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Radar-based SLAM without odometric sensor

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Abstract

For environmental management, remote sensing techniques are of major interest as they can provide global and local coverage of natural environments. Considering the visibility conditions that are often poor in outdoor environments (day/night cycles, clouds, shadows, fog, etc.), a microwave system offers an alternative solution in order to overcome the difficulties of use of optical sensors. In order to deal with the need of high spatial resolution, close temporal acquisition, and low-cost data availability, we developed a small-sized microwave radar sensor called K2Pi. This radar is based on the principle of Frequency-Modulated Continuous Wave (FM-CW) technology. An application in simultaneous localization and mapping using scan matching of radar images (R-SLAM algorithm) has been developed in order to build radar map of the environment. Avoiding the use of odometric sensors, this SLAM algorithm allows placing the radar on every kind of vehicles. We present in this paper its potentialities through an application of natural environment mapping.

1. Introduction

Anthropogenic or natural processes have important effects on natural environments evolution. The monitoring of these evolutions is crucial for global change research (large scale) (Nemani 1995), but is also important at a local scale because of direct and imminent influences on vulnerable and small ecosystems or human life (Lambin 2006). In the domain of sustainable development, the environment risk diagnosis or the monitoring of particular environmental parameters imply to develop environmental models in order to estimate and predict the consequences of specific human behaviors or natural phenomena. The development of numerical models implies the availability of accurate and redundant data. But robust solutions for perception in extended outdoor environments are not so frequent, particularly with regard to the problem of resistance to the environmental conditions (Hague 2000; Hellström 2002). Laser and video based systems are common optical based sensors, particularly well adapted in indoor environments. However, these systems are affected by visibility conditions that are often poor in outdoor environments: day/night cycles change illumination, weather phenomena as fog, rain or dust may deteriorate the quality of information provided. In the microwave range, data can be acquired independently of atmospheric conditions and time of the day. So radar can provide an alternative solution to overcome the shortcomings of optical sensors. Moreover, backscattering signal has an unquestionable potential for environmental applications, as it can be shown in satellite remote sensing (Hallikainen 1993).

In response to new requirements related to the monitoring of environment at lower scales in comparison to airborne/spaceborne radar systems, we developed a small-sized radar sensor easy to embark on board of different vehicles and we show in this paper its potentialities through a preliminary application in natural environment mapping.

Because of its intrinsic characteristics, microwave radar is particularly well suited for outdoor applications and large scale mapping, and particularly in outdoor mobile robotics. Microwave radar has been successfully used in numerous domains such as terrain imaging (Scheding 2002; Brooker 2004; Brooker 2003), target tracking (Brooker 2005), three-dimensional map building (Foessel 2001), vehicle localization and vehicle navigation (Clark 1997). Moreover in recent years different simultaneous localization and mapping algorithms based on microwave radar sensor have been developed (Dissanayake 2001; Jose 2004; Foessel 2000).

The principle and the characteristics of the K2Pi radar imager is presented in Section 2. Section 3 develops and describes the R-SLAM algorithm which is based on a scan matching approach and the description of the environment with an occupancy grid. Two results obtained in natural environments are presented in Section 4.

2. Presentation of the K2Pi radar imager

2.1. Radar principle

For short-range distance measurements i.e. few hundreds of meters, the classical pulse radar technology is not the best adapted solution. For example, a precision of 1 meter in distance measurement imposes a precision of 3.3 ns in time measurement, therefore fast and expensive electronics. We developed the K2Pi microwave radar (meaning 360° scanning in K band) using the *frequency modulation continuous wave* (FMCW) principle. This principle is known and used for several decades (Collette 1957; Monod 1995). When the range is some hundreds of meters, frequency modulation presents the following advantages:

- low transmission power, as it is the mean power which determines the range, which is safer for the user,
- transposition of the temporal variables into the frequency domain: a very short delay time Δt is transformed into a broad variation of frequency Δf, easier to measure.

The principle of FMCW radar consists to mix the emitted signal following a linear modulation waveform, with the received signal delayed after reflecting on the targets present within the view of the antenna (Skolnik 1980). Let us consider a sawtooth modulation at frequency F_m over a range ΔF and a distribution of i stationary targets at respective distances R_i in the antenna beam. When the echo signal is heterodyned with a portion of the transmitted signal, a beat signal S_b will be produced (Monod 1995; Rouveure 2004):

$$S_b = k\sum_i V_e V_{ri} \cos\left(2\pi\left(2\,\Delta F\, F_m \frac{R_i}{c}\right)t + \Phi_i\right). \tag{1}$$

V_e is the amplitude of emitted signal, V_{ri} and Φ_i respectively the amplitude of received signal and a phase term depending on target i, c the light velocity and k a mixer coefficient. When more than one target is present within the view of the radar, the mixer output will contain a sum ΣF_{bi} of frequency components, each of them corresponding to a particular target i:

$$F_{bi} = 2\,\Delta F\, F_m\, R_i / c\,. \tag{2}$$

The range R_i to each target may be determined by measuring the individual frequency components by the mean of a Fourier transform. At each angle of sight a power spectrum is computed. Contrary to laser measurement which gives the nearest echo received in the beam, the aperture of the radar beam allows multi-targets detection in the same angle-of-sight. An example of radar power spectrum is presented in Fig. 1. We will notice that moving targets which introduce a Doppler frequency shift are not considered in this paper.

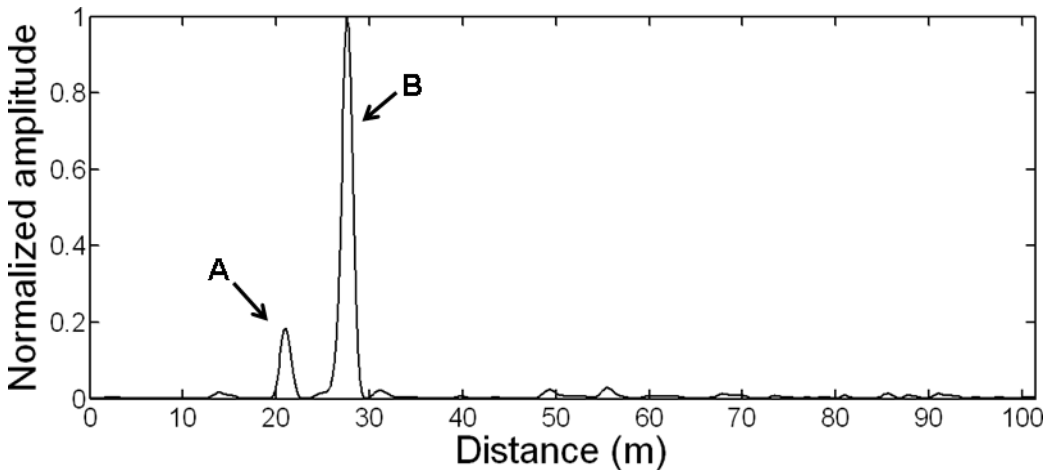

Figure 1. Example of radar power spectrum. The frequency peaks indicate the presence of two targets (A and B) in front of the antenna.

2.2. Radar image construction

A so-called “panoramic radar image” covering 360° in the horizontal plane is carried out using a PPI (Plan Position Indicator) representation, which displays range of targets versus angle. Considering the combined effect of antenna rotation and vehicle motion (translation and rotation), one would observe intra-scan distortions on the final 360° image. To achieve a *vehicle motion correction*, two proprioceptive sensors are used to estimate the displacement of the vehicle and to take into account these distortions: an odometer to measure the longitudinal displacement of the vehicle and a gyrometer to measure the rotation of the vehicle.
Once the vehicle motion has been corrected, an anti-speckle filter is added. The speckle effect is a random amplitude modulation which exists in any radar image construction. Speckle noise reduction can be achieved either by spatial filtering or multi-look filtering (Lee 1994; Guoqing 1999). We chose the latter approach: n independent images of the scene are incoherently combined (by space-domain averaging) to produce a single final image.

2.3. Lack of odometric sensor

Depending on the vehicle or the environment, odometric sensors can be unavailable. For example if we consider a boat on a river, it is placed on a “moving environment” and no odometric sensor is available to estimate the displacement of the radar (odometric information are used during the Vehicle Motion Correction and the Anti-Speckle Filter steps).
Data from a kinematic GPS system (with a centimetric precision) could be employed, but we try to avoid the use of such a system for different reasons:

- we want to build a radar imager independent of any localization system,
- the cost of a kinematic GPS system is very high,
- if no differential GPS correction signal is available, it is necessary to install its own GPS ground station and the cost of the GPS system is doubled,
- considering the GPS satellite constellation, the terrain topography, the presence of high vegetation or various obstacles, etc., GPS signals can be intermittently available or completely unavailable.

So a direct estimation process of the vehicle displacement was developed: it allows estimating of the movement of the vehicle within initial radar images (before vehicle motion and anti-speckle corrections).

The K2Pi radar is monostatic, i.e. a common antenna is used for both transmitting and receiving. The rotating antenna achieves a complete 360° scan around the vehicle in one second, and a radar acquisition is realized each degree. The sensor includes microwave components, electronic devices for emission and reception, data acquisition and signal processing units. A general view of the K2PI radar is shown in Fig. 2.
Data acquisition and signal processing units are based on a Pentium M / 2 GHz PC/104 processor card. Computed data are transmitted for visualization and further treatment using an Ethernet link. Main characteristics of the radar are described in Table 1.

Figure 2. General view of the K2Pi radar.

TABLE 1
Characteristics of the K2PI FMCW Radar

Carrier frequency F_0	24 GHz
Transmitter power P_t	20 dBm
Antenna gain G	20 dB
Range	3-100 m
Angular resolution (horizontal)	4°
Distance resolution	1m
Distance precision	0.02 m
Size (length-width-height)	27-24-30 cm
Weight	10 kg

3. Map construction: the R-SLAM algorithm

In the robotics domain, the simultaneous localization and mapping (SLAM) problem asks if it is possible for a mobile robot to be placed at an unknown location in an unknown environment and for the robot to build a consistent map of this environment, while simultaneously determining its location within this map. This problem has been intensively treated, particularly for autonomous navigation problems. In our application, we have been interested by the SLAM methodology to build a representation of the environment, using a succession of panoramic radar images. One interest of this approach is that this construction is “sensor-based” and avoids the use of an absolute positioning system like GPS.

The majority of SLAM formulations are based on the ability of landmarks locations in the environment, assuming that these locations are time invariant. Whatever the sensor used, the most difficult problem for this approach is beacon validation and data association (Ho 2007). It means that a major difficulty is (i) to confirm that the detected beacon is a valid beacon, and (ii) to associate it with a known beacon in the computed map. The data association process is an essential problem in SLAM algorithm. It has been addressed by looking for stable beacons in the environment, or using a combination of sensors (multisensorial approach) (Zhang 2004).

But *non-ambiguous target detection and identification based on radar signal interpretation* are still open problems (Chen 2007). This is particularly true in outdoor and natural environment, where landmarks which are detected by the radar cannot be modeled as simple geometric primitives. Power/range spectra contain a large amount of information mixed with various sources of noise, so detection and tracking of particular landmarks are not simple problems (Jose 2004). The detection of landmarks in power/range spectra can be treated through constant false-alarm rate (CFAR) techniques that estimate the level of noise and the setting of a threshold (Rohling 1983). But in very poor structured environment, the clutter, which is traditionally considered as noise in radar applications, must be taken into account because it can be the only available information (clutter traditionally refers to natural echoes such as ground, sea, precipitation -rain, snow or hail-, sand storms, animals -especially birds- or insects, etc). In such situations, a detection approach based on threshold selection will fail. It is for that reason we developed a particular R-SLAM algorithm which does not treat the landmarks individually, but considers the entire radar scan. A radar image is constituted by a scan over 360° around the vehic le and is considered as an occupancy grid (matrix of cells), which divides the area of interest in regular cells. Each cell is related to a small area (20 cm $\times$ 20 cm), the occupation level of which is given by the power of the reflected signal. The global grid is updated for each 360° scan, using a data merging process. The first scan is directed at 0° referring to the initial direction of the vehicle. The absolute orientation in reference to magnetic north may be obtained by the addition of a compass.

The R-SLAM process includes two main steps:

- map matching between the current radar scan and the constructed map, in order to estimate the inter-scan displacement,
- global map updating to integrate the current radar scan through a data merging process.

3.1. Map Matching

Classical feature extraction and matching imply to recognize the same feature repeatedly during the map construction. Then it is necessary to detect persistent and reliable features in the scan. But because of limited angle and distance resolutions, radar scans can not offer the same resolution than optic images or laser scans. Another problem is that target's reflected power depends on the orientation of the target, so the reflected signal will be different according to the angle of observation: such a property is particularly disadvantageous in performing long-term tracking of individual landmarks.
Considering the particularities of radar data, the best adapted method here is scan-matching, which performs a 3D cross correlation (two translations and one rotation), between the current image and the constructed map. The maximum of the correlation matrix gives the estimate of the radar displacement and rotation between two scans.

3.2. Global Map Updating

Once the inter-scan displacement and rotation estimated, the observation from the current radar scan has to be integrated in the global radar map.
The radar data interpretation requires a representation tool that facilitates the study of sensor-scene interaction. In that sense *occupancy grids* are powerful and flexible representation tools that capture the relevant scene aspects for radar-data interpretation (Martin 1996). Occupancy grid represents environment by fine-grained, metric grids of variables that reflect its occupancy. Each cell of the occupancy grid contains a number that represents accumulated evidence of occupancy or emptiness in the space. In the R-SLAM process, the number contained in the cell is proportional to the microwave power of the reflected signal. This reflected power is proportional to the radar cross section (RCS) of the target. For most common types of targets such as buildings, vegetation and terrain, the radar cross section does not necessarily bear a simple relationship to the physical area, except that the larger the target size, the larger the cross section is likely to be. As the radar moves, a data merging process is applied in order to estimate the value of the cell according to the successive values of the reflected radar signal.
This data merging process faces an ambivalent situation:
- the necessity to take into account the new information from the current radar image,
- the necessity to preserve the information previously stored in the global map.

The principle retained is to consider that the probability for a target to appear in the map is proportional to the number of times it has been observed at the same place.

4. Results

Two experiments are presented. Radar data are acquired and stored in real time during these experiments. The R-SLAM algorithm has been implemented in Matlab language on a Quadri-Core 2.5 GHz Pentium PC with an off-line process. It takes 3 seconds to compute a radar image and to update the radar map. Simultaneously with radar data acquisitions, GPS data are recorded in order to have a localization reference.

For the first experiment, the radar is placed on a Cemagref research vehicle, 3.3 meters above the soil. The vehicle moves on a country road in the middle of a natural and low structured extended environment near Clermont-Ferrand, France (latitude 45°44’41” N, longitude 3°07’04” E, elevation 465 m). The aerial image (from Google Earth; date: August 31st, 2006) is presented in Fig. 3(a), and the GPS trajectory is superimposed with yellow dots. The covered distance is about 1374 m, with a mean velocity of 7.9 km/h (maximum velocity: 16.6 km/h). A total of 610 radar images was stored and treated to work out the global radar map and trajectory (red dots) presented in Fig. 3(b). Few strong cooperative targets such as buildings are present within the area (lower-left part of the trajectory). Most of the elements such as trees, soil surfaces, and vegetation are slightly cooperative targets.

The second experimentation has been done on the Aydat Lake near Clermont-Ferrand, France (latitude 45°39'51" N, longitude 2°59'09" E, elevation 840 m). The radar is positioned at the front of an experimental boat from the Cemagref Institute. The radar antenna is 1.5 m above the water surface. An aerial view of the lake (from Google Earth; date: April 24th, 2004) is presented in Fig. 4(a). One can observe that a part of the lake is hidden by clouds. The covered distance is about 4 km, with a mean velocity of 1.2 m/s. Yellow dots indicate the successive GPS positions. A total of 3176 panoramic radar images was stored and processed to work out the global map and trajectory (red dots) presented in Fig. 4(b).

5. Conclusion

For outdoor environment perception, microwave radar is a sensor which presents a considerable potential, overcoming the limitations of vision-based sensors. In order to construct consistent maps of the environment, the R-SLAM algorithm presented in this paper exploits all the richness of radar signal, avoiding the detection of particular landmarks. The algorithm builds simultaneously a map of the environment and a localization of the vehicle within the map, without using a global positioning system. The range of radar, combined with the R-SLAM algorithm performances, makes it possible to deal with extended and low structured environments.

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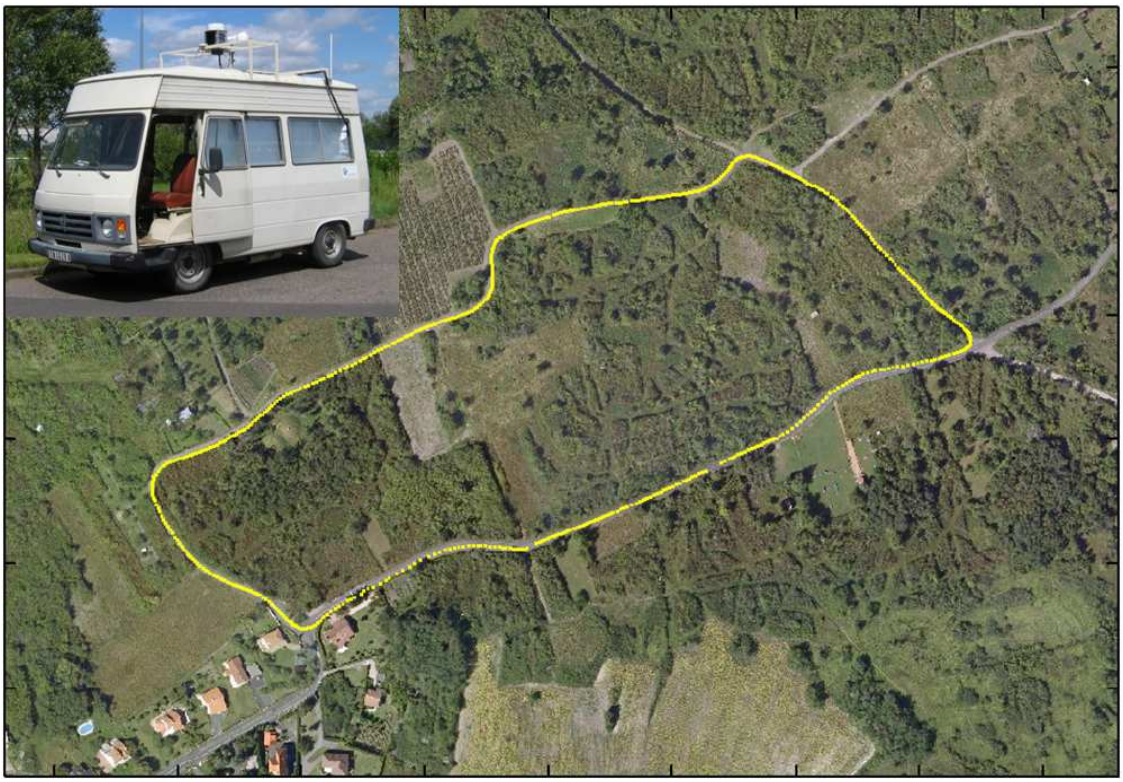
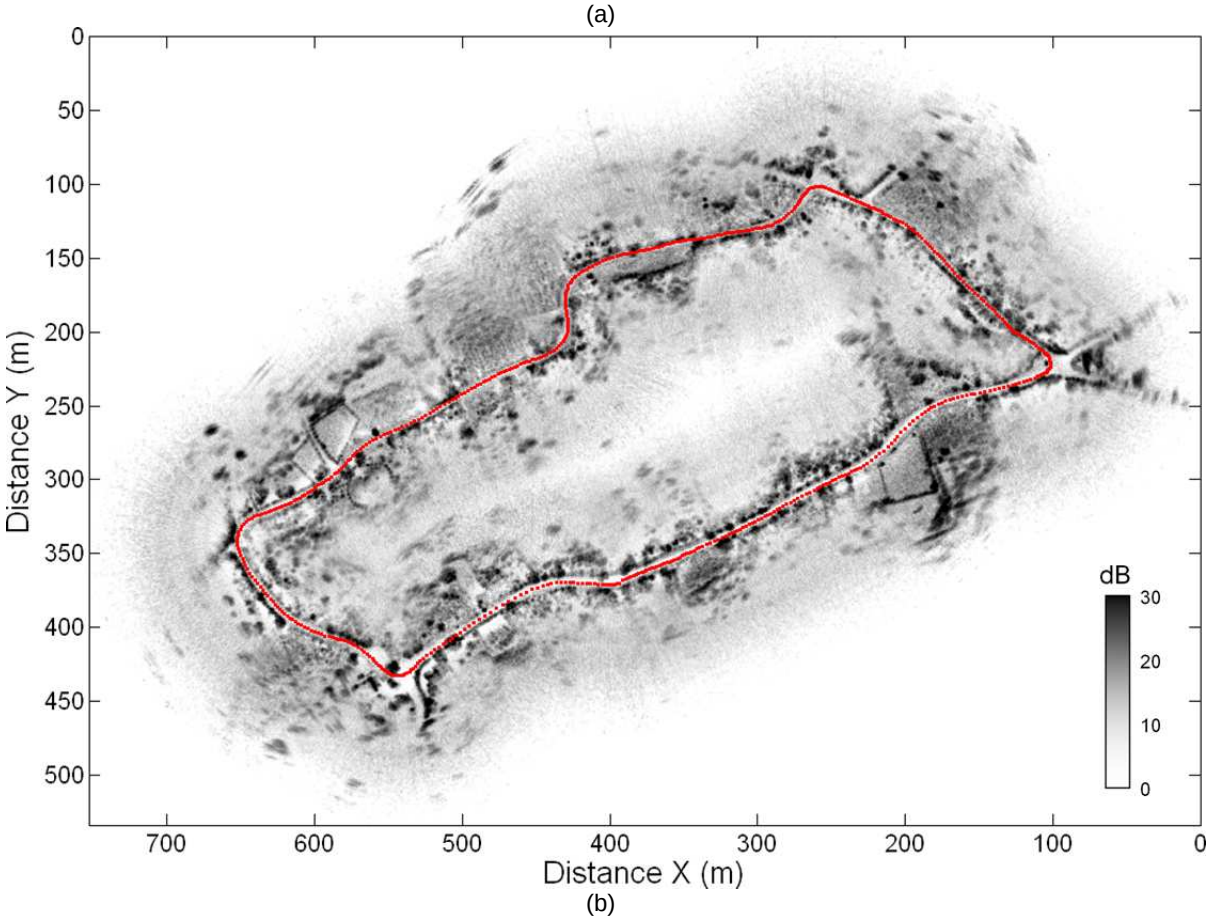


(a)



(b)

Figure 3. R-SLAM result in natural and outdoor environment. The total length of the loop is 1374 meters, the mean velocity is 7.9 km/h. (a) Aerial image from Google Earth. Yellow dots indicate GPS trajectory. (b) Global radar map and estimated trajectory (red dots). A total of 610 radar images was treated to work out the map and trajectory

(a)

(b)

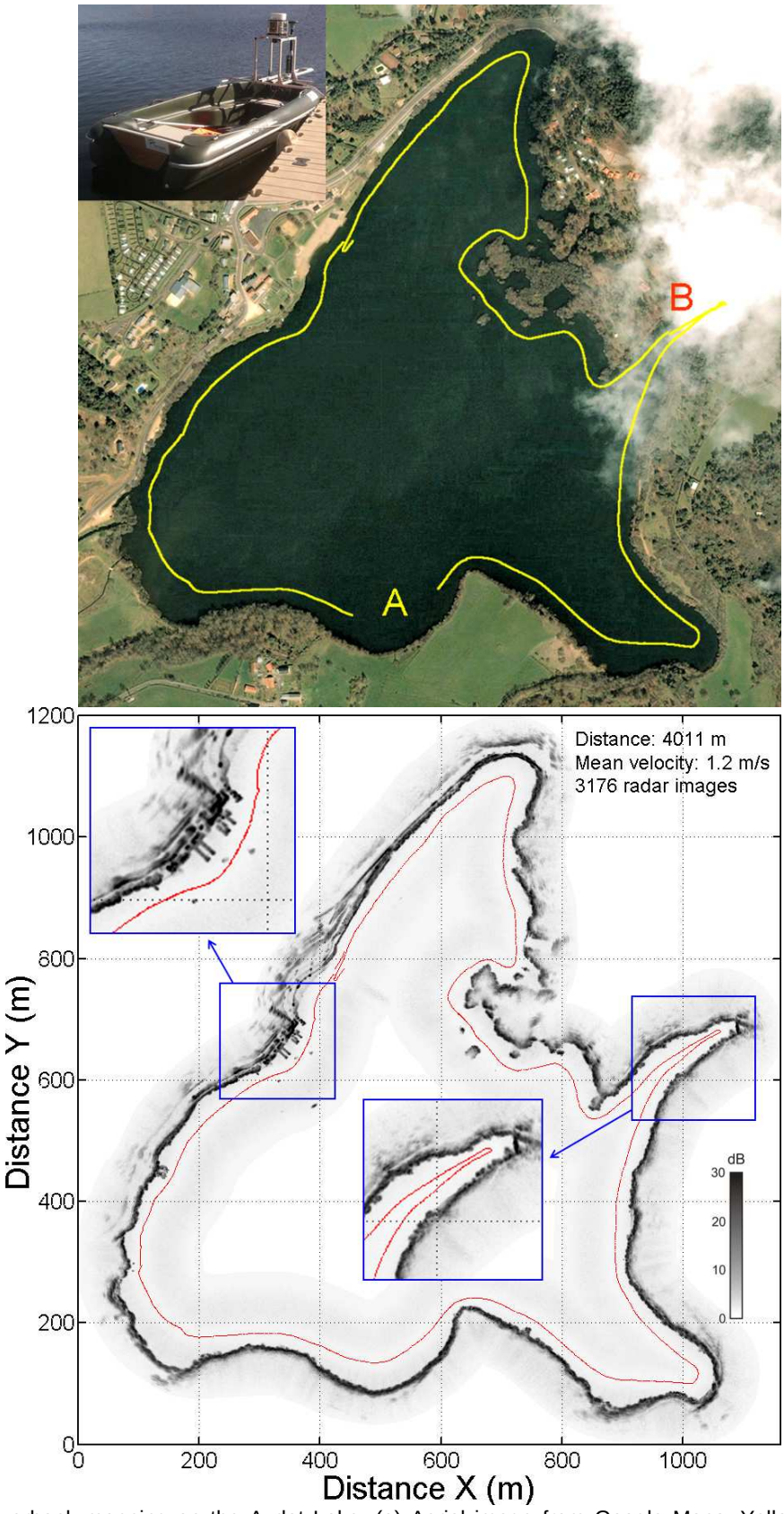


Figure 4. Riverbank mapping on the Aydat Lake. (a) Aerial image from Google Maps. Yellow dots show GPS trajectory. Mark A indicates a lack of GPS information (GPS signal unavailable). A part of the trajectory (mark B) is hidden by clouds. (b) Radar cartography. The grayscale level indicates the relative amplitude of the backscattering signal. The red dots indicate the estimated boat trajectory. A total of 3176 radar images was treated to work out the map and trajectory.