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Testing a handheld radar to measure water velocity at the surface of channels

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ABSTRACT. – Among the non-contact instruments to measure water velocity in open channels, two handheld radars are available on the market since ten years. Due to the lack of information about these instruments, one model was tested in the laboratory and in the field. The radar was able to estimate the velocity of a water surface within [p = 0.95] ± 0.3 m/s at medium velocities (from 0.3 to 3 m/s) and within ± 10 % of the measured value at large velocities (up to at least 6 m/s). Although this is not very accurate, the ease of using handheld radars still makes them attractive to quickly estimate discharge at gauging stations, safely determine water velocity during a flood and investigate how water flows under difficult access conditions. Nevertheless, the tested radar was tending to underestimate the water velocity, above all when it was looking downstream. More studies are necessary to know why.

Key-words: SVR (surface velocity radar), Doppler radar, microwave, water velocity, open channels, gauging.

Evaluation d'un radar portable pour mesurer la vitesse de l'eau à la surface des canaux

RÉSUMÉ. – Parmi les instruments sans contact pour mesurer la vitesse de l'eau dans les canaux, deux radars portables sont disponibles sur le marché depuis une dizaine d'années. En raison du manque d'information sur ces instruments, l'un d'eux a été testé au laboratoire et sur le terrain. Le radar a permis d'estimer la vitesse à la surface de l'eau avec une incertitude [p = 0.95] de ± 0.3 m/s pour des vitesses moyennes (0.3 à 3 m/s) et ± 10 % de la valeur mesurée pour des vitesses plus élevées (jusqu'à au moins 6 m/s). Bien que ce ne soit pas très précis, la simplicité d'utilisation des radars portables les rend attractifs pour estimer rapidement le debit dans les stations de jaugeage, déterminer sans risque la vitesse de l'eau en cas de crue et savoir comment l'eau s'écoule dans des conditions difficiles d'accès. Néanmoins, le radar testé tendait à sous-estimer la vitesse de l'eau, surtout quand il pointait vers l'aval. Des études complémentaires sont nécessaires afin de savoir pourquoi.

Mots-clés : SVR, radar à effet Doppler, micro-ondes, vitesse de l'eau, canaux, jaugeage.

I. INTRODUCTION

In Hydraulics, *current meters* are light instruments designed to measure the velocity of a small water volume (< 1 dm^3). They are useful in open channels to determine the discharge or investigate some certain hydrodynamic features. The most common instruments for field applications are [*e.g.* ISO 2007]: mechanical current meters (MCM), electromagnetic velocimeters (EMV) and acoustic Doppler velocimeters (ADV). Acoustic Doppler current profilers (ADCP) mounted on a floating platform can be used as well. When used properly, current meters can accurately determine water velocity: their uncertainty [p = 0.95] is better than ± 0.01 m/s for low velocities (below ≈ 0.5 m/s) and ± 2 % of the measured value for medium velocities (up to ≈ 3 m/s) [*e.g.* Hubbard *et al.* 2001; ISO 2007]. Nonetheless, they must be inserted into water, which can be time-consuming and dangerous.

There is therefore an interest in developing instruments that can measure water velocity in open channels with no need to submerge them. For field applications, the two main techniques are image velocimetry (LSPIV/STIV) [*e.g.* Le Coz *et al.* 2010] and Doppler radar (considered in this study). Unfortunately, none of these is still operational to determine velocity below the water surface (*i.e.*, at a depth > 0.2 m). In this case, it is worth noting that measuring the water velocity only at the free surface - instead of measuring it at different depths - is still considered a reliable - although less accurate- method to estimate discharge in open channels [*e.g.* ISO 2007; Le Coz *et al.* 2010; Dramais *et al.* 2014].

Among the non-contact instruments to determine velocity in open channels under field conditions, two handheld radars are available on the market since ten years. Although they look attractive for their rather low cost (< 4,500 USD) and ease of use (Fig. 1), little is known about their performances. The goal of this study was therefore to test a handheld radar to determine the velocity at the surface of open channels.

II. LITERATURE REVIEW

II.1. What is known about the handheld radars ?

Handheld radars look like a pistol (for this reason, they are often called *radar gun*). They can be defined as *monostatic* (the receiving antenna is near the emitting antenna) and *microwave* (they emit a signal in the microwave range)

Doppler radar, designed to be easily transported by a walking person and operated from a steady position. Handheld radars were originally developed to determine the speed of cars. They have also become popular to determine the speed of animals and sporting balls. The idea of using similar instruments to determine water velocity in open channels was patented ten years ago [Smith *et al.* 2003]. There are currently two models of this type (called *surface velocity radar* by their manufacturers). Both look very similar for their shape and specifications; it is worth noting that their *(3 dB) beam width* is large in practice (12°) and that they emit a signal with a *circular polarization*.

Little has been published about the performances of handheld radars in the field of Hydraulics. First, the "SVR" model from Decatur Electronics [2011] has an operating frequency of 24 GHz (*K-band*). Its claimed uncertainty [p = 0.95][1] is ± 10 % of the measurement for a range from 0.3 to 9 m/s. A few evaluations of this instrument [Song *et al.* 2006; Fulton & Ostrowski 2008; Zolezzi *et al.* 2011; Dramais *et al.* 2011, 2014] suggest that it can indeed estimate surface velocity within ± 10 % for medium to large velocities (≈ 0.5 - 5 m/s), but does not always operate at low velocities (< 0.5 m/s). Second, the "Stalker Pro II SVR" model from Stalker Radar [2008] has an operating frequency of 35 GHz (*Ka-band*). Its claimed uncertainty [p = 0.95] is ± 0.2 m/s for a range from 0.2 to 18 m/s. Compared to the previous radar model, its maximum operating velocity is therefore claimed to be larger (twice) and it is claimed to be more accurate at large velocities (> 2 m/s). Until now, there is no publication about the performances of the "Stalker Pro II SVR" radar; this model will be considered below.

II.2. Principle of operation of a handheld radar

A *radar* is a remote sensing system that sends an electromagnetic signal of a given frequency to a target and then measures some properties of the signal that is sent back (time delay, Doppler shift and/or intensity) in order to determine its distance, speed and/or texture.

As for any other fixed and monostatic Doppler radar, a handheld radar determines the velocity of a target by sending a signal of a given frequency (f_0, Hz) to the target, retrieving the backscattered signal and determining its frequency (f, Hz). The *Doppler effect* is used by the instrument to internally compute the *radial velocity* of the target, that is, the component of its velocity relative to the radar's line-of-sight (V_r, m/s):

$$V_r = -\frac{c_a}{2}\frac{\Delta f}{f_0} \quad (1)$$

where c_a is the speed of light through the air (≈ 3 × 10^8 m/s) and $\Delta f = f_0 - f$ is the *Doppler shift* (negative when the target gets closer and positive when it goes away). So, unless the radar is placed exactly in front of a moving target, a trigonometric correction must be applied to estimate the velocity of the target in its main direction of movement. Consider a radar oriented in such a way (*e.g.* from a bridge) so that it looks in the main direction of a stream. Provided that the radar signal is backscattered (as discussed in Section II.4) and assuming that it is emitted as a narrow beam (as discussed in Tamari *et al.* 2013), the velocity of the water surface (V_s, m/s) can be estimated as:

$$V_s = \frac{V_r}{\sin\theta} \quad (2)$$

where V_r (m/s) is the radial velocity of the water surface and θ (°) is the radar's incidence-angle relative to the water surface. At the scale of several metres, it can be usually assumed that the water surface of open channels is a horizontal plane: this is realistic (with a tolerance of ± 1 °) provided that the channel slope is gentle (< 0.017 m/m) and that there is no hydraulic jump. In this case, the angle θ of Eq. 2 is simply the *incidence angle* of the radar (θ_o), *i.e.* the angle between its line-of-sight and the vertical. Commercial handheld Doppler radars have a built-in inclinometer, so that they can automatically determine such an angle and use it to estimate the velocity of a horizontal water surface.

Next, the case of a plane but inclined water surface will be also considered. This situation occurs in steep artificial channels and in the middle part of some spillways. In this case, the angle of Eq. 2 is: $\theta = \theta_o - \beta$ for a radar looking upstream, and $\theta = \theta_o + \beta$ for a radar looking downstream, where β is the slope of the water surface ($0 \leq \beta < 90°$). In practice, the water surface is often almost parallel to the channel bottom and edges, which can be easily checked visually. If so, the

1. In the following, *any uncertainty that is reported by a manufacturer without specifying its confidence interval is assumed to be a standard uncertainty* [p = 0.68]. In this case, we report a twice larger uncertainty, considering a 95 % level of confidence [p = 0.95].

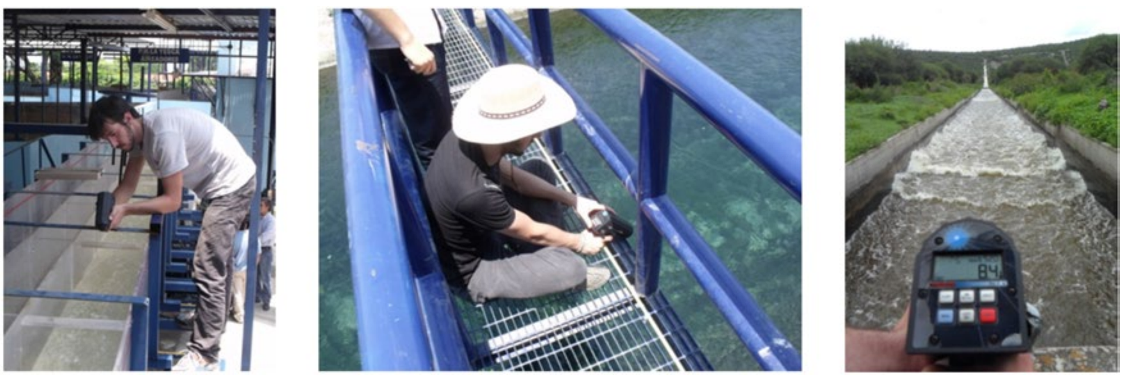

Fig. 1: *Different types of sites where the radar was tested: (left) laboratory spillway, (middle) irrigation channel and (right) rapid with rolling waves.*

angle β can be rapidly estimated by measuring the channel's slope with the built-in inclinometer of a handheld radar or any other inclinometer. Nevertheless, it becomes more difficult to determine the angle β when the water surface is curved; such a situation is out of the scope of this study.

II.3. Which incidence angle for the radar ?

To reduce the effect of the trigonometric correction (Eq. 2) as much as possible, a radar should be placed so that it looks at the water surface with a relative incidence angle as large as possible. Nonetheless, when a handheld radar looking at a water surface is oriented with a too large incidence angle, it becomes difficult in practice to know at what it is pointing. During this study, no attempt was made to use the handheld radar with a relative incidence angle larger than 70°. Assuming that V_r and θ are normally-distributed and independent random variables, a simple model to estimate the uncertainty of V_s can be derived from Eq. 2:

$$U(V_s) = \sqrt{\frac{1}{\sin^2\theta} U^2(V_r) + \frac{V_s^2}{\tan^2\theta} U^2(\theta)} \quad (3)$$

where $U(\bullet)$ denotes the uncertainty of each variable (at a given confidence level); please note that the term $U(\theta)$ must be expressed in radians. Strictly speaking, the model does not agree with what is claimed by the manufacturers of handheld radars (Section II.1); in fact, it predicts that the uncertainty of the surface velocity ($U(V_s)$) is neither a constant value nor a fixed proportion of the measured value. In the case of the studied radar, assuming that its claimed uncertainty is for the radial velocity: $U(V_r) = 0.2$ m/s [$p = 0.95$] and considering that the claimed uncertainty of its built-in inclinometer is: $U(\theta) = 0.07$ rad (4°) [$p = 0.95$], the expected uncertainty $U(V_s)$ can be computed using Eq. 3 for different scenarios (different values of V_s and θ). The results suggest that the radar should be oriented with an incidence angle $\theta > 45°$, otherwise its uncertainty will rapidly increase (for more details, see Tamari *et al.* 2013).

II.4. Detection of a water surface by a microwave radar

To be able to determine the velocity of a water surface, a Doppler radar must first detect it: the signal sent by the instrument must be reflected by the water in such a way that it goes back to the instrument and can be processed. This phenomenon has been studied for 50 years in the laboratory and on the sea. Considering that the handheld radar emits microwaves, the backscattering of its signal by water (at least, for $20 \leq \theta \leq 70°$) is currently described by the *Bragg / composite surface* theory [*e.g.* Plant and Keller 1990; Plant *et al.* 2004]. On the one hand, the theory considers that the microwaves are mostly backscattered by small water waves (traveling nearly in the plane of incidence, either toward the radar, either away from it), *i.e. ripples* with a wavelength $\Lambda_B \approx 6$ mm in the case of the studied radar (according to the *Bragg resonant condition*). In open channels, these ripples can be produced by external factors (the wind and the rain) and internal factors (the distortion of larger waves and the turbulence of water). On the other hand, the theory considers that the ripples backscattering the radar signal are mostly driven by larger water waves. In open channels, these larger waves (gravity-capillary waves and hydraulic boils) are due to the wind and turbulence of water. On average, they are assumed to move at the velocity of the water surface.

The above theory predicts that the tested radar will not work if there are virtually no ripples on a water surface, as it may occur under low water flow and clear weather conditions [*e.g.* Plant *et al.* 2005] or if there is an oil film on the water [*e.g.* Gade *et al.* 1998]. It also predicts that the raw data recorded by a radar (a time-series of Doppler shifts) are "noisy". The main reason for that is that each water wave (ripples and larger waves) tends to propagate in several directions. So, a radar should detect water waves that sometimes move faster than the average water surface (*advancing waves*) and that sometimes move slower (*receding waves*). Ideally, the histogram of the raw data recorded by the radar (converted into surface velocities, according to Eqs. 1-2) should have two peaks: one corresponding to ($V_s + c_B$) and the other corresponding to ($V_s - c_B$), where c_B is the *phase speed* of the water waves that backscatter the radar signal. If so, processing the raw radar data simply consists in extracting the midway point between the two peaks. However, it is often difficult to discern this theoretical couple of peaks when working with a microwave radar. In this case, processing the raw radar data is not straightforward anymore. If data are not processed carefully, the estimated surface velocity (V_s) can be erroneous up to about $\pm c_B$ [Plant *et al.* 2005]. For the studied radar, $c_B \approx$ 0.3 m/s [Tamari *et al.* 2013]; it is worth noting that the minimum expected uncertainty of the radar (computed from Eq. 3 with $\theta = 45°$) is close to this value.

II.5. Difficulty in interpreting the velocity measured by a radar

Assuming that the data have been averaged over a sufficiently long period of time, the surface velocity determined by a Doppler radar (V_s) can be decomposed as an algebraic sum of four terms:

$$V_s = V + W + U_s + \upsilon \quad (4)$$

where V is the drift caused by the underlying current (m/s), W is the drift caused by the wind blowing in the direction of the radar's line-of-sight (m/s), U_s is the Stokes drift (m/s) and υ is an eventual bias due to the way a radar "sees" a water surface (m/s). Considering the goal in Hydraulics is to determine the underlying current (V), taking it to be equal to the surface velocity measured by a radar (V_s) may lead to three types of systematic errors:

- *Wind effect (W)* - During this study, the handheld radar was tested under low wind conditions, at most equivalent to a *gentle breeze* on the Beaufort scale. In this case, the wind effect was expected to be rather small ($W < 0.1$ m/s) [Tamari *et al.* 2013].
- *Stokes drift (U_s)* - The Stokes drift is accounted for by a Doppler radar (as well as by small surface drifters), but not by a conventional current meter that would be maintained at a fixed position and just below the water surface. Nevertheless, the Stokes drift was expected to be rather small for the studied channels ($U_s < 0.14$ m/s) [Tamari *et al.* 2013].
- *Bias term due to the radar (υ)* - Due to the specific motion of the water waves that backscatter the radar signal, there may be a systematic difference ($\upsilon \neq 0$) between the surface velocity determined by a Doppler radar and the true surface velocity for a number of reasons; this will be discussed further below (Section IV).

II.6. Experience with microwave radars in open channels

As shown, it is not so simple to use a radar to estimate the velocity of a water surface. In this context, microwave radars with different configurations have been tested over open channels over the last fifteen years. Above all, prototypes [Plant *et al.* 2005; Costa *et al.* 2006; Fulton & Ostrowski 2008] and commercial instruments [Song *et al.* 2006; Dramais *et al.* 2011, 2014; Sung-Kee *et al.* 2012] fixed to a bridge (radars looking in the direction of the main stream) have been tested. Prototypes [Plant *et al.* 2005; Costa *et al.* 2006] and commercial instruments [Sung-Kee *et al.* 2012] located at a channel bank have been also tested. Prototypes moved across a channel using a cableway or a helicopter have been tested as well [Plant *et al.* 2005]. It is worth noting that a radar with an operating frequency of 10 GHz (*X-band*) and a design very similar to that of the commercial handheld radars has been described and tested by Lee & Julien [2006]; nonetheless, it seems to have been forgotten for an unknown reason. All the mentioned field testing suggest that microwave radar can usually determine the surface velocity of open channels with an uncertainty [$p = 0.95$] of ± 0.2 m/s, which is consistent with that claimed by the manufacturers of handheld radars. Nevertheless, testing have been conducted in rivers but not in artificial channels (where the roughness of the water surface may be different) and only for water velocities ≤ 5 m/s.

III. MATERIALS AND METHODS

III.1. Sites where the radar was tested

Based on the literature review, it was decided to test the handheld radar over a series of open channels:

• *Wide range of water velocities* - The radar was tested for the widest range of velocities as possible, *i.e.* from 0.3 to at least 6 m/s. To achieve this range, tests were performed not only over horizontal channels, but also over the plane part of inclined channels (slope as large as 28°). It was not sure whether the radar would work under clear weather conditions at low velocities (< 0.5 m/s), and the comparison with conventional current meters was quite challenging at large velocities (> 3 m/s).

• *Several types of open channels and flow conditions* - Compared to other radars designed to study open channels, the handheld radar can be very easily transported from one site to another, which makes it possible to rapidly test this instrument under several flow conditions. For this study, 18 sites were chosen for testing, with a special interest in artificial channels. The testing was performed in straight portions of narrow (*aspect ratio* ν as low as 1) and wide (ν as large as 40) channels, with different wall roughness (walls made of glass, acrylic, cement, concrete or earth and stones). Both subcritical (*Froude number Fr* as low as 0.2) and supercritical (*Fr* as high as 5) flow conditions were considered.

• *Clear weather conditions* - The radar was tested in the laboratory (13 sites) and in the field (5 sites). In the field, testing was made under low wind (not more than a gentle breeze) and no rain conditions. Although these conditions are convenient for the user and should ensure that the water surface is mostly driven by the underlying current, they are known to be challenging for the radar when water flows slowly. The water surface may indeed be too smooth to produce a significant backscattering of the radar signal [Plant *et al.* 2005].

• *No oil at the water surface* - The radar was tested over channels with clear, turbid and very turbid water, but *not* in channels contaminated by gasoline or detergent, where the presence of an oil film could prevent the radar from detecting the water surface [*e.g.* Gade *et al.* 1998].

III.2. Conditions for using the tested radar

The only parameter for configuring the tested radar was its "power output", which was set at 20 mW (as recommended by the manufacturer for taking data close to a water surface). After that, taking a measurement with the tested radar was easy: once oriented in the main direction of a stream, its built-in inclinometer was used to incline the radar to a desired incidence angle ($\theta_o = 90° - \varphi_o$, where φ_o is the *grazing angle* that was actually displayed by the radar); the radar was then maintained in the same position and its trigger was pressed. About 30 s later, the radar was usually displaying a symbol saying whether water was moving forward or downward and an average velocity data (V_s^*); because the radar has been designed to be used over horizontal channels, this data is a projection in an horizontal plane of the determined radial-velocity ($V_r = V_s^* \times \sin \theta_o$). During testing, the radar was operated as follows:

• *Radar oriented in the main-stream direction* - The radar was always oriented in the main-stream direction. So, field testing was made from bridges of gauging stations. No attempt was made to use the radar from a channel edge; in this case, there was no need to correct the radar data for the azimuthal angle relative to the channel direction (as done by Lee & Julien 2006) and there was no concern with secondary or cross currents (as discussed by Plant *et al.* 2005).

• *Radar looking upstream / downstream* - Each time, a measurement was taken with the radar looking upstream and another with the radar looking downstream. In the laboratory, special attention was paid to locate the radar so that it was pointing at the same part of a channel. While this was not possible in the field, the studied channels were long and uniform enough to reasonably assume that the transversal velocity-profile was the same along the section where the measurements were taken.

• *Radar located as close as possible to the water surface* - As a first approximation, the tested radar should "see" an area at the water surface *(footprint)*, which is an ellipse with a transversal diameter: $D_T \approx 0.2 \times L$, where L (m) is the distance to the surface in the line-of-sight direction [Tamari *et al.* 2013]. It must be recognized that this relation applies only if the distance L is larger than a certain value, which is: $L_f = 0.6$ m for the studied radar (according to the *far field condition*). In the field, the radar was located at $3 \le L \le 10$ m, resulting in $0.6 \le D_T \le 2$ m. In the laboratory, it was empirically located at $0.1 \le L \le 0.3$ m; this is smaller than L_f, resulting in $D_T < 0.12$ m. Thus, it was felt that the area sampled by the radar was not too large, so that the radar data could be used on channels with a width $b \ge 0.3$ m and so that its data could be compared to the data provided by current meters.

• *Measurements taken rather quickly* - Once a first value for the average velocity was displayed by the radar, the instrument was left to take more data and average them during ≈ 20 - 40 s. This duration was usually sufficient to achieve repeatable data with a tolerance of ± 0.15 m/s.

• *Intermediate incidence angle* - Based on the results of a preliminary testing [Tamari *et al.* 2013], the radar was used with its handle downward and a relative incidence angle (θ) between 45 to 50° for moderately inclined channels (slope $\beta \le 10°$) and between 50 to 60° for steeper channels.

• *Radar's inclinometer considered as unbiased* - The radar's built-in inclinometer has a claimed uncertainty [p = 0.95] of ± 4 °. This was checked in the laboratory against a comparison with an external inclinometer with a tolerance < 1 ° (model "MTi", Xsens Technologies, Enschede, The Netherlands). Although systematic differences were found, their magnitude was always < 2.6 ° (Fig. 2).

III.3. Reference techniques for testing the radar

Most of the radar testing was conducted taking an ADV (model "FlowTracker", Sontek/YSI) as the reference at low to medium velocities (< 2.5 m/s) and a Pitot tube (model "630", Lambrecht) as the reference at larger velocities. To estimate the surface velocity in open channels, these meters were located as close as possible to the water surface (sensor top at ≈ 2 cm below the surface), with special care to avoid cavitation around them during the measurements. The ADV was expected to be several times more accurate than the studied radar at low to medium water velocities, whereas the Pitot tube was expected to be much more accurate at large velocities [Tamari *et al.* 2013]. In addition, an MCM (model "Price AA", Rossbach) was taken as the reference for testing the radar in a river and a simple PIV technique was used as the reference in a field channel where water was flowing very rapidly [Tamari *et al.* 2013].

IV. RESULTS AND DISCUSSION

IV.1. Global performances of the tested radar

When tested in the laboratory and looking upstream, the handheld radar was found (Fig. 3) to estimate water velocity at the surface of open channels from 0.3 to 6 m/s with an uncertainty slightly better [p > 0.95] than what was expected at the beginning of this study (Section II.3); please note that the uncertainty of the reference techniques has been neglected because it was *a priori* several times lower than that of the radar. Roughly, it corresponds to: $U(V_s) \approx 0.3$ m/s at medium velocities (from 0.3 to 3 m/s) and $U(V_s) \approx 0.1 \times V_s$ at large velocities. Such an uncertainty is similar to that previously reported for the other model of handheld radar (Section II.1) and slightly larger than that previously reported for other types of microwave Doppler radars that have been tested in rivers (Section II.6).

When tested in the laboratory and looking downstream, the radar was found to estimate water velocity with an uncertainty still [p = 0.95] consistent with what was expected at the beginning. It could be argued that the laboratory results underestimate the usual performances of the radar, because it has been tested very close to the water surface (Section III.2). However, the radar data obtained in the field were consistent with those obtained in the laboratory (Fig. 3).

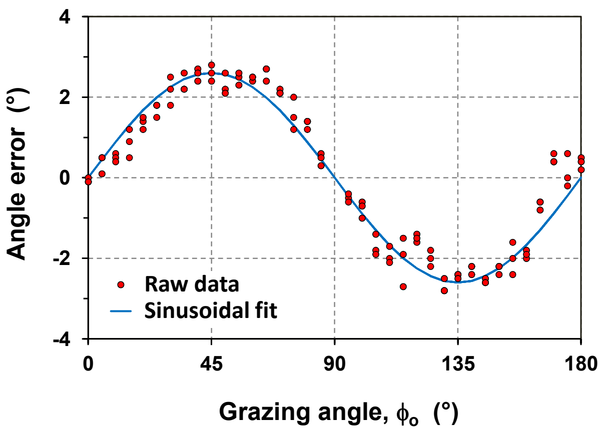

Fig. 2: *Laboratory verification of the radar's built-in inclinometer. The error is the difference between the angle displayed by the radar and the actual angle. Please, note that the radar displays the* grazing angle *(φ_o),* i.e. *the angle between its line-of-sight and the horizontal.*

IV.2. Underestimation of the reference velocities

Although the performances of the tested radar were consistent with what was expected at the beginning, two biases were found during this study. This will be discussed in this section and in the next one. According to a regression analysis, the radar data were significantly different from the reference data: on the average, the radar data were lower by ≈ 5 % of the value when the radar was looking upstream, and lower by ≈ 8 % of the value when the radar was looking downstream. This trend is still unexplained:

• *A bias of the radar's inclinometer ?* - Contrary to what has been reported for the other commercial model of handheld radar [Dramais *et al.* 2014], the trend cannot be explained by the bias of the radar's inclinometer: in a preliminary attempt to correct for this bias (Fig. 2), no significant improvement of the radar's performances was obtained.

• *A bad choice of the reference techniques ?* - It could be argued that the current meters used as a reference for testing the radar (Section III.3) may have underestimated the velocity at the surface of narrow (*i.e.* aspect ratio < 5) and rectangular channels, due to the *dip phenomenon*. However, the radar was also tested in the central part of wide rectangular channels and of trapezoidal channels, where the dip phenomenon should not occur [Tominaga *et al.* 1989].

IV.3. Radar looking downstream vs. looking upstream

The radar was found to usually estimate a lower velocity when looking downstream (V_s^{down}) instead of upstream (V_s^{up}). Roughly, the velocity difference ($\Delta V_s = V_s^{up} - V_s^{down}$) was increasing as a function of water velocity, when it was larger than ≈ 1 m/s (Fig. 4). No clear trend was found in V_s as a function of other quantitative (Froude number, aspect ratio, channel slope) or qualitative (laboratory or field testing) variables. It is still difficult to know why:

• *A wind effect ?* - The histogram of the raw data recorded by a microwave Doppler radar (converted into surface velocities) is often skewed. Many studies performed in water tanks [*e.g.* Gade *et al.* 1998; Plant *et al.* 2004] and on the sea [*e.g.* Plant and Keller 1990] have shown that this can be due to the wind (even a light air, with a speed as low as ≈ 0.3 m/s), unless it is blowing perpendicularly to the radar's line-of-sight. If a radar is looking upwind, it should record a histogram with a larger peak corresponding to the advancing water waves ($V_s + c_B$). On the opposite, if the radar is looking downwind, it should record a histogram with a larger peak corresponding to the receding waves ($V_s - c_B$). Under those circumstances, if the radar does not process carefully the raw data (*i.e.* if it does not extract the midway point between the two theoretical peaks of the histogram, but computes an average value, or -even worse- takes the mode), the absolute value of ΔV_s could be as large as $\approx 2 \times c_B$, which is ≈ 0.6 m/s for the studied radar (Section II.4). Since

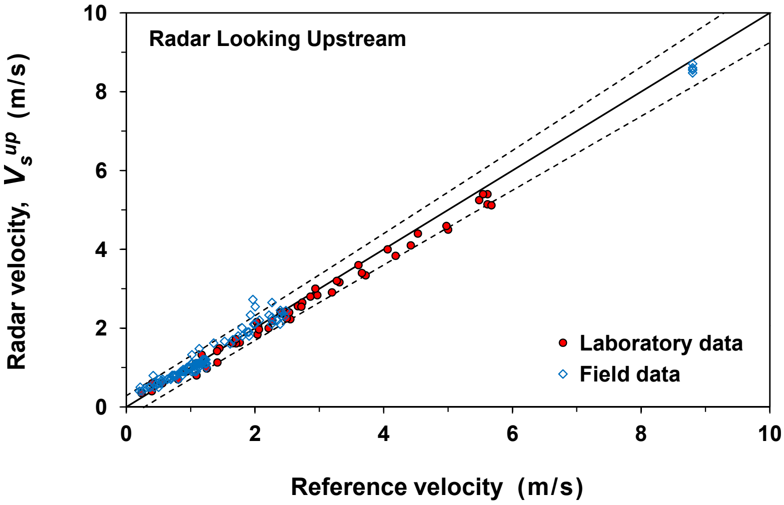

Fig. 3: *Velocity measured by the radar looking upstream (V_s^{up}) vs. velocity measured by reference techniques. The dashed lines show the expected radar uncertainty [*p *= 0.95].*

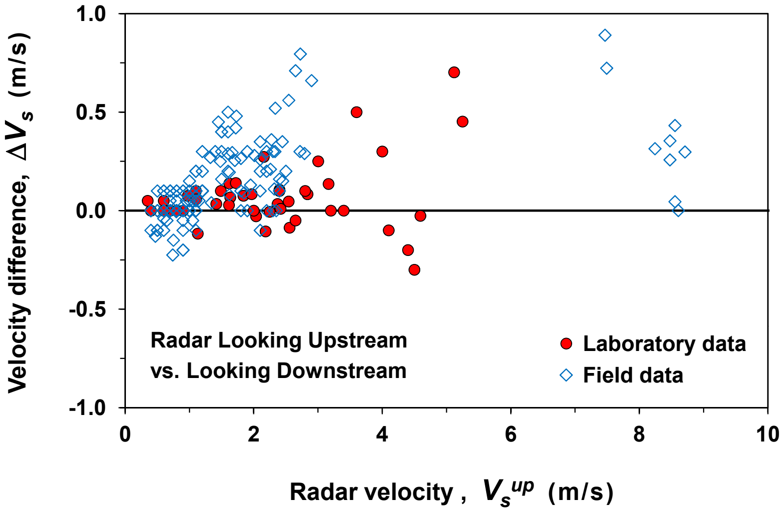

Fig. 4: *Difference in velocity between the radar looking upstream and downstream (ΔV_s) as a function of the velocity measured by the radar looking upstream (V_s^{up}).*

most of the observed values of ΔV_s were within ± 0.6 m/s (Fig. 4), they could be due to a wind effect and to an inaccurate data processing.

• *An hydrodynamic effect ?* - If the observed values of ΔV_s were due to the wind, the fact that they were usually positive would mean that the wind was usually blowing from upstream in the studied channels. Although, the wind direction and speed have not been systematically measured during this study, it seems that the observed values of ΔV_s were not always due to the wind: in the field, larger values of ΔV_s were obtained in some specific parts of channels where the water surface was more irregular due to turbulence, even under a light air condition or a light breeze coming from downstream [Tamari *et al.* 2013]. More studies are necessary to know if this is a general feature of microwave Doppler radars when used in open channels under clear weather conditions or an imperfection of the studied radar (unfortunately, its data processing algorithm is a "black box").

V. CONCLUSION

Over the last fifteen years, a growing number of studies have shown that Doppler radar technology is a promising tool to estimate water velocity at the surface of open channels. In this context, a commercial handheld radar was tested. The testing covered a broad range of velocities (from 0.3 to at least 6 m/s) and channel types (including inclined channels). The radar was able to estimate the water velocity within [p = 0.95] ± 0.3 m/s at medium velocities (from 0.3 to 3 m/s) and ± 10 % of the measured value at large velocities. Although this is not very accurate, the ease of using handheld radars still makes them attractive to quickly estimate discharge at gauging stations and to investigate how water flows under difficult access conditions. Nonetheless, the tested radar was tending to underestimate the water velocity, above all when it was looking downstream. More studies are necessary to know if this is due to a wind effect and an imperfection of the tested radar or if this is a general feature of microwave Doppler radars when used in open channels under clear weather conditions. Meanwhile, it is a good precaution to compare - whenever possible - the velocities obtained with a radar looking upstream and downstream.

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