Construction of digital elevation models of the environment with lightweight airborne radar: simulation results

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Highlights: There is a growing need for lightweight airborne platforms that could provide precise information about the environment even in degraded visual conditions. Due to its wavelength, microwave radar provides an alternative solution to overcome the shortcomings of optical solutions. A simulator is developed to define the main parameters of future airborne radars.

Key words: *FMCW radar; DEM; drone; simulation.*

Introduction

For several situations, satellite imagery and remote sensing analysis are the only way to see what has occurred on the ground. If many types of satellite imagery are readily available, they sometimes cannot offer sufficiently high resolution, cover the specific area of study, or capture the time series necessary to fulfill the entire purpose of a project. Considering this situation, a low-cost and high-resolution perception system based on unmanned aerial vehicle (drone) can fill the data gap between satellites/airplanes and ground surveying systems.

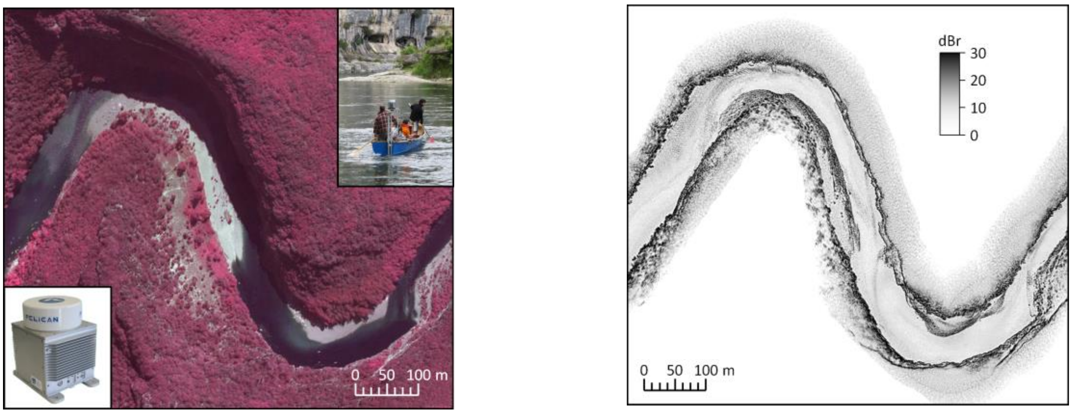
In a report of May 2013, the United Nations Environment Programme (UNEP) outlines that drones can provide a low-cost and low-impact solution to environmental managers working in a variety of ecosystems [1]. Drones used for these purposes are referred to as *eco-drones* or *conservation drones*. The agility and the imaging abilities of drones make them advantageous as a mapping tool for the monitoring of the environment, but there are still several challenges and concerns to be surmounted.

One of these challenges is related to perception and navigation in degraded visual environments (DVE). DVE refers to circumstances wherein optical perception systems (vision, laser) are ineffective due to weather conditions (rain, fog, etc.) or the presence of obscurants (dust, smoke). In such situations, microwave radar can provide an alternative solution to overcome the limitations of optical sensors: due to a millimeter or centimeter wavelength, radars are robust sensors in DVE conditions. In remote sensing applications, radars have been initially designed for large platforms such as airplanes or satellites. With the development of drone-based applications, these systems are progressively adapted for smaller platforms in terms of dimension, weight, energy consumption and cost. In [2], a Synthetic Aperture Radar (SAR) is developed: the system provides 2D maps of the environment, but the complexity of the overall system makes it incompatible at the moment with low-cost civilian applications. Our objective is to develop a radar for light airborne platforms such as drones, in order to be able to build digital elevation models (DEM) of the overflown environments independently of visual conditions and time of day. Applications being considered are related to all-weather perception: monitoring of natural areas, DEM construction and obstacle detection for crisis intervention, drone autonomous navigation, etc. And as a first step of a future radar sensor, it has been decided to develop a simulator of airborne radar, in order to help the designer to define the best radar configuration.

This paper presents an overview of the developed radar simulator. The radar model is based on Frequency Modulated Continuous Wave (FMCW) principle, which is well-intended for short and medium range applications. Moreover, the relative simplicity of FMCW architectures can help to develop small-sized systems, compatible with drones. Preliminary results obtained in 2D radar map construction are presented in the first part of the paper. The second part describes the principle of DEM construction with FMCW radar measurements. The main elements of the simulator are presented more in details: environment modeling, trajectory modeling and radar modeling. The last part presents an example of DEM construction obtained with the simulator.

From 2D mapping to 3D mapping

PELICAN panoramic radar has been developed at Irstea Institute for perception and mapping applications in the domain of autonomous robotics and environmental monitoring [3]. With small size and light weight, PELICAN can be positioned on various vehicles including robots and small boats. It is associated with the R-SLAM algorithm allowing the construction of 2D maps of the environment. An example of river gorge monitoring application with PELICAN radar is presented in Figure 1.



(a) (b)

Figure 1: 2D radar map obtained with PELICAN radar and R-SLAM algorithm. (a) IR aerial image of the test zone (Ardèche river, France). The lower left image is a view of PELICAN radar. The upper-right image shows radar positioned on a boat. (b) 2D radar map. Grayscale levels refer to the amplitude of the reflected radar signal.

PELICAN radar is using a *fan-beam* antenna: narrow aperture in the horizontal plane (*azimuth*) and wide aperture in the vertical plane (*elevation*). Such an antenna is well-intended to make the radar robust to some severe positioning variations in pitch and roll of the platform. But, as the targets' elevations are not measured, only 2D maps can be constructed. Thus, it is necessary to design new radar in order to be able to build DEM of the environment. Within this framework, it has been decided to develop a simulator in order to assist the user in defining the most suitable radar configuration, with the perspective of developing a new radar sensor for small UAV applications.

Overview of the simulator

The simulator is based on the following structure:

- A model of the overflown environment, described with geometrical and electromagnetic properties,
- A geometrical model of the trajectory of the airborne platforms, in terms of position, attitude and velocity,
- A model of FMCW radar, in order to describe the radar antenna and the backscattered radar signal.

Once these models are configured, a radar survey is simulated. Based on radar measurements and radar localization, a DEM is computed and compared to the model of the environment. Different test scenarios (trajectory, environment) will be used in order to estimate the best radar configuration.

3D radar mapping principle

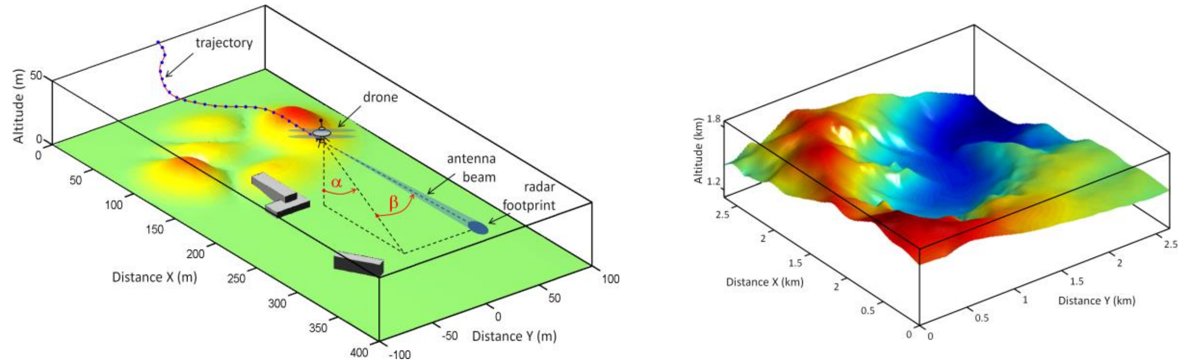
The developed solution uses radar with a *pencil-beam* antenna which produces small radar footprint. Such radars are used to develop "see-through" solutions for helicopter landing in DVE [4]. But in order to reduce the mechanical complexity of the scanning, the antenna has only one degree of freedom (scanning angle β). The antenna rotation covers transversal scan, so that a strip of ground perpendicular to the aircraft trajectory is illuminated in front of the platform. The longitudinal scan is obtained with the displacement of the aircraft. An illustration of this approach is presented in Figure 2(a). The incidence angle α is maintained constant (in the aircraft axis system), but it can be adjusted depending on the altitude and/or the velocity of the aircraft. Radar distance measurements are combined with the 6D localization of the aircraft in order to produce a synthetic 3D image of the overflown environment.

Environment model

The simulator is designed so that the user can work with a whole range of environments. The starting point of the spatial discretization of the environment is a Delaunay triangulation. Each modeled point is characterized by 3D coordinates (x_e,y_e,z_e) in the reference frame, a normal vector $\vec{n}$ to the surface of the corresponding triangle, and a backscatter coefficient σ_0.

Positions (x_e,y_e,z_e) allow to compute the radar-point distances r. The normal vector $\vec{n}$ is used to determine the local incidence angle α_l. The local incidence angle α_l is the angle between the incident radar signal and the normal vector to the surface. Associated with the velocity vector of the platform, it allows computing the radial velocity of each point of the environment. The backscatter coefficient σ_0, also called normalized radar cross-section (radar cross-section per unit of area) is a representation of the strength of the signal backscattered by a given ground resolution cell and measured by the radar. We are using a constant gamma model which is a simple model of σ_0 but often used in radar remote sensing [5].

The constructed environment is virtual. The user adds buildings (parallelepiped forms), defining sizes, locations and orientations. Data extracted from georeferenced databases can also be used to build more realistic environments. An example with the Vallée de Chaudefour (Auvergne, France) computed from data of the French database BD Alti® (IGN©) is shown in Figure 2(b).



(a) (b)

Figure 2: 3D radar mapping principle. (a) The pencil-beam antenna scans a strip perpendicular to the aircraft trajectory. The displacement of the drone is used to produce DEM of the environment. (b) Example of realistic environment constructed with the French database BD Alti® (Vallée de Chaudefour, Auvergne, France).

Trajectory model

The different phases of flight can be modeled, either takeoff, climb, cruise, descent or landing. The trajectory is created by the user; or it can be based on real data collected by a flight recorder. The objective of the trajectory modeling module is to simulate data provided by the Inertial Navigation System (INS) that will be used on the airborne platform.

Radar model

Radar model and future radar developments within this project are based on Frequency Modulation Continuous Wave (FMCW) principles [6]. FMCW radar is well-adapted to short and medium range distance applications, because it eliminates the blind zone near the radar (in the case of pulse radars, the blind zone is introduced by the duration of the transmitted pulse). Due to the coupling between transmitting and receiving stage, the transmitted power and thus the maximum range are limited with FMCW radar. But it is not a limitation in our application considering the envisaged radar-target distances ($\ll 1\,\mathrm{km}$).

In FMCW radars, the oscillator transmits a signal of linearly increasing frequency Δf over a period t_m. This signal is transmitted into the air via the antenna. At the receiver stage, a part of the transmitted signal is mixed with the signals received from the i targets present in the field of view of the radar. The signal which appears at the output of the mixer is filtered and amplified in order to isolate the beat signal s_b. Let us consider i targets located at distance r_i from the radar, with radial velocities v_i. The transmitted signal is linearly modulated over a period $t_m = 1 / f_m$ with a sawtooth function, with a frequency sweep Δf centered about f_0. In that case, the beat signal s_b can be written as [7]:

$$s_b\left(t\right) = k \sum_i V_e\, V_{ri} \cos\left(2\pi \underbrace{\left(2\,\Delta f \;\; f_m \frac{r_i}{c} + 2\; f_0 \frac{v_i}{c} \right)}_{f_{bi}} t + \Phi_i \right) \tag{1}$$

where V_e is the amplitude of transmitted signal, V_{ri} and Φ_i respectively the amplitude of received signal and a phase term depending on target i, and k a mixer coefficient. As it can be seen in (1), the beat signal s_b is the sum of i frequency components f_{bi}, (plus a phase term Φ_i), each of them corresponding to a particular target i. The first part of f_{bi} only depends on the range r_i, and the second part is the Doppler frequency shift induced by the radial velocity v_i.

Two angles define the -3dB antenna aperture: the azimuth angle θ_{az} and the elevation angle θ_{el}. Pencil beam antennas will be simulated, with aperture angles typically between 2° and 3°. The antenna radiation pattern follows a Gaussian shape (in azimuth and elevation). Side lobes can be considered.

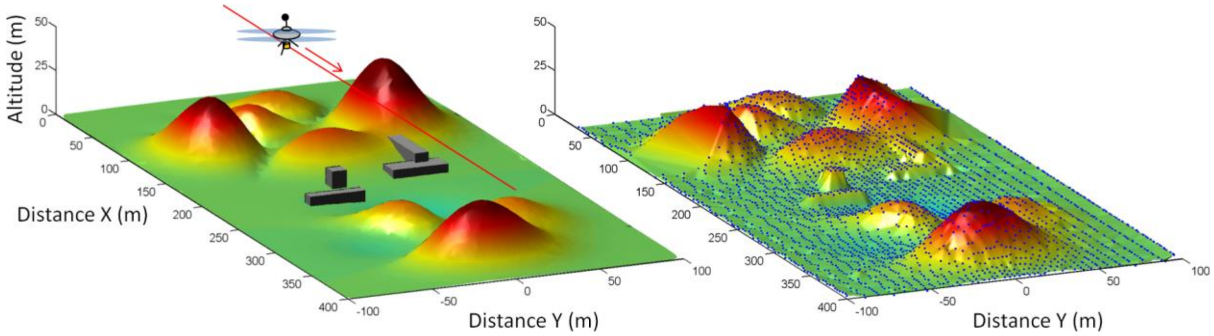
Results

The simulation of radar surveys includes (1) the simulation of an environment and of an aircraft trajectory; (2) the simulation of the radar signal; (3) the simulation of the antenna and of the scanning; and (4) the simulation of signal processing. At each computation step, the position (x_p,y_p,z_p) and the attitude (φ,θ,ψ) of the aircraft are determined from the trajectory. The angle of incidence α and the angle of scanning β are calculated in absolute coordinates in order to identify the points of the environment which are intercepted by the antenna pattern. Once the radar signal is computed, a radar spectrum is estimated based on classical FFT analysis or on other spectral method [8]. A Constant False Alarm Rate (CFAR) processor is then used for targets detection. And finally, a radar-target distance r_i is computed for each detected target. Considering the position and attitude of the aircraft, the incidence and scanning angles of the antenna, and the computed radar-target distances r_i, the detected points can be projected in an absolute reference frame and a DEM is computed by interpolation of these detected points. An example of simulation is presented in Figure 3. Figure 3(a) is the environment model. The red line indicates the trajectory of the drone (straight horizontal line, altitude 50m, velocity 10m/s). Radar parameters are described in Table 1.

Table 1: FMCW radar parameters.

Carrier frequency f_0	77GHz	Antenna aperture (θ_{az}, θ_{el})	2°, 2°
Modulation frequency f_m	360Hz	Antenna rotation velocity V_a	180rpm
Sweep frequency Δf	500MHz	Incidence/scanning angles α, β	30°, ±60°

Figure 3(b) is the reconstructed DEM. Blue points indicate the detected points used to compute the DEM. A differential DEM can be computed between the input model (a) and the computed DEM (b). For this example, the RMS error (which does not provide information about the spatial distribution of the error) is 73.3cm.



(a) (b)

Figure 3: Example of modeling and simulation of a radar survey. (a) Model of the environment. The red line indicates the drone's trajectory: altitude 50m, velocity 10m/s. (b) Reconstructed DEM.

Conclusion

A simulator for 3D mapping based on airborne FMCW radar measurements has been presented. It is using three main modules: (1) environment model, (2) trajectory model, and (3) FMCW radar model. These modules are used to compute the radar signals and a DEM of the overflown environment. The objective of the simulator is to help the user in defining the most efficient FMCW radar configuration for DEM reconstruction of the environment, with the future objective of a radar sensor development. The user can test a wide range of FMCW radar parameters in various environment/trajectory contexts. First simulation results indicate that there is no impossibility for the definition of a practical radar configuration (taking into account the characteristics of microwave components). With the introduction of new sensor models (vision, etc.), it will be possible to work on multisensor data fusion applications within the framework of the simulator.

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