtered out for inversion afterwards. In full-wave inversion, the sensitivity of the reflection coefficient at an interface with respect to dielectric permittivity and the electrical conductivity vary with frequencies. For instance, the conductivity can be ignored when operating frequency is high e.g., > 1 GHz (Lambot et al., 2006). In that respect, a very low frequency GPR is necessary for soil conductivity measurement. In this study, we use a 5-meter half-wave dipole mounted on a drone for the soil conductivity mapping. The radar system consists of a handheld vector network analyser (VNA), a computer stick, and a differential GPS for positioning. The whole system is powered by a power bank, and measurement is controlled remotely by a smartphone or a tablet. It works in the frequency domain with operating frequency range of 15-45 MHz, and inversion is conducted in the time domain for focusing on the soil surface reflection. A 3-D look-up table (LUT) is pre-computed for a shorter processing time during inversion. The conductivity map is generated by kriging interpolation method.

Theory

Radar Equation

The generalized antenna model accounts for the interactions between the antenna and planar layered medium, and relies on a solution of the 3-D Maxwell's equations. In far-field conditions, it is expressed in the frequency domain as (Lambot et al., 2004a; Lambot and André, 2014):

$$S_{11} = H_i(\omega) + \frac{H(\omega)G_{xx}^{\uparrow}(\omega)}{1 - G_{xx}^{\uparrow}(\omega)H_f(\omega)} \quad (1)$$

where ω is the angular frequency, and S_{11} is the radar signal measured directly by a VNA. H_i , H and H_f are, respectively, the return loss, the transmitting-receiving complex global transmission coefficient and feedback loss transfer functions of the antenna. G_{xx} is the Green's function, representing the backscattered electric field at the antenna phase centre for a normalized unit source. From the raw data, G_{xx} is calculated from Eq. (1) as:

$$G_{xx}(\omega) = \frac{S_{11} - H_i(\omega)}{H(\omega) + S_{11}H_f(\omega) - H_i(\omega)H_f(\omega)} \quad (2)$$

Full-wave Inversion

The inversion is conducted in the time domain to focus on the soil surface reflection only, and its problem is described using the least-squares formulation (Lambot et al., 2006). The objective function is defined as:

$$\phi(\mathbf{b}) = \left(\mathbf{g}_{xx}^{\uparrow*}(t) - \mathbf{g}_{xx}^{\uparrow}(\mathbf{b}, t) \right)^T \left(\mathbf{g}_{xx}^{\uparrow*}(t) - \mathbf{g}_{xx}^{\uparrow}(\mathbf{b}, t) \right) \quad (3)$$

in which $\mathbf{g}_{xx}^{\uparrow*}(t)$ and $\mathbf{g}_{xx}^{\uparrow}(\mathbf{b}, t)$ are, respectively, the measured and modelled Green's functions, and obtained by inverse Fourier transform of G_{xx} in Eq. (2). $\mathbf{b}$ is the parameter vector $[h_0, \epsilon_r, \sigma]$, where h_0 is the distance between the antenna phase centre and the medium surface, ϵ_r is the dielectric permittivity and σ is the electrical conductivity. In the forward model, we fixed:

$$\mathbf{h}_0 = [5.000 \quad 5.005 \quad 5.010 \quad \dots \quad 7.995 \quad 8.000]^T \text{ m}$$

$$\epsilon_r = [5 \quad 10 \quad 15]^T$$

$$\sigma = [1 \quad 2 \quad 3 \quad \dots \quad 99 \quad 100]^T \text{ mS/m}$$

leading to $601 \times 3 \times 100$ calculations (180300 times), and its results are stored in a 3-D LUT. This LUT is calculated only once, which greatly reduces processing time during inversion.

Drone-borne GPR and Field experiment

The drone we used is an X8 model from RCTakeOff (Overijse, Belgium), and it has 4 arms with 8 motors and propellers. The payload is about 5 kg. The radar system consists of a handheld VNA (Planar R60, Copper Mountain Technologies, Indianapolis, USA), a half-wave dipole antenna with an aperture of 5 m (VHA9103, Schwarzbeck Mess-Elektronik, Germany), a differential GPS for positioning, a microcomputer with homemade control application packages written in C++ and Javascript, and a power bank to provide electricity to the whole radar system. The microcomputer connects to the wifi hotspot launched by a smartphone, which provides a user interface so that radar measurement can be controlled remotely. The drone-GPR is shown in Fig. 1. Considering the size of the antenna, calibration is conducted over a lake through several measurements with the antenna being at different heights. The measurement was performed over a vineyard in the region of Bousval, Walloon region, Belgium. The test site is about 0.42 ha. This measurement was conducted on March 3, 2021. The operating and processing frequency range is set as 15-45 MHz with a step of 1 MHz. 4-5 measurements were acquired per second. Flying height is around 7 m above the soil. The result is shown in Fig. 2(a), and in Fig. 2(b) we present an EMI map measured in 2018. It is observed that the electrical conductivity values fall well within the possible values. While the difference between Fig. 2(a) and Fig. 2(b) mainly originates from the sensitivity of detection depth, with drone-GPR is about 1 m but EMI is about 2 m. Some error might result from the limited stability of drone flight. In addition, errors are also expected to arise from the correlated effect of the permittivity on the surface reflection, which is relatively small but not negligible in that frequency range.

Conclusion

In this study, we proposed a low-frequency drone-based GPR for soil conductivity mapping. The lightweight radar system consists of a handheld VNA, a microcomputer, a differential GPS and a power bank. A 5-meter half-wave dipole antenna is used to provide the operating frequency range of 15-45 MHz. For the data processing, antenna-drone effects are filtered out with the antenna transfer functions generated from calibration, and 3-D LUT is used for fast and robust inversion. The soil conductivity is obtained from point measurements using kriging interpolation. The result shows a good spatial correlation, and reasonable conductivity values comparing with EMI, which initially proves the concept of drone-borne GPR for soil conductivity mapping. Our future works will focus on the validation of the low-frequency drone-borne GPR for soil conductivity mapping, by providing more ground-truths or existing technologies.



Fig. 1. Drone-borne GPR.

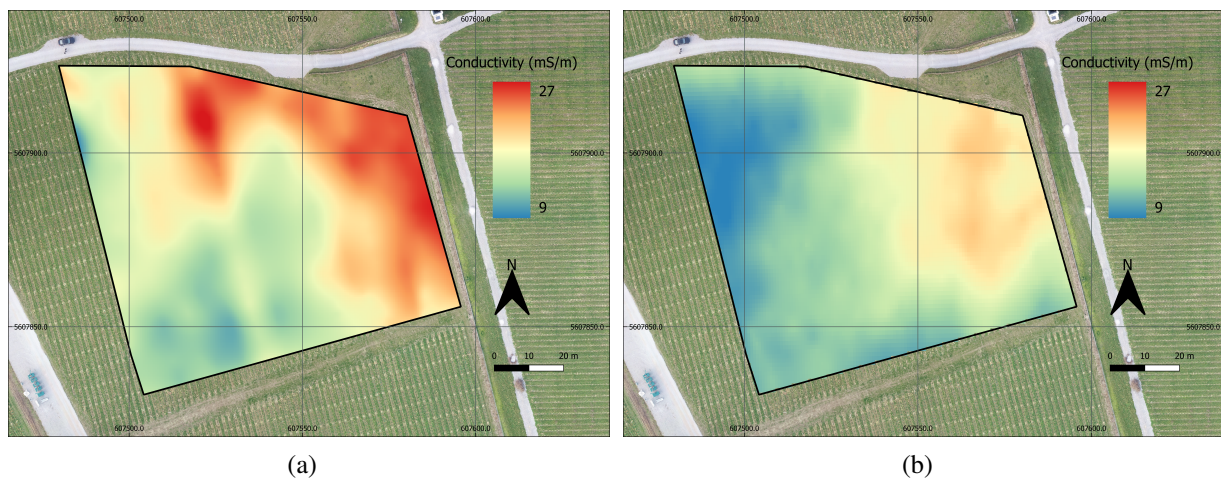


Fig. 2. Soil conductivity map in Bousval, Belgium measured by (a) drone-GPR in 2021 and (b) EMI38 in 2018. Coordinates are in WGS72/UTM zone 31N (m).

Acknowledgements

This research was funded by the Fonds de la Recherche Scientifique (FNRS, Belgium). We acknowledge the Vignoble du Château de Bousval for giving us access to the field.

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