C. R. Physique 19 (2018) 72–84

Contents lists available at ScienceDirect

Comptes Rendus Physique

www.sciencedirect.com

Radio science for Humanity/Radiosciences au service de l'humanité

Drone-borne GPR design: Propagation issues

Conception GPR pour drone : propagation

Madhu Chandra[a], Tullio Joseph Tanzi[b,*]

[a] *Chemnitz University of Technology, Germany*
[b] *Institut Mines Télécom, Télécom ParisTech, LTCI, Paris, France*

ARTICLE INFO

Keywords:
Risk assessment
Remote sensing
GPR
Propagation

Mots-clés :
Évaluation du risque
Télédétection
Radar à pénétration de sol
Propagation

ABSTRACT

In this paper, we shall address the electromagnetic wave propagation issues that are critical to determining the feasibility of a drone-borne ground-penetrating radar sensor for humanitarian applications, particularly in the context of disaster management. Frequency- and polarization-dependent scattering, attenuation and dispersion of radar signals penetrating into the sub-surface region will determine the applicability of a drone-mounted radar sensor capable of registering radar echoes for observing and monitoring sub-surface features. The functionality of the radar will thus be assessed depending on key radar parameters that include the central radar frequency, the modulation depth, and the mode of radar operation (pulsed FM, FM-CW), the antenna type, the available power-budget.

In the analysis to be presented, the radar equation, together with the aforementioned propagation effects, will be used to simulate the signal strength of radar echoes under different conditions arising from the chosen key-radar parameters and the assumed physical properties of the sub-surface earth medium. The analysis to be presented will indicate whether or not the drone-borne ground-penetrating radar is a feasible system and if it could be constructed with the technologies available today.

Taking into account the strict constraints involved to design drone applications for Public Protection and Disaster Relief (PPDR), the ideas developed hereafter are both prospective and exploratory. The objective is to see if a solution can be found in the near future.

RÉSUMÉ

Dans cet article, nous allons aborder les problèmes de propagation d'onde électromagnétique qui permettra de déterminer la faisabilité d'un capteur radar à pénétration de sol, embarqué sur un drone, destiné aux applications humanitaires, notamment dans le cadre des catastrophes. L'étude de la fréquence, de la polarisation, de la diffusion, de l'atténuation et de la dispersion des signaux radar pénétrant sous la surface permettra de déterminer l'applicabilité d'un capteur sur drone. La fonctionnalité du radar est donc évaluée en fonction de paramètres clés, qui incluent la fréquence radar, la profondeur de modulation et le mode de fonctionnement des radars (pulsé FM, FM-CW), le type d'antenne, en fonction du budget puissance disponible.

---

[*] Corresponding author at: Institut Mines-Télécom-Télécom ParisTech, Université Paris-Saclay, LCTI, Campus SophiaTech Les Templiers, 06410 Biot, France.
E-mail address: tullio.tanzi@telecom-paristech.fr (T.J. Tanzi).

https://doi.org/10.1016/j.crhy.2018.01.002

Dans l'analyse présentée, l'équation radar, ainsi que les effets de propagation susmentionnés, serviront à simuler la puissance du signal des échos radar sous différentes conditions découlant des paramètres clés choisis et les propriétés physiques du milieu sous la surface. L'étude a pour objectif de démontrer si le système est réalisable et s'il peut être construit avec les technologies disponibles aujourd'hui.

En raison du contexte très contraignant des applications pour la protection du public et secours en cas de catastrophe, les idées ici développées ont un caractère tout à la fois prospectif et exploratoire, l'objectif étant d'examiner si, dans un avenir proche, une solution se dessinerait.

---

1. Introduction

When a natural disaster occurs in a populated zone, a fast and effective organization of disaster management is necessary to assist the affected population, reduce the number of victims, and limit the economic impact [1]. At all phases of disaster management (pre-disaster, response, post-disaster), one of the first actions to be taken is to set up a 'disaster cell' for coordination. The detection and the monitoring of the impact of natural disasters on terrain are mainly performed by space-borne and air-borne radio and optical instruments [2,3]. In contrast to limitations in the time window of observations attached to optical instruments (i.e. no observation at night or in the presence of cloud cover), radio observations are available 24/7 and relatively insensitive to atmospheric conditions: these are, therefore, particularly useful during the 'response phase' of the disaster management cycle, when information must be delivered to the disaster cell with the shortest possible delay [4–6].

Unmanned Aerial Vehicles (UAV) may bring significant improvements with respect to these issues. They can be easily equipped with various kinds of sensors in addition to optical ones depending on the mission. Their low altitudes make it easy to observe below a cloud cover. Finally, search and rescue teams may carry UAVs and deploy them upon need on site, for instance to explore some flooded area in order to find a stable path to victims, or a ruined building. In this respect, UAVs extend the exploration range of rescue teams, while at the same time they improve the latter's safety in areas that may be dangerous. The senseFly UAV has, for instance, demonstrated the automated mapping capabilities of small drones and how they are able to save the lives of the victims in the aftermath of the Haiti 2010 earthquake, by enabling the authorities to quickly draw maps of the devastated areas [7].

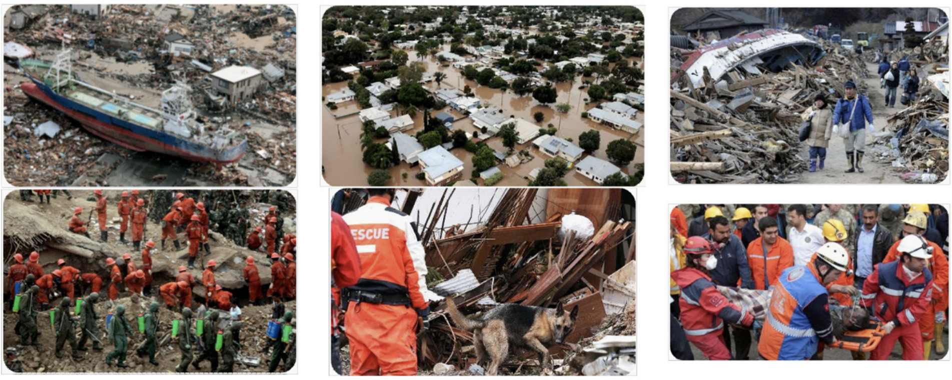
Developing and integrating autonomous features into the UAV is key to this application. Indeed, the UAV is likely to be in situations where it will be unable to communicate with the control centre, either sporadically due to interferences, or for extended periods of time if it explores the terrain behind obstacles or beyond the reach of any radio relay. Depending on the real-time requirements, the communication capabilities, and the complexity of the sensors deployed, the data sensed will either be processed appropriately in terms of navigation and sensor deployment, or data fusion algorithms have to be developed [8]. Autonomy does not mean that the UAV will not be controlled remotely, for instance in order to zoom-in on some scene that would be of interest to rescue teams even if it were not considered so by the UAV itself.

As explained in [9–11], new approaches and the use of new technologies are required for a more efficient risk management, before, during, and after a potential crisis. Every specific action at each step of the crisis must be specifically considered. For that purpose, new dedicated tools and methodologies are required to better handle crisis situations.

1.1. Related works

The numbers of event-related cases, where drones have already been useful in humanitarian settings, are many; the ones described here are just a small subset of these. Danoffice IT has a commercial drone solution for disaster response [12]. It was already used in real operation sites such as the typhoon Yolanda in Tacloban, Philippines, where it helped in the identification of the operations site, and in the identification of usable roads. In the same disaster event, the CorePhil DSI team [13] used a fixed wing drone, eBee, to capture aerial imagery of downtown Tacloban. These images were further analysed through crowdsourcing and helped in the generation of the most detailed and up-to-date maps of the region. These maps were used by different humanitarian organizations, and even by the Filipino Government.

Controlling a fleet of drones is an established and on-going topic as well. In fact, it is a well-studied subject in the military context. However, even never mind the fleet control proposals are basically meant to help humans to control the fleet rather than having an autonomous fleet. For example, Cummings et al. [14] proposed an automation architecture to help humans in the supervision of a drone fleet, but the drones are not fully autonomous and it is the human operator who always decides drone missions. The same comments are valid for other works in the field, e.g., the work of Arslan and Inalhan [15], where the whole effort relies on helping one operator to control multiple drones.



Japan earthquake/tsunami, March 2011

Queensland Floods, February,2012

Japan earthquake/tsunami, March 2011

Zhouqu County, mudslides, Aug 10, 2010

Japan earthquake/tsunami, March 2011

Soma, Turkey, May 14, 2014

Fig. 1. Conditions in post-catastrophe areas.

1.2. Drone applications in disaster management

In a disaster scenario, drones can perform a number of different tasks to help relief efforts. Tasks may vary from providing communication to the creation of high-resolution maps of the area and the autonomous search for victims. Maintaining communication over disaster areas is challenging. One cannot just rely on the public communication network, firstly because it may be unavailable in remote areas, and secondly because even if it is available, the network may be damaged or destroyed. Nevertheless, the coordination of the relief efforts requires communication. Drones can work as temporary mobile access points for extending the coverage on affected areas. This service may be offered not only for the rescuers, but also for the general population with the creation of small pico-cells. For example, after hurricane Katrina, at New Orleans, the public network was out of service, and Verizon, the local provider, granted the right to use their frequencies to the first responders.

Another important task, which can be autonomously performed, is the creation of high-resolution maps of the affected area. Disasters may drastically change the affected region, which may introduce substantial voids in previously available maps. Drones can fly over the region with 3D cameras and, with the help of GPSs and publicly available relief maps of the region, automatically create up-to-date 3D maps of the area. These maps can be used to understand the impact of the disaster over the region and, for example, decide which roads need to be closed, find the best paths to reach the most damaged areas or even plan the delivery of relief supplies.

Drones can also actively assist in search and rescue (SaR) operations, where they can perform an infrared scan of the region, in order to try finding people buried under the debris. The use of ground penetration radars for finding people under the debris and the monitoring of portable devices, which may be a signal that some people may be buried in that region, is an appropriate strategy.

2. UAVs relief requirements

As can be seen from the images in Fig. 1, the environment and the conditions after a disaster are very chaotic. This environment is very dangerous, of course for people impacted, but also for the rescue teams. It is important to acquire knowledge on the event without endangering more people. This knowledge is dedicated to decision making. It must be reliable and must be available 24 hours a day in all weather conditions (day or night, sunny or rainy, etc.).

Another very important aspect characterising these situations is time. When there are people in critical condition, losses increase as time goes on. It is therefore necessary to be expedient.

The needed information to facilitate relief may be broken down into two parts:

- on the one hand, produce up-to-date information, as reliably and as quickly as possible. This information is intended for the decision-making process. It must be updated regularly;
- on the other hand, we are in a devastated environment. Information regarding networks (power, communications, water, roads, etc.) needs to be similarly considered.

Communication and coordination become very difficult in the region of a disaster. Therefore, it is necessary to facilitate the deployment of ad-hoc networks. These networks are required to distribute and share various information acquired and to allow a chain of command to coordinate the ground teams. In order not to endanger more people, autonomous systems provide a good solution, even if it is not the only one. But it is necessary to design systems that are fast to deploy. They must be deployed without requiring special skills. The design of systems for interventions in post-disaster conditions is an important challenge. Drones do not touch the ground or debris. They have the potential to facilitate assistance after the disaster and to expand the capabilities of rescue teams, even if some problems need to be solved urgently. By increasing the capability of flying drones associated with the use of non-conventional sensors such as LIDARs, IR cameras, etc., will strongly increase the capabilities of operational rescue regarding detection of victims, field mapping, damage assessment, etc. However, their use does not require special skills and must not obstruct rescue teams in their regular duties. This prerequisite explains our guidance on mission management issues and the capacity of autonomous flight.

All these requirements will lead to new research in robotics, image processing, embedded systems architecture, wireless communications, and security, etc. These aspects, in turn, raise new questions: which types of human–machine interface are the most appropriate for victims in the face of a drone? How can the presence of drones help relieve victims in critical conditions or provide them with useful information?

2.1. Payload requirements

We have selected three types of functions:

- Firstly, the function dedicated to Search and Rescue (SaR) operations. They mainly aim at the detection of people present on the site of the event. A simple detection is not enough. It is necessary to classify people (for example: victims or relief, adult or child, etc.). To count people. To establish contact with these people and to inform or educate them: where are the emergency teams, how to join, etc.
- The functions dedicated to ground recognition. It must ensure the completeness of the coverage of the area. We cannot forget a small location of the area because there could be victims waiting to be rescued.
- Finally, there are the functions for communication and coordination. This dictates the need to embed different sensors, which will be selected according to the type of mission, the conditions and parameters characterizing the event.

2.1.1. Search operations

In a similar fashion to terrain reconnaissance, satellites and aircraft are currently used to locate and count the victims of natural disasters, with equally problematic liabilities in terms of weather and diurnal conditions, as well as availability. Autonomy also plays a key role in this application, but specific features have to be developed in order to look for victims. An appropriate range of detectors will have to be combined in order to distinguish between human beings and inanimate objects, especially when victims are buried under ruins or debris and cannot be detected optically. The UAV should also be able to discern victims from rescue teams. Algorithms finally have to be adapted to the detection and monitoring of victims and groups of victims in order to anticipate their movements and to determine the medical treatment they may require.

2.1.2. Terrain-oriented reconnaissance

The detection and the monitoring of the impact of natural disasters on terrain are mainly performed by space-borne and air-borne methods relying on radio and optical instruments. Due to limitations of observation periods attached to optical instruments (i.e. no observation at night or in presence of cloud cover), radio observations are available 24/7 and relatively insensitive to atmospheric conditions: these are, therefore, particularly useful during the 'response phase' of the disaster management cycle, when information must be delivered to the disaster cell within the shortest possible delay [4–6].

Access to the data sensed by the UAV must be managed by the control centre. This should be in effect during in-flight communications, as well as in case of a crash for the data stored, within the UAV. In effect, the data sensed may be valuable commercially or may have political implications. However, the deployment of UAVs should not be diverted by third parties and ultimately result in hampering the relief operations.

2.1.3. Communications and coordination

UAVs might extend the communication range available as they may be deployed as mobile radio relays. UAVs may also convey messages in a disruption-tolerant network (DTN), during their normal operations, typically between the actors involved. Of course, the operation of a UAV generates its own communication needs, and a UAV control centre must be operated either by the disaster cell or by mobile units on site. The operation of such a centre should be as seamless and intuitive as possible, which can only be made possible by rendering the UAV navigation autonomous.

Data-sensing results have to be communicated as they are recorded, and will serve for the coordination of relief operations. In this sense, the UAV should also be autonomous in deciding which data to pre-process and to communicate in order to establish operational priorities.

Communications between a control centre and UAVs and between UAVs must be secured to prevent any unwanted interferences (pranksters and unlawful intervention, for instance), to prevent unauthorized access to the sensitive data sent to third parties, as explained below, and possibly to detect communication anomalies (crash of an UAV, radio jamming, etc.).

3. General requirements

Safety issues are a major concern in the use of drones for disaster relief. The low altitude and autonomy of navigation of a UAV may potentially cause injuries to nearby victims or rescuers in case of a crash, for instance. This means that UAVs

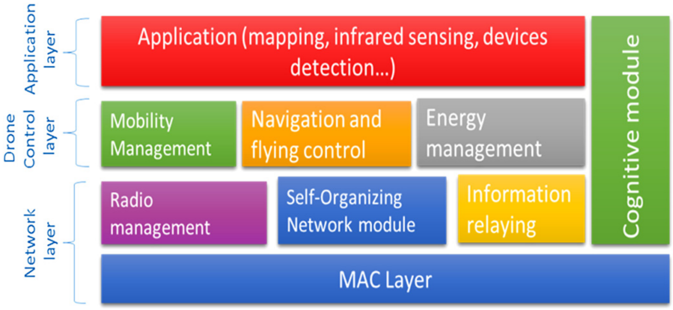


Fig. 2. Layered organization of drone modules [16].

must encompass this aspect from the very early phases of their design and include safety mechanisms in order to handle possible mechanical, hardware, and software failures. It is for instance possible to operate the UAV in a degraded mode with limited motor power in order to land safely or to open a parachute to reduce the impact speed.

The security of the data collected and stored on-board UAVs may be especially sensitive with respect to the victims' privacy. For instance, there have been situations in the past where pictures of recognizable victims have made the headlines without their agreement.

The deployment of UAVs for such applications will also bring up social challenges. Indeed, the apparition of a UAV may be terrifying to an unprepared victim, which might reduce the effectiveness of the detection operations. In contrast, victims may not notice UAVs flying at a high altitude and therefore they may fail to signal their position, as they would try to do for an aircraft. New standards will probably have to be defined in this respect.

The size of the systems is a significant problem. The system must be small enough to navigate through a maze of debris. So, the dimension of the drone, and the equipment that it embeds, needs to be limited to facilitate manoeuvrability.

The weight is also very important, especially for a flying drone system. Currently, we have autonomies of flight in operational conditions, with electric propulsion, for durations of about 30 min. In monitoring, a drone may not be enough. It is necessary to also have systems such as rovers on the ground, which are capable of 'sneaking' under the debris.

All these constraints demand the UAVs to have the following characteristics:

- to possess a scaling/sizing system in dependence of the type of event,
- a configuration of the payload (choice of sensors) depending on the type of mission,
- a design taking into account the weight (mainly of the batteries),
- optimal management of resources, in respect of low consumption of electrical power, so that low CPU powers (in the computer sense) are realised,
- and its corollary: it is necessary to have the ability to permit automatic reconfiguration during the mission, based on the changes that may occur (excessive power consumption, evolution of atmospheric conditions, etc.).

3.1. *Drone architecture*

Independently from the mapping, sensing or scanning methods, we wish to design autonomous drones, which are able to communicate and organize themselves. All drones, independently of their type, should be able to communicate with others and autonomously coordinate the actions to divide the tasks to be done. The organization layers proposed in Fig. 2 represent this common internal organization. Even though the implementation may change to consider the specifics of the drone, each one of the activities represented in Fig. 2 needs to be implemented by all drones.

The roles of each one of these boxes are the following: the MAC (Medium Access Control) layer provides the network abstraction to all the other modules. It hides the specifics of the network technology used and can be interchanged to adapt to local regulations and standards. The radio management sub-system is responsible for controlling the power of the radio and optimizes the communication with the other drones. The self-organizing network module is responsible for exchanging messages with the nearby drones to coordinate the efforts and divide tasks. The relaying of information is crucial for receiving data from the other drones and either forwarding it to the next drone in the direction of the destination, or passing on the information further until we find either the destination, or some other drone that is going in that direction.

The mobility management module is responsible for planning the mobility of the drone considering the objectives and the probable actions of the other drones in the region. The navigation and flying control module is responsible for implementing the planning done by the mobility management module. Based on geographic information, e.g., Global Positioning System (GPS) data, it controls the route and the power of the engines. This is the component of the architecture, which will guarantee that the drone will fly in the right direction and speed. The energy management module is in charge of keeping track of the remaining energy and for warning when it is time for the drone to return to the base. In case the energy gets critically low, it is this module that is responsible for starting the emergency procedure. The emergency procedure, among others actions, consists of sending a distress message with the current position, and safely landing the drone while repeating the distress message at regular intervals.

The application layer relates to the task to be done at the time, the kind of drone, and the type of sensors available on the drone. The application section should also be interchangeable and versatile, since the tasks for the drones may evolve during the rescue operation effort.

The cognitive module, transverse with to all the others, provides generic AI (artificial intelligence) algorithms that help in the decision-making activities of all other modules. For example, the mobility management module can use it to try to infer the actions that other drones will take to optimize the coverage of the area. The energy management module can use it to decide the best moment to return to the base. i.e. based on the energy consumption, and how much energy the drone should spend to fly from its present location to the base.

3.2. Radar specifications

3.2.1. General considerations

The main application of the ground-penetrating drone-mounted instrument would be to detect, not only the sub-surface environment, but also to possibly detect human beings buried under debris generated by landslides or the collapse of buildings.

In the area of hardware realisation, the key problem will be to have a final ‘radar’ unit weighting no more than a few kilograms that can be mounted, powered and flown on a small copter-type-based carrier (drone) capable of autonomous operation.

Given the low capacity of drones in terms of both weight and energy payload, on the one hand, and the operational context and observational conditions – both quite specific –, on the other hand, there is no question to simply transpose the concepts used for GPR ground-based equipment. By contrast, since priority is primarily given to the search of victims, the detection of mobile phones, widely used in urban areas, could be a pertinent indicator to be exploited. Moreover, it would be useful to take advantage of the drone mobility, flying either alone or grouped. Existing methods and technologies for electronic warfare (EW) are certainly a non-negligible advantage.

In all cases, the estimation of propagation loss and wave dispersion in the sub-surface medium is the main challenge. Many existing documents dealing with the various aspects of propagation are available [17–20]. However, in the present context, the conditions of observation are very specific.

In particular, a deep knowledge of propagation conditions (both ways) in the bands used by mobile phones is essential to evaluate the losses and dispersions of EM waves transmitted by buried phones, even if they are located near the surface through chaotic soil. Since mobile phones have only a short duration of transmission, the use of drones offers the advantage of a quick intervention.

A further phase would be to transmit from the drone signals similar to those of cellular phone base-stations.

The main challenges addressed in this contribution are:

- the identification of a ‘radar-method’ based on scattering geometry that will potentially permit drone-borne application of a ground-penetrating radar (GPR), which has neither ground contact nor the conventional ground-‘hugging’ ‘normal incidence’; the estimation of propagation loss and estimation of GPR echo power following sub-surface penetration;
- wave dispersion in the form of signal attenuation in dependence of frequency and the sub-surface medium;
- these features are the key constraints on the performance of a GPR system. In this regard, we first of all identify the scattering mechanism that will yield measurable sub-surface echoes. Secondly, we consider sub-surface propagation using a realistic range of values of the electrical properties of soil and water volumes drawn from open literature. In the area of hardware realization, the key problem will be to have a final radar unit weighing no more than a few kilograms that can be mounted, powered, and flown on a small copter-type-based carrier (drone) capable of autonomous operation. To the best of our knowledge, there is no literature that reports on the viability of a drone-mounted GPR. In the next two sections, we address this issue.

3.2.2. General issue: key radar design questions

The design of any radar system requires that we identify the essential technical parameters. In this regard, we consulted references [21] and [22]. The design parameters of the sought drone-mounted GPR may be classified as follows.

Imaging parameters/field of view (basic requirements)

- swath-width (footprint dimension in the cross-track direction)
- along-track resolution
- penetration depth
- maximum unambiguous range

Radar system parameters

- frequency

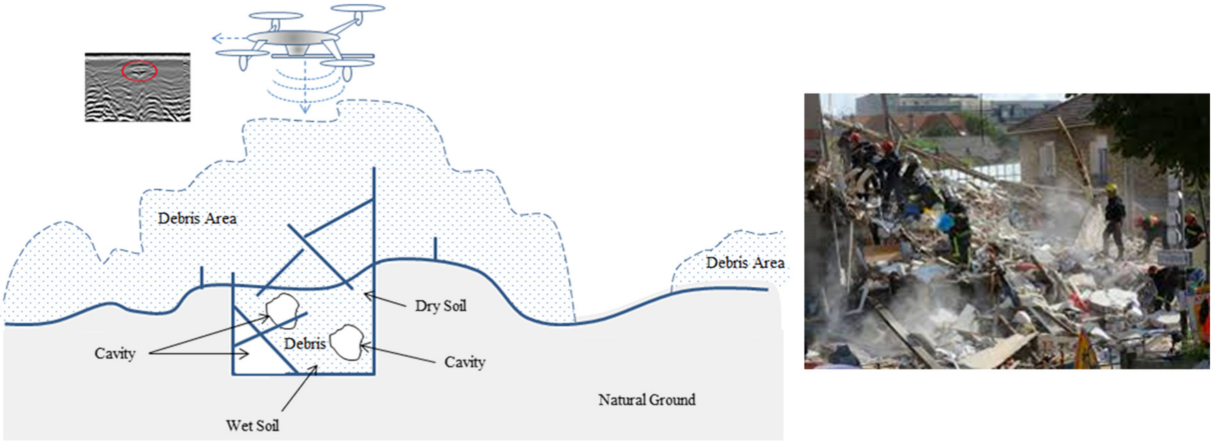


Fig. 3. Characterization of the soil after an earthquake.

- antenna
- polarisation
- pulse bandwidth
- prf or waveform repeat frequency
- transmit power (watts)
- radar platform height

Given the need to identify the above parameters, we also need to ask which type of radar system will be able to provide the functionality embodied in the above parameters. In this regard, we will seek the most befitting combination out of the following possibilities.

- Direct aperture
- or synthetic aperture
- or both
- pulsed or frequency modulated continuous wave (FMCW)

We start by identifying fixed parameters levelled by the essential physics and the end-user requirements.

Imaging parameters / field of view (ideal requirements)

- swath width: 30–50 m
- range resolution: much less than 1 m
- along-track resolution: much less than 1 m
- penetration depth:1–10 m
- maximum unambiguous range: 5–10 m

Radar system parameters

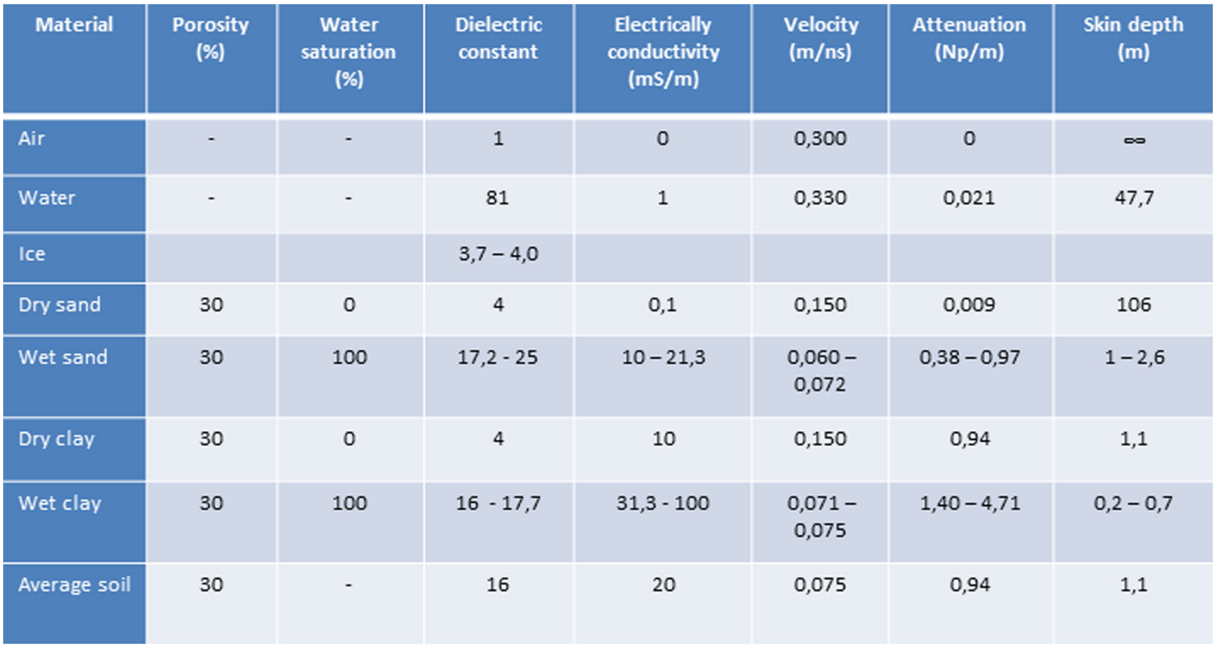
- Antenna: aperture length (along- and cross-track directions): 1 m
- available payload power: ideally less than 10 W
- available payload weight: ideally less than 1.5 kg
- pulse bandwidth: 100–150 MHz
- Pulse repetition frequency (PRF): that permit the measurement of Doppler velocities down to 1 m/s
- transmit power: 1 W[1]
- maximum radar platform height: 5 m

3.2.3. *Post-earthquake soil organisation*

Organisation of soil is heterogeneous and chaotic (see Fig. 3), the properties change with every layer and the depth of buried people is unknown. So, how do we define the basic physical features velocity, permittivity or dielectric constant? Fortunately, according to the type of construction, we can deduce the maximal depth of the underground section of the building.

---

[1] A 1-W RF output over 10 W overall available electric power seems very high; this RF power level is only taken as a parameter for simulation.



Material	Porosity (%)	Water saturation (%)	Dielectric constant	Electrically conductivity (mS/m)	Velocity (m/ns)	Attenuation (Np/m)	Skin depth (m)
Air	-	-	1	0	0,300	0	∞
Water	-	-	81	1	0,330	0,021	47,7
Ice			3,7 – 4,0				
Dry sand	30	0	4	0,1	0,150	0,009	106
Wet sand	30	100	17,2 - 25	10 – 21,3	0,060 – 0,072	0,38 – 0,97	1 – 2,6
Dry clay	30	0	4	10	0,150	0,94	1,1
Wet clay	30	100	16 - 17,7	31,3 - 100	0,071 – 0,075	1,40 – 4,71	0,2 – 0,7
Average soil	30	-	16	20	0,075	0,94	1,1

Fig. 4. Representative low-frequency properties of basic constituents of soil.

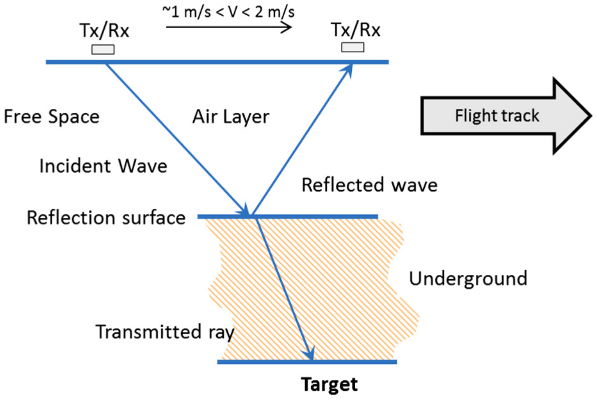


Fig. 5. Propagation scenario: ‘air’ layer.

The physical characteristics of soils are highly variable. In the context that interests us (earthquakes), the soil is very chaotic. Fig. 4 displays an example of representative low-frequency properties of basic constituents of soil. Due to this variability, it is very difficult to use the usual equations without changes. Fig. 4 is only meant to provide a general impression. More specific propagation analysis is reported in section 4 of this contribution.

3.2.4. Propagation issues

Our adopted approach: an unconventional approach in measuring echoes from sub-surface objects (see Fig. 5). We consider slantwise incidence. This approach is unconventional in the sense that most traditional GPRs use normal incidence. The reader may rightly question the rationale for doing this: for instance, it may be argued that the reflected ray will reduce the backscattered power for the monostatic case depicted in Fig. 5. In section 4, we will address this issue.

Propagation constant

In the simulation used, we referred to reference [23] for calculating the complex propagation constant in a lossy medium such as soil.

$$\gamma = \alpha + \mathrm{j}\beta = \mathrm{j}\omega\sqrt{\mu_0\mu\varepsilon_r(\varepsilon'_{0r} - \mathrm{j}\varepsilon''_r)} = \alpha + \mathrm{j}\beta$$

The complex propagation constant accounts for both the attenuation (the real part) and the phase shift (imaginary part).

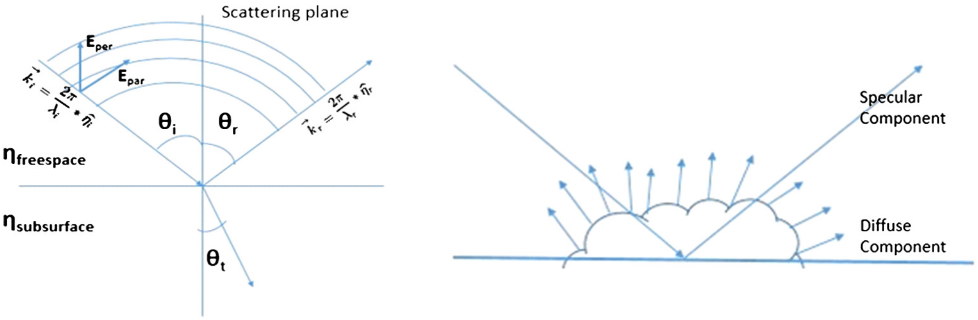


Fig. 6. Scattering mechanism.

Basic scattering scenarios

As mentioned, we consider, as shown in Fig. 5, a drone-borne GPR that employs slantwise incidence and measures the backscattering from the illuminated ground surface. In order to elucidate the idea behind this strategy, we first recall Fresnel's equations for computing the reflection coefficients for slantwise incidence. The reflection coefficients for the transverse magnetic and transverse electric incidences are given below in dependence of the angle of incidence in the free-space ('fs') and the angle of transmission in the sub-surface ('ss') domain (Fig. 6).

$$\Gamma_{TM} = \frac{\eta_{\text{ss}} * \cos\theta_{\text{ss}} - \eta_{\text{fs}} * \cos\theta_{\text{fs}}}{\eta_{\text{ss}} * \cos\theta_{\text{ss}} + \eta_{\text{fs}} * \cos\theta_{\text{fs}}}$$

$$\Gamma_{TE} = \frac{\eta_{\text{ss}} * \cos\theta_{\text{fs}} - \eta_{\text{fs}} * \cos\theta_{\text{ss}}}{\eta_{\text{ss}} * \cos\theta_{\text{fs}} + \eta_{\text{fs}} * \cos\theta_{\text{ss}}}$$

At this stage, we simply note that the relationship between the angle of incidence and the angle of transmission can be calculated using Snell's law of reflection and refraction. Using the basic physics outlined in this section, we consider various simulations given in the next section.

4. Simulations and specifications

In the following section, we consider simulations of: (1) the scattering behaviour from diverse terrain surfaces in dependence of polarisation in order to highlight the Brewster angle effects, (2) the amplitude dispersion of EM waves depending on frequency and the type of medium, (3) the received echo powers from buried human beings in different media and depending on radar frequency. The physical parameters used in the simulation are either presented on the figures or detailed in the short discussion following these (Fig. 7).

4.1. Scientific discussion of the simulation results and their implications on the radar design

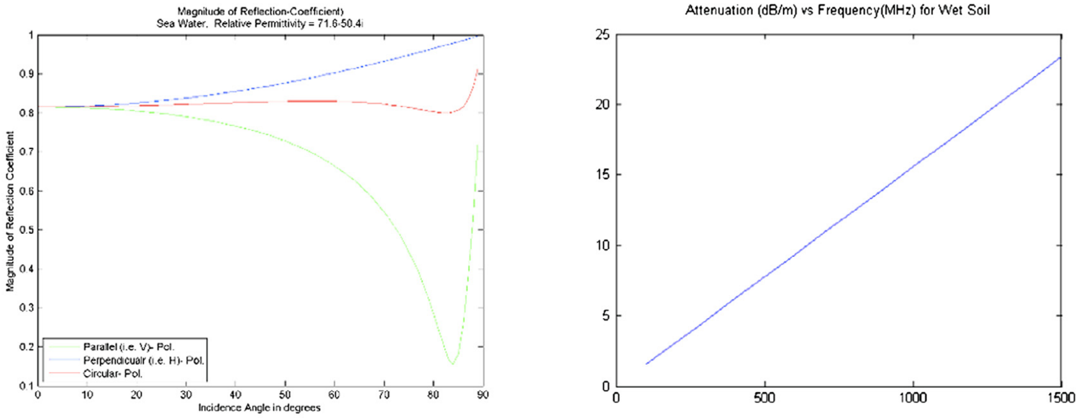
First of all, we note that the 'Brewster effect', shown typically by the reflection coefficient of sea water, is clearly and significantly present in lossy media such as sea water. The fact that for the Brewster incidence the reflection coefficient is at a minimum implies that, for such incident angles, the incident power is preferentially and maximally transmitted into the sub-surface region. Herein lies the justification of the suggested unconventional approach of employing slantwise incidence instead of the traditional normal incidence. This strategy assumes that the drone-borne GPR is set to radiate at Brewster incidences appropriate to the surface medium. Using this concept, summarised above are also the two-way radar-received power budget graphs (i.e. received radar echo power in dependence of sub-surface penetration) realised with the Brewster incidence angles appropriate to the considered media. In this spirit, we have included the 'power budget' response for sea water (the worst case) and wet soil (also a high attenuation case).

In the simulation given above, we assumed an antenna aperture of 30×30 cm^2 and a backscatter cross section of 1 m^2 [2] for the 'buried human being'. The peak radar transmit power was set to 1 W. The path loss and the estimated received powers, summarised in the simulations above, show that the d-borne GPR could yield measurable echo power greater than -100 dBm from subsurface depths up to 1–10 m in certain parts of the frequency range of 1–450 MHz.

In view of the limited electrical power and the heavy demand on resolution, we suggest the method of FMCW–SAR to be employed on the drone-borne GPR. A more limited case would be to consider a frequency-modulated synthetic aperture radar (SAR). In any case, a more judicious analysis needs to be conducted in this regard. We also note that a more detailed analysis of phase dispersion and amplitude dispersion will be required before a prototype drone-mounted GPR can be

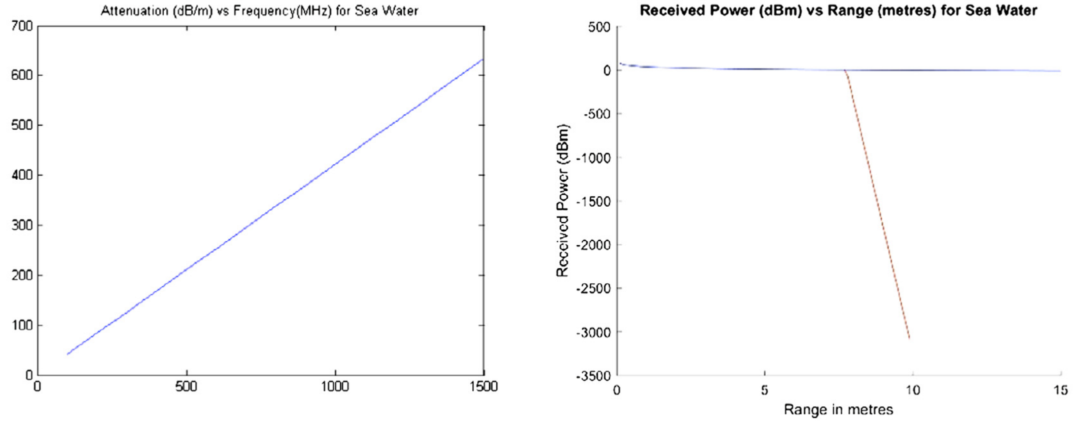
---

[2] It is certainly a larger figure of radar cross section (RCS) than a real one; again it is a convenient arbitrary figure to use for comparative simulations.



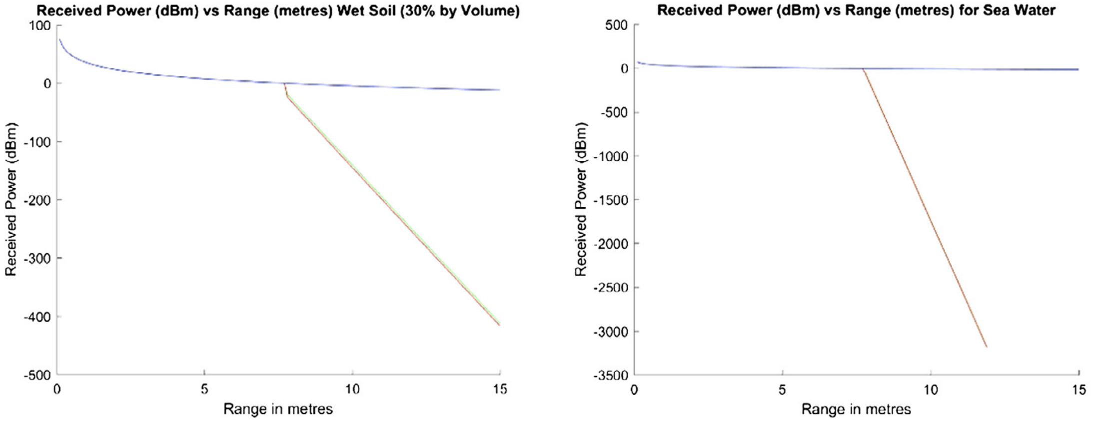
Reflection coefficient vs. incident angle and polarisation: sea water @ L-band

Attenuation (dB/m) vs. frequency (MHz): wet soil



Attenuation (dB/m) vs. frequency (MHz): sea water

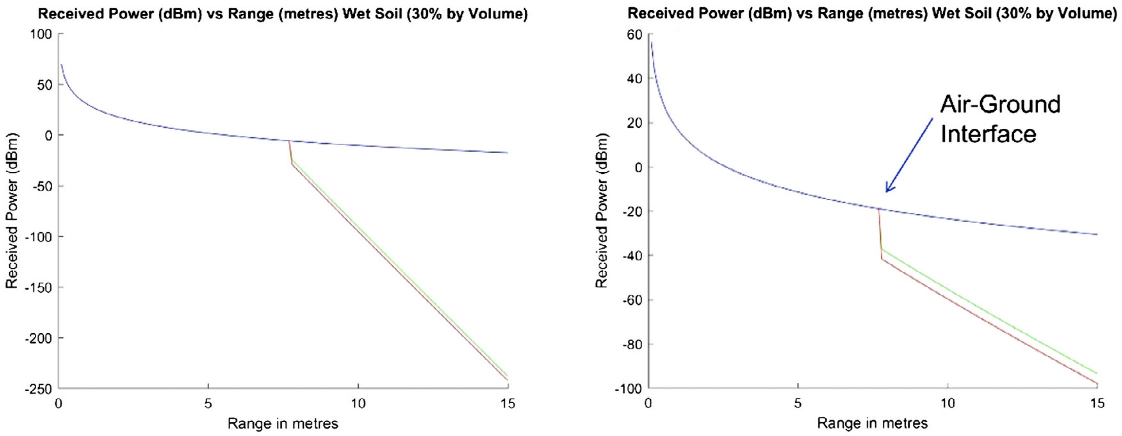
Rx power vs. range and subsurface penetration in sea water @850 MHz with TM (given in green colour) and TE Incidence (given in blue colour) @50°. The two graphs overlap.



Rx power vs. range and sub-surface penetration in wet soil @850 MHz with TM (given in green colour) and TE incidence (given in blue colour) @50°

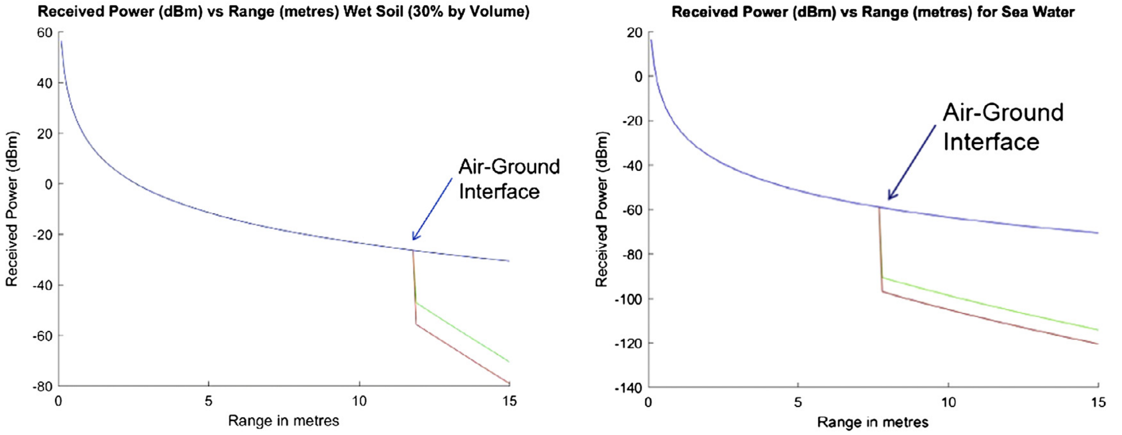
Rx power vs. range and sub-surface penetration in sea water @450 MHz with TM (given in green colour) and TE incidence (given in blue colour) @50°. The two graphs overlap.

Fig. 7. Summary of the simulation results summarising the following dependences: (i) reflection from sea water as a function of the angle of incidence and polarisation, (ii) the received radar echo power for slantwise incidence in the region of Brewster scattering from sea water and wet soil in dependence of frequency and the angle of incidence (chosen from the region Brewster scattering appropriate to the medium in question). In calculating the echo power, a peak transmit power of 1 W and a human backscatter cross section of one square metre was assumed. For instance, in the lowest graph on the left, for wet soil and a radar frequency of 1 MHz, the received echo power at the range of 15 m (about 7 metres into the sub-surface region) is above the −100 dBm level.



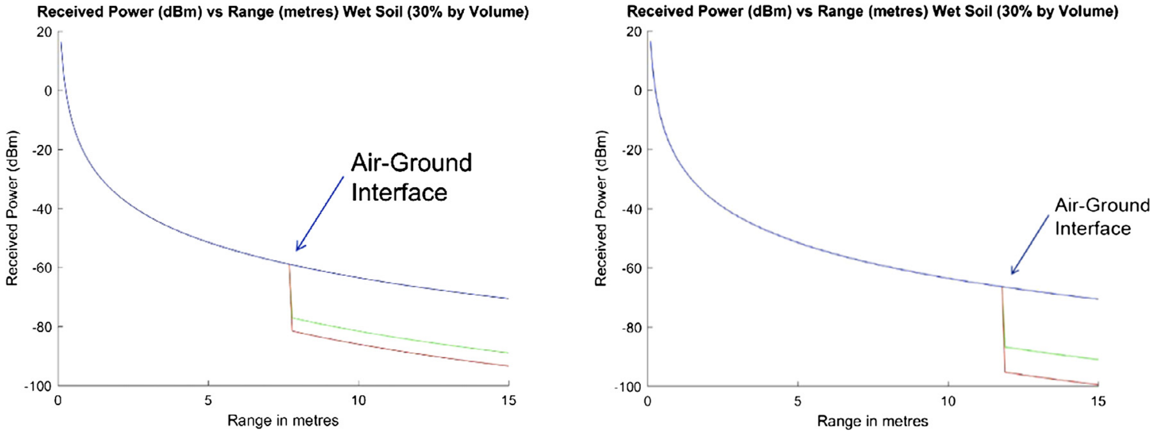
Rx power vs. range and sub-surface penetration in wet soil @450 MHz with TM (given in green colour) and TE incidence (given in blue colour) @50°

Rx power vs. range and sub-surface penetration in wet soil @100 MHz with TM (given in green colour) and TE incidence (given in blue colour) @50°



Rx power vs. range and sub-surface penetration in wet soil @100 MHz with TM (given in green colour) and TE incidence (given in blue colour) @65°

Rx power vs. Range and Sub-Surface Penetration: sea water @1 MHz with TM (given in green colour) and TE incidence (given in blue colour)



Rx power vs. range and sub-surface penetration in wet soil @1 MHz with TM (given in green colour) and TE incidence (given in blue colour) @50°

Rx power vs. range and sub-surface penetration in wet soil @1 MHz with TM (given in green colour) and TE incidence (given in blue colour) @65°

Fig. 7. (*continued*)

designed. The frequency dependence of attenuation, considered here, is simply meant to confirm that the dispersion effects are also a major issue.

Crucial to the application of the proposed measurement strategy is the judicious use of polarisation dependence, which permits the optimum application of the Brewster angle effect in the case of TM incidence. This feature ensures optimal sub-surface penetration, which in turn yields measurable echo powers from buried 'objects'. Nevertheless, in addition to the needed detailed analysis of dispersion effects, one challenge remains, namely the miniaturisation of the HF antenna.

4.2. Risks of interference

Frequency management organizations face new challenges in relation to GPR and similar devices resulting from Ultra Wave Band (UWB) technology used on the one hand, and the tendency of radio Administrations to facilitate the spectrum access, on the other one.

UWB devices include not only GPR, but also very short communications and location tracking at short distances. In addition, they use a broad variety of technologies: pulses, code division multiple access (CDMA), orthogonal frequency-division multiplexing (OFDM)... [24].

The general characteristics are [20,21]:

- large bandwidth, 500 kHz–5 GHz,
- low power or e.i.r.p. density levels,
- potential for high-density deployment increasing the risk of impacting a variety of radio communication services.

Numerous interference scenarios are possible, for example,

- interference produced by one single device on others,
- interference produced by several devices emitting simultaneously.

Both types of scenarios have to be envisaged in the present context.

5. Conclusion

The reported analysis of GPR signals indicates that measurable echo powers greater than -100 dBm may be anticipated under the application of the 'Brewster incidence' using the radar parameters considered here. We may therefore conclude that a drone-borne GPR may be entirely feasible, providing the GPR is enabled to operate in the region of Brewster incidences. Using this method, SAR radar systems using either the frequency-modulated continuous wave (FMCW) and/or pulse modulated signals would be viable options for GPR design.

Search and rescue operations can surely make use of drones for a fair amount of activities. However, if not autonomous and capable of self-organization, these elements can be more of a burden than a help in a catastrophe scenario. Rescuers must focus on the activity they have at hand, that is saving lives. It is not their job to spend their time handling drones and simultaneously doing their tasks. The proposed architecture intends to provide the organization required from a fleet of drones to autonomously, at the push of a button, scan the region and provide useful information. Another intention of the proposed architecture is to use this fleet to provide communication over disaster areas, even for severely affected areas.

It is important to notice also that drones should be able to perform opportunity-driven communication and coordinate with the nearby nodes. In a disaster scenario, store-carry-and-forward techniques may be the only way to convey important information among the computational elements. Drones can exchange information with each other about the route and strategies they are taking, and if they are, for example, moving in the direction of the operations centre, they can carry the messages of other drones until their final delivery at the destination. In the same way, message ferries are designed [5].

Different kinds of drones may provide different services and, ideally, should play the roles they fit best. Even though we could exchange some of the tasks among the different drones, it would have an impact on the end results. For example, we could, without doubt, use fixed-wing drones to create a mobile backbone. However, not only would the organization of the drones to provide constant full coverage be more complex, but also the lifetime of the backbone would be much shorter.

Among all the high-tech objects of our modern environment, drones have an impressively high potential to offer fast and efficient responses in rescue conditions, even if some difficulties must be tackled. The new applications, such as intervention in hostile environments, require an effective autonomy of mini-drones concerning the energy (duration of the mission) and the control command (decision autonomy). Hardware and software issues have to be addressed: Which algorithmic architectures are to adopt? Which embedded system configuration is the most suitable one? Which kinds of GUI are the most appropriate for victims ahead of the drone? How can a drone help to provide relief to people in critical conditions or to provide useful information?

The design of a civilian UAV intended for intervention in post-disaster conditions is an important challenge. The gain in autonomy of mini-drones, coupled with the use of non-conventional sensors, such as Lidar, IR camera, etc., will strongly increase response capabilities – e.g., detection of human beings, rapid mapping, damage estimation, etc. – of the rescue teams on the ground. To be effective, these customized sensor systems must perform their duties in an independent manner and transmit their data. This information will then be inserted in the decision-making cycle. It is also imperative that the manipulation of these systems does not require special skills. This condition is a '*sine qua non* condition' which explains the rationale of our focus on autonomous flights and missions. Without such capacity and capability, it would not be possible to correctly integrate these new tools within the rescue teams.

The next step consists in carrying out terrain measurement experiments and to acquire data to validate our approach. Indeed, we were not able for the moment to anticipate some actions. For instance, a typical mobile phone is supposed to look for a network while none is detected. This search requires the device to use full power, which drains the battery severely. For this reason, some manufacturers may decide a time-out mode to reduce this problem. We thus have to check if this kind of policy is still compliant with the goals we are trying to achieve.

Another aspect concerns the adaptation of the approach considering the geographical area. Of course, it has a reasonable chance to work in various places with an average standard of life. However, disasters can strike anywhere. So, the question is to determine how such a system can behave in developing countries with emerging networks infrastructures.

Once we address these issues, we can fully utilize autonomous drones for supporting disaster relief.

References

[1] D. Guha-Sapir, P. Hoyois, R. Below, Annual Disaster Statistical Review 2012: The Number and Trends, CRED, Brussels, 2013.
[2] T.J. Tanzi, F. Lefeuvre, Radio sciences and disaster management, C. R. Physique 11 (2010) 114–224.
[3] M. Chandra, Overview of modern multi-parameter methods of radar remote sensing in context of disaster management, in: XXXIst General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS 2014), ISPRS-URSI Disaster Management Special Session, Beijing, China (CIE), 17–23 August, 2014.
[4] P. Wilkinson, D. Cole, The role of the radio sciences in the disaster management, Radio Sci. Bull. 3358 (2010) 45–51.
[5] F. Lefeuvre, T. Tanzi, International Union of Radio Science, International Council for Science (ICSU), Joint Board of Geospatial Information Societies (jBGIS), in United Nations Office for Outer Space Affairs (OOSA), 2013.
[6] T. Tanzi, F. Lefeuvre, The contribution of radio sciences to disaster management, in: International Symposium on Geo-Information for Disaster Management, Gi4DM 2011, Antalya, Turkey, 2011.
[7] E. Ackerman, Drone Adventures Uses UAVs to Help Make the World a Better Place, IEEE Spectrum, May 2013.
[8] T.J. Tanzi, Y. Roudier, L. Apvrille, Towards a new architecture for autonomous data collection, Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. XL-3/W3 (2015) 363–369.
[9] T. Tanzi, P. Perrot, Télécoms pour l'ingénierie du risque (in French), Collection technique et scientifique des Télécoms, Éditions Hermès, Paris, France, 2009.
[10] A. Gademer, B. Petitpas, L. Beaudoin, T.J. Tanzi, B. Riera, J.-P. Rudant, in: Using Centimetric Visible Imagery Obtained from an UAV Quadrotor for Classification of ERS Images ESA Living Planet Symposium, European Space Agency, Bergen, Norway, 2010.
[11] O. Sebastien, F. Harivelo, D. Sebastien, Using general public connected devices for disasters victims location, in: 31th URSI GASS, Beijing, China, August, 2014.
[12] J. Pedersen, Use of UAVs in the NGO world, in: CRS Conference, ICT4 Development, Nairobi, Kenya, 25–28 March, 2014.
[13] P. Meier, Humanitarians in the sky: using UAVs for disaster response, http://irevolution.net/2014/06/25/, 25 June 2014, last viewed, 30 June 2014.
[14] M.L. Cummings, S. Bruni, S. Mercier, P.J. Mitchell, Automation architecture for single operator, multiple UAV command and control, Int. C2 J. 1 (2) (2007) 1–24.
[15] O. Arslan, G. Inalhan, Design of a decision support architecture for human operators in UAV fleet C2 applications, in: 14th, International Command and Control Research and Technology Symposium, ICCRTS, Washington, DC, June 2009.
[16] D. Camara, Cavalry to the rescue: drones fleet to help rescuers operations over disasters scenarios, in: IEEE Conference on Antenna Measurements & Applications, CAMA, Antibes, France, 2014.
[17] Rec. ITU-R P. 527-4 Electrical characteristics of the surface of the Earth.
[18] Rec. ITU-R P. 2040-1 Effects of building materials and structures on radiowave propagation above about 100 MHz.
[19] Report ITU-R P. 2346-0 Compilation of measurement data relating to building entry loss (in support of the material in Rec. ITU-R P.2040).
[20] Rec. ITU-R SM.1754 Measurement techniques of ultra-wideband transmissions, Rec. ITU-R SM.1755 Characteristics, Rec. ITU-R SM.1756 Framework & Rec. ITU-R SM.1757 Impact of ultra-wideband technology.
[21] R. Persico, Introduction to Ground-Penetrating Radar: Inverse Scattering and Data Processing, John Wiley, ISBN 9781118305003, 2014.
[22] H.D. Griffiths, C. Baker, D. Adamy (Eds.), Stimson's Introduction to Airborne Radar (Electromagnetics and Radar), 3rd edition, ISBN-13:978-1613530.
[23] D.M. Pozar, Microwave Engineering, 4th edition, John Wiley, December 2011, ©2012, ISBN:978-1-118-29813-8.
[24] P. Tristant, in: ITU/WMO seminar on use of radio spectrum for meteorology: weather, water and climate monitoring and prediction, 16–18 September 2009.