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Testing a handheld radar for measuring the water velocity at the surface of open channels

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ABSTRACT

There is an interest in developing instruments that can measure the water velocity in open channels with no need to submerge them. In this context, few handheld radar are commercially available since ten years. Due to the lack of publications about these instruments, one model ("Stalker Pro II SVR") was tested in the laboratory (over horizontal and inclined channels) and in the field (measurements taken from a bridge, no rain, maximum wind equivalent to a gentle breeze). From a comparison with a conventional (electromagnetic) velocimeter, it is concluded that the radar can measure the velocity at the surface of open channels with an uncertainty of ± 0.3 m/s [$p = 0.95$] at low to medium velocities (from 0.4 to 3 m/s) and ± 10 % of the measured value at large velocities (at least, up to 6 m/s). Although this is twice less accurate than more-sophisticated Doppler radar and five to ten times less accurate than conventional velocimeters, the easiness of use and low cost of the handheld radar still makes it attractive for some applications, such as: quickly check the discharge data provided by some gauging stations, safely estimate the maximum water velocity during a flood and study how water flows under difficult access conditions (e.g., very shallow channels or the straight part of some spillways).

KEY WORDS: Surface Velocity Radar (SVR), radar gun, water velocity, open channels, gauging.

INTRODUCTION

In Hydraulics, the *handheld velocimeters* are light instruments (< 10 kg) designed to measure the velocity of a small water volume (typically < 1 dm^3). They are useful in open channels (artificial channels and rivers) to determine the discharge or to investigate some hydrodynamic features. For field applications, the most common instrument are (Rantz & Col. 1982; ISO 748: 2007; Turnipseed & Saueur 2010): the mechanical current meters (with rotating cups or with a helix), the electromagnetic velocimeters (EMV) and the acoustic Doppler velocimeters (ADV). Acoustic Doppler current profilers (ADCP) mounted on a floating platform can be used as well (Oberg & Mueller 2007).

When used properly, the conventional velocimeters can accurately determine the water velocity: their uncertainty is better than ± 0.01 m/s [$p = 0.95$] at low velocities (from 0.1 to 0.5 m/s) and ± 2 % of the measured value at larger velocities (up to at least 3 m/s) (Hubbard et al. 2001; ISO 748: 2007). However, they must be inserted into water, which is not always practical. It can be time-consuming, because the operator must get close to the water edge and then control the position of the instrument that it is let into water. It can be also dangerous, especially when water flows rapidly (i.e. faster than 2 m/s), when there are floating debris or when there are crocodiles. It can be even unhealthy, when a meter has to be inserted into residual water and cleaned after that. Finally, a velocimeter that is repeatedly submerged into water can get damaged, due to corrosion, incrustation, clogging or fouling.

There is therefore an interest in developing handheld instruments that can measure the water velocity in open channels with no need to submerge them (or, at least, not where this is dangerous for the operator). Such an interest is not new: forty years ago, an optical current meter (OCM) was developed for measuring the velocity at the surface of open channels (Rantz & Col. 1982), but this stroboscopic device with a telescope is not popular anymore. Now, other non-contact techniques for open channels are emerging, above all image velocimetry (LSPIV/STIV; e.g. Fujita et al. 2007; Le Coz et al. 2010) and Doppler radar (considered in this study). Unfortunately, none of these is still operational for determining the 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 as a reliable -although less accurate- method to estimate the discharge in open channels (Rantz & Col. 1982; ISO 748: 2007); several researchers are now testing this method and trying to improve it (Costa et al. 2006; Le Coz et al. 2010; Corato et al. 2011; Negrel et al. 2011).

Among the emerging techniques to determine the water velocity at the surface of open channels, few handheld radar are available on the market since ten years: these instruments look attractive for their low cost (< 3,000 USD) and easiness of use (**Figure 1**); however, little is known about their performances. The goal of this study was therefore to test a handheld radar for determining the velocity at the surface of open channels.

BACKGROUND

A *radar (RAdio Detection And Ranging)* is a remote sensing system that send an electromagnetic signal of a given frequency to a target and then measures some properties of the signal sent back by the target (time delay, Doppler shift and/or intensity) in order to determine its distance, speed and/or texture. There are radar of different signal frequency (ITU 2000) and design (Ulaby et al. 1981), depending on their purpose and level of sophistication. In particular, the *Doppler radar* are designed to determine the speed of a target.

What is known about the handheld radar ?

The handheld radar look like a pistol (for this reason, they are often called *radar gun*). They can be defined as *monostatic* (i.e. the receiving antenna is near the emitting antenna) and *microwave* (i.e. they emit a signal in the microwave range) Doppler radar, designed to be operated from a fixed position. In addition, the current instruments are *Continuous Wave* (a cheap technology, that does not allow the instrument to measure the distance to a target) and *Ka band* (the emitted signal has a frequency between 26.5 and 40 GHz) radar.

The handheld Doppler radar have been originally developed for determining the speed of cars (e.g., Jendzurski & Paulter 2008). They have become also popular for determining the speed of sporting balls (Newton & McEvoy 1994) and flying animals (Evans 1994). The idea of using similar instruments for determining the water velocity in open channels was patented ten years ago (Smith et al 2003). However, it is not the same -in terms of data processing- to determine the velocity of a water surface, instead of the speed of a single solid object. So, there is a need to test the handheld radar designed for measuring the water velocity.

Now, two models of handheld radar are sold for measuring the water velocity; both are called *surface velocity radar* (SVR). Although some authors seem to use them routinely for estimating the discharge in rivers (Corato et al. 2011), little has been published about their performances:

- *Handheld radar from Decatur Electronics* (Decatur Electronics 2011) - The last version - released in 2010- has a claimed uncertainty of ± 10 % of the measurement [$p = 0.95$] (*assuming that the manufacturer reports a standard uncertainty*) for a range from 0.3 to 9 m/s. A few recently published evaluations of this instrument (Fulton & Ostrowski 2008; Dramais et al. 2011; Zolezzi et al. 2011) suggest it can estimate the surface velocity within ± 10 % at medium to high velocities (≈ 0.5 - 4 m/s), but does not always operate at low velocities (< 0.5 m/s).

- *Handheld radar from Stalker Radar* (Stalker Radar 2008) - The last version -released in 2010- has a claimed uncertainty of ± 0.2 m/s [$p = 0.95$] (*assuming that the manufacturer reports a standard uncertainty*) for a range from 0.2 to 18 m/s. As far as we know, this is the only commercial velocimeter claimed to work at velocities above 10 m/s (something very fast for a free water surface). Compared to the radar from Decatur Electronics, it is also claimed to be more accurate at high velocities (> 2 m/s). In addition, it can measure incidence angles larger than 60 ° (as shown below, this option is useful for studying steep channels). Until now, there is no publication about the performances of the radar from Stalker Radar; this model will be therefore considered in the following.

Due to the lack of information about the performances of the handheld radar in the field of Hydraulics, some concepts about the Doppler radar are reviewed in the following, in order to know better what can be expected from these instruments.

Principle of operation of handheld radar

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 to internally compute the *radial velocity* of the target, that is, the component of its velocity relative to the radar line-of-sight (V_r, m/s):

$$V_r = c\,\frac{f - f_0}{f_0} = c\,\frac{\Delta f}{f_0} \qquad (1)$$

where c is the speed of the light in the air ($\approx 3 \times 10^8$ m/s) and $\Delta f = f - f_0$ is the *Doppler shift* (positive when the object get closer, and negative 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 the main direction where it moves.

Consider a radar oriented in such a way (e.g. from a bridge), so that it looks in the main direction of the stream (**Figure 2**). If the water backscatters the radar signal (as discussed further), the velocity of the water surface (V_s, m/s) can be estimated as:

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

where V_r (m/s) is the radial velocity of the water surface and θ (^{o}) is the radar angle of incidence relative to the surface. As far as we know, all the studies using a Doppler radar to determine the velocity of a water surface assume that the surface is horizontal. For open channels, such an assumption is usually realistic (with a tolerance of $\pm 1^o$) provided that the channel slope is gentle (< 0.017 m/m) and that there is no hydraulic jump (a shown on **Figure 1a**). In this case, the angle θ of **Equation 2** is simply the *angle of incidence* of the radar (θ_o), i.e. the angle between its line-of-sight and the vertical. The commercial handheld Doppler radar have a built-in inclinometer so that they can automatically determine such an angle and use it for estimating the water velocity (Smith et al. 2003).

In the following, the case of a water surface that is an inclined plane -as it occurs in steep channels and in the middle part of some spillways- will be also considered (as shown on **Figure 1b**). In this case, the angle θ of **Equation 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 ($0 \leq \beta < 90^o$). There is *a priori* no difficulty to measure the angle β using an external inclinometer and use this information for estimating the water velocity.

Finally, it must be recognized that when the water surface is not a plane anymore (as in the case of a hydraulic jump or over the bended part of a spillway), it becomes difficult to estimate the water velocity with a Doppler radar. This situation is out of the scope of the present study.

Which angle of incidence for the radar ?

To reduce as much as possible the effect of the trigonometric correction, a radar should be placed so that it looks the water surface with an angle of incidence as large as possible (i.e. $\theta \to 90^{\circ}$, so that $\sin(\theta) \to 1$ in **Equation 2**). However, there is a practical limit, because the instrument cannot be let too close to the surface. In addition, the angle cannot be too large, otherwise the radar will not "see" roughness at the water surface, and therefore will not detect it (Hasselmann et al 1985). In practice, the Doppler radar are oriented above a water surface with an angle of incidence $20 < \theta < 80^{\circ}$ (Hasselmann et al 1985; for more details, see the **Appendix**).

Assumes that V_r and θ are normally-distributed and independent random variables, a simple model for computing the uncertainty of V_s can be derived from **Equation 2**:

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

where $U(\bullet)$ denotes for the uncertainty of each variable at a given confidence interval (e.g. [p = 0.95]); please, note that the term $U(\theta)$ must be expressed in radians. Such a derivation is based on

Section [5.1.2] of JCGM (2008); it is slightly more rigorous than the uncertainty model proposed by Fulton & Ostrowski (2008). Strictly speaking, the model does not agree with what is claimed by the manufacturers of handheld radar (Stalker Radar 2008; Decatur Electronics 2011); in fact, it predicts that the uncertainty on the surface velocity ($U(V_s)$) is neither a constant and neither a fixed proportion of the measured value, unless the angle of incidence of the radar is very large ($\theta \to 90\ ^{o}$) or measured very accurately ($U(\theta) \to 0$).

For instance, the expected uncertainty $U(V_s)$ has been computed using **Equation 3** for $U(V_r) = 0.2$ m/s and $U(\theta) = 0.07$ rad ($4\ ^{o}$). As discussed further, this example is realistic for the tested radar (at a confidence level: $p = 0.95$). It suggests that the radar should be oriented with an incidence angle $\theta > 45\ ^{o}$, otherwise the uncertainty on the estimated surface velocity will increase rapidly (**Figure 3**).

Detection of a water surface by a microwave radar

To determine the radial velocity of a water surface (i.e. V_r in **Equation 1**), a Doppler radar must first detect it: the signal it sends must be reflected by the surface and go back to the instrument in order to be processed. As said, the handheld radar considered in this study are microwave radar. The backscattering of their signal by a water surface (at least, in the range $20 \le \theta \le 80\ ^{o}$) is currently described by the theory of *composite surface scattering* (e.g. Hasselmann et al 1985, Plant & Keller 1990; Plant et al 2005).

On the one hand, the theory considers that the water waves producing most of the backscattering are rather small: these are ripples (for more details, see the *resonant Bragg condition* in the **Appendix**), which are produced by the turbulence of water, the wind (including the wind produced by the helix of an helicopter) and/or the rain, and which tend to propagate in several directions at a specific (phase) speed.

On the other hand, the theory considers that the small water waves producing backscattering are often bounded to -and therefore driven by- larger water waves; in open channels and rivers, these larger (gravity) waves are due to the turbulence of water (including the transverse waves due to the reflexion of water at the edges of a channel and the vortices (or hydraulic boils) in shallow water and/or in channels with an irregular bottom) and to the wind; although they may also tend to propagate in several directions at their own (phase) speed, on the average, they are assumed to follow the displacement of the water surface. Several laboratory experiments (e.g., Gade et al. 1998; Plant et al. 2004) and numerical simulations (e.g., Dias & Kharif 1999) suggest that there are often small (capillary) waves on the top and/or in the forward part of larger periodic (gravity) waves.

Many recent tests performed on rivers have shown that microwave radar can determine the velocity of a water surface (V_s) with an uncertainty of about ± 0.2 m/s [p = 0.95], provided that the data are processed carefully (e.g., Plant et al 2005). Although the manufacturers of handheld Doppler radar claim a similar accuracy (see next section), they do not provide details about how their instruments process the data (in fact, this is probably a trade secret). This emphasizes the need to test the handheld radar.

Which factors affect the surface velocity measured by a radar ?

Because a free water surface is driven both by the underlying current and by the wind, the water velocity measured by a Doppler radar is not necessarily easy to interpret (Plant et al. 2005; Chapron et al. 2005). In fact, such a surface velocity (V_s) can be expressed as the algebraic sum of four terms (**Figure 4**):

$$V_s = V + W + U_s \pm v \tag{4}$$

where V is the velocity of the underlying current, W is a velocity component due to the effect of the wind (blowing in the direction of the radar line-of-sight), U_s is the Stokes drift produced by the waves at the water surface, and v is a component due to the specific motion of the water waves that backscatter the radar signal (i.e., some are advancing faster and some are advancing slower than the mean water surface).

In Hydraulics, the goal is to use Doppler radar for determining the velocity of the underlying current (V). But in this case, **Equation 4** shows that assuming that it is equal to the surface velocity determined by the radar (V_s) can lead to three kinds of systematic errors:

- *Backscattering water wave effect* (v) - For a microwave radar (for more details, see the **Appendix**), uncertainties larger than 0.1 m/s can be expected if there are not enough ripples at the water surface and / or if the raw radar data are not carefully processed. Such a problem has been reported for rivers, when there is no rain to create ripples (Plant et al 2005). It is also expected to happen if there is an oil film above the water surface (e.g., Gade et al. 1998).

- *Wind effect* (W) - Roughly, the magnitude of the drift caused by the wind (in the wind direction) on a water surface is $W \approx 0.02 \times W_{10}$, where W_{10} (m/s) is the wind speed measured at a height of 10 m above this surface (e.g. Plant & Wright 1980 [cited by Plant et al 2005]). For a wind blowing at a speed $W_{10} < 5.5$ m/s (i.e. a *gentle breeze* on the Beaufort scale), it gives: $W < 0.1$ m/s.

- *Stokes drift* (U) - The Stokes drift is a displacement of the water surface produced by the water waves themselves. It is accounted by a Doppler radar (as well as by small drifters that would be let on the surface), but not by a conventional velocimeter that would be maintained at a fixed position and just below the water surface (Monismith & Fong 2004). So, the Stokes drift could be a reason for a systematic difference between the radar and the conventional estimation of the velocity at a water surface. The Stokes drift can be significant only when the water waves are large, as in the ocean. However, it is not expected to be larger than ≈ 0.1 m/s in open channels (for more details, see the **Appendix**).

Summarizing, the handheld radar sold for determining the water velocity at the surface of open channel look very simple. However, the literature about microwave Doppler radar suggest that they may not work if there are oriented with a too extreme angle of incidence (i.e. out of the range $20 < \theta < 80\ ^{o}$) or if the water surface is not agitated enough (something that may happen if water flows slowly or if there is an oil film at the surface). The literature also suggest that the data of a microwave radar (i.e. the recorded Doppler shifts) must be carefully processed; otherwise uncertainties larger than 0.1 m/s in the estimation of the water velocity may arise. Finally, when the goal is to use a radar for studying how water flows in open channels, the literature suggest that windy conditions (i.e. stronger than a gentle breeze on the Beaufort scale) should be avoided.

MATERIALS AND METHOD

Preliminary testing of the radar

The tested radar was model "Stalker Pro II SVR" (Stalker Radar 2008). It has an operating frequency of 34.7 GHz (Ka band) and a circular polarization (a configuration that makes it less sensitive to the rain). According to its manufacturer, the built-in inclinometer of the handheld radar has an uncertainty of $\pm 4\,^{\circ}$ [$p = 0.95$] (*assuming that a standard uncertainty is reported*). This was checked from a comparison with an external inclinometer with an uncertainty of $\pm 1\,^{\circ}$ [$p = 0.95$] (model MTi, Xsens Technologies, Enschede, The Netherlands).

Because a Doppler radar *a priori* does not work if its angle of incidence is too low or too high, some preliminary tests were made to check this point: measurements were taken with the tested handheld radar located at different angles of incidence (either upstream either downstream) over a few laboratory channels (horizontal or inclined), and the consistency of the radar data was evaluated. In all cases, the slope of the water surface (β) was assumed to be the slope of the channel, which was measured using an external inclinometer. Whereas Doppler radar are usually considered to work in the range $20 \leq \theta \leq 80\ ^{\circ}$ (see the **Appendix**), the results obtained with the handheld radar suggest that it should not be used outside of the range $30 \leq \theta \leq 50\ ^{\circ}$ (**Figure 5**).

Conditions for using the tested radar

During the testing, the handheld radar was operated as follows:

- *Radar oriented in the direction of the main stream* - The measurements were always taken so that the radar was oriented in the direction of the main stream (i.e. in the field, the measurements were taken from a bridge across the open channel). In this case, there was no need to correct the velocity data for the orientation of the radar in the horizontal plane (as should be done, if the radar is located at the edge of a channel).

- *Radar close to the water surface* - Assuming that the radar signal is sent like a cone, the instrument will "see" an area at the water surface (*footprint*) whose length is:

$$W = L\ \cos(\theta)\left[\ \tan\left(\ \theta + \frac{\gamma}{2}\ \right) - \tan\left(\ \theta - \frac{\gamma}{2}\ \right)\right] \qquad (5)$$

  where L (m) is the distance to the water surface, θ ($^{\circ}$) is the angle of incidence and γ ($^{\circ}$) is the aperture of the cone containing most of the radar signal (*3 dB beam width*). Considering $\gamma = 12\ ^{\circ}$ (according to the radar manufacturer) and $\theta \approx 45\ ^{\circ}$ (i.e. the usual orientation of the radar during this study), it gives: $W \approx 0.3 \times L$. In order to obtain a good spatial resolution, the radar was located close to the water surface, at a distance $L \approx 0.25$ m in the laboratory (which gives $W \approx 0.07$ m) and $L \approx 1.5$ m in the field (which gives $W \approx 0.45$ m). Like this, it was felt that the area sampled by the radar was not too small (so that the radar would "see" enough of the water waves that backscatter its signal; see the **Appendix**) and not too large (so that it can be compared to the data provided by conventional velocimeters).

- *Intermediate angle of incidence* - During normal operation, the radar was oriented with an angle of incidence relative to the water surface (θ) between 45 and 50 °: at larger angles, it is difficult in practice to control what the radar "sees" (in addition, the radar sometimes does not work; see **Figure 5**), whereas at smaller angles, the uncertainty analysis (**Figure 3**) suggests that the radar data will be inaccurate.

- *Measurement taken rather quickly* - To take a measurement with the radar, it was first oriented at a given incidence angle (on the basis of the data provided by its built-in inclinometer and from the knowledge of the channel slope), and its trigger was then pressed; once a first velocity data appeared on the radar screen, the instrument was let to take and average more data during ≈ 10 - 30 s. The only parameter for configuring the radar was its power output, which was set at 20 mW (i.e., the minimum value, as recommended by the manufacturer for taking data close to a water surface).

Experimental plan

Considering the (very few) previous testing of handheld Doppler radar and what can be expected *a priori* of this type of instrument (i.e. microwave Doppler radar), it was decided to test the handheld radar under the following conditions:

- *Wide range of water velocities* - For open channel, the most interesting application of the handheld radar is to measure high water velocities (> 2 m/s); however, the testing (comparison with conventional velocimeters) becomes challenging in these conditions. Before, it is a good precaution to test the radar at lower velocities; in particular, the literature suggests that it should hardly work at low velocities (< 0.5 m/s), because the water surface is too smooth (unless it is rainy or windy).

- *Various kinds of open channels* - Compared to the other radar developed for studying open channels (instruments fixed to a bridge or a mast, or embarked on an airplane or an helicopter), the easiness of use of the handheld radar (very easy to transport from one site to the other and with immediately available data) makes it possible to test them rapidly in a many places. It is worth noting that the Doppler radar have been tested in rivers, but not in artificial channels (where the roughness of the water surface may be different, due to different turbulence conditions). So, the radar considered in this study was tested in a number of open channels, with a special interest in artificial channels.

- *Conditions favorable for the operator, but not necessarily for the radar* - The radar testing was always performed under the following conditions: wind as low as possible (not more than a gentle breeze) and no rain (it is worth noting that the response of a Ka band radar can be affected by the rain droplets; e.g. Decatur Electronics 2011). These conditions are convenient for an operator and they should ensure that the water surface is mostly driven by the underlying current; when water flows slowly, they are however challenging for a radar, because the water surface tends to be smooth (in the absence of ripples produced by the wind or by the rain; e.g. see Plant et al. 2005).

Sites where the radar was tested

The handheld radar was tested in a number of open channels with *a priori* different kinds of roughness at the water surface (**Table 1**):

- *Channels with walls of different roughness* - Smooth (laboratory channels made of acrylic or cement), moderately rough (artificial channels made of concrete, masonry or earth) and very rough (rivers with stones or weeds at the bottom) open channels were considered. This corresponds to a range for the *Manning's coefficient* from ≈ 0.015 to 0.035.

- *Different flow conditions* - Subcritical ($Fr < 1$) and supercritical ($Fr > 1$) were considered in this study. It is reminded that the *Froude number* (Fr) is: $Fr \approx V / \sqrt{g\ y}$ (assuming shallow water waves and a rectangular channel cross section), where $g \approx 9.8$ m s^{-2} and y (m) is the water depth.

- *Different turbulent conditions* - Channels with boils expected at the water surface ($\kappa > 3$, according to Nezu 2005) and with no expected boils ($\kappa < 3$) were considered, on the basis of the criterion proposed by Nezu (2005): $\kappa = b / y$, where b (m) is the width of the channel bottom and y (m) is the water depth. Channels with an *a priory* large (rotational) vorticity (e.g., after a curve) were also considered.

- *Waters of different quality* - Waters of "good" (for irrigation) an "bad" (residual water) qualities were considered. Water of "bad" quality may be indeed more difficult to be detected by a microwave Doppler radar, if there is an oil film at the surface that dumps the ripples (Gade et al. 1998).

Instruments for testing the radar

The radar velocity data were compared with those obtained using a velocimeter, taken as a reference: the model "Flo-Mate" (Marsh-McBirney 1990) was used; this is an electromagnetic velocimeter, with a claimed uncertainty of ± 4 % of the measurement plus ± 0.015 % [$p = 0.95$] at velocities up to 6 m/s. Although not claimed to be very accurate in practice (*assuming that the manufacturer reports a standard uncertainty*), this conventional velocimeter was chosen because it can be used at velocities > 4 m/s. In addition, the design of its sensor (rather small and symmetrical) makes it possible to locate it close to the water surface; during the testing, the top part of this sensor was let into water ≈ 10 - 20 mm below the free surface. Velocity data were taken with a measuring time of 40 s.

RESULTS AND CONCLUSION

Radar uncertainty

Form the comparison with conventional velocimetry in different channels, it is concluded that the tested handheld radar (oriented with an incidence angle $\theta > 45\ ^{o}$) can measure the water velocity at the surface of open channels in the range 0.5 to (at least) 6 m/s with an uncertainty [p = 0.95] better than the model expressed in **Equation 3** with: $U(V_r) = 0.2$ m/s and $U(\theta) = 0.07$ rad (4 ^{o}) (see the dashed lines in **Figure 6**). As expected, the radar was usually not working at low water velocities (< 0.5 m/s). These results agree with the previously published studies about handheld radar (Fulton & Ostrowski 2008; Dramais et al. 2011; Zolezzi et al. 2011); however, more flow conditions were considered during this study.

The velocity profiles at the surface of some open channels are shown on **Figure 7**; no trend in the differences between the data provided by the handheld radar and the conventional velocimeter was detected, except at the edges of the channels: in this case, the radar was usually overestimating the water velocity (such a situation has been reported previously for a river by Dramais et al. 2011).

Finally, the tested radar was determining higher velocity when looking downstream (with an incidence angle relative to the water surface of ≈ 45 °) instead of upstream (see **Figures 5, 7 and 8**); although this systematic difference is rather small (≈ 0.1 m/s), it is still unexplained.

Conclusion

The tested handheld radar could measure the velocity at the surface of open channels with an uncertainty of ± 0.3 m/s [$p = 0.95$] at low to medium velocities (from 0.4 to 3 m/s) and ± 10 % of the measured value at large velocities (at least, up to 6 m/s). Although this is twice less accurate than more sophisticated Doppler radar and more than five times less accurate than conventional velocimeters, the easiness of use and low cost of the handheld radar still makes it attractive for some applications, such as: quickly check the discharge data provided by some gauging stations, safely estimate the maximum water velocity during a flood and investigate how water flows under difficult access conditions (e.g., very shallow channels or the straight part of some spillways).

APPENDIX - SOME DETAILS ABOUT RADAR AND WATER WAVES

History of radar for measuring the water velocity

Fifty years ago, it was discovered that the Doppler radar technology can be used to determine the speed of water waves (Crombie 1955; Plant & Keller 1990). This finding was first used in Oceanography, to estimate the magnitude of the two main factors that advect the sea waves: the wind above the ocean and the superficial currents (Teague et al. 1997; Chapron et al. 2005). In the last ten years, a growing number of studies has shown that the Doppler radar technology can be adapted to determine the velocity at the surface of rivers. Different types of radar have been developed for this purpose (Plant et al. 2005; Costa et al. 2006) and some of these are now commercially available (e.g., "RiverSonde" from Codar Ocean Sensors; "Flo-Dar" from Marsh-McBirney; "RQ-24" from Sommer GmbH; "(Doppler) Kalesto" from OTT Hydrometry).

Above all, two broad categories of radar for measuring the water velocity must be distinguished, according to their signal frequency. On the one hand, the "*HF radar*" (Teague et al. 2001; Shen & Wen 2010) send a signal in the HF/VHF/UHF range ($f_0 \approx 3$ to 3000 MHz), which corresponds to a wavelength λ between ≈ 0.1 and 100 m ($\lambda = c / f_0$, where $c \approx 3 \times 10^8$ m/s is the speed of the light in the air); these radar have large antennas, a rather large beam angle (meaning that the radar signal tends to be spread over -and received from- a large area), and their signal is scattered by rather large (gravity) water waves. On the other hand, the "*microwave radar*" (Plant et al 2005, Costa et al 2006, Fulton & Ostrowksi 2008) send a signal in the SHF/EHF range ($f_0 \approx 3$ to 300

GHz), which corresponds to a wavelength λ between ≈ 0.001 and 0.1 m; these radar have small antennas, a rather small beam angle (of a few degrees), and their signal is scattered by small (capillary-gravity) water waves.

The theory of how a radar signal is backscattered by a water surface is not straightforward (e.g. Hasselmann et al 1985; Elfouhaily & Guérin 2004; Chapron et al. 2005). As a first approximation, it is considered that a water surface reflects a radar signal as a mirror would do: first, the radar signal almost does not penetrates into water (not more than a few cm for a microwave signal; see Plant and Wright 1980 [cited by Plant *et al.* 2005]; Chapron et al. 2005); and second, the signal of an inclined radar ($\theta \neq 0$) will not be backscattered, unless there are some facets at the water surface that are oriented perpendicularly to the line-of-sight of the radar (which implies that the water surface must be agitated enough).

Bragg resonant condition

In addition, for a moderately inclined radar (in the range $20 \leq \theta \leq 80\ ^{o}$), the theory considers that most of the backscattering will be produced by (periodic) water waves (traveling in the direction of the radar line-of-sight, either forward or backward) with a specific wavelength (Λ_o, m) that depends on two radar characteristics: the wavelength of the radar signal (λ, m) and the radar angle of incidence (θ, ^{o}). This has been verified by many studies performed in the laboratory (e.g. Gade *et al.* 1998) and above the sea (e.g., Crombie 1955, Hasselmann et al 1985, Plant & Keller, 1990), as well as a growing number of studies performed above rivers (e.g. Plant et al. 2005). The relation is known as the *resonant Bragg condition*:

$$\Lambda_0 = \frac{\lambda}{2\ \sin(\theta)} \tag{6}$$

For instance, the frequency of the signal emitted by the studied handheld radar is f_0 = 34.7 GHz (Ka band), which corresponds to a wavelength of λ = 8 mm (i.e. $\lambda = c / f_0$); so, if such a radar is oriented with an incidence angle $\theta \approx 45\ ^{o}$, the waves at the water surface that are expected to contribute to the backscattering of the radar signal will have a wavelength $\Lambda_0 \approx 6$ mm. From a hydraulics point of view (e.g., Dias & Kharif 1999), these small waves ($\Lambda_0 < 17$ mm) are classified as "ripples" (or "capillary waves"). Of course, the shape of an agitated water surface is quite irregular. In this case, it is considered that it can be decomposed in a superposition of periodic waves, each of one having a specific wave length.

A consequence of the above theory is that the data obtained by a Doppler radar above a water surface are "noisy": the water waves that backscatter the radar signal do not indeed travel exactly at the mean velocity of the surface (V_s), but they also tend to move forward and backward at a velocity (v) that depends -at least- of their own (*phase*) velocity. So, the histogram of the velocities recorded by a radar looking at a moving water surface will ideally show two marked peaks (not necessarily of the same amplitude): one for the advancing water waves ($V_s + v$) and the other for the receding ones ($V_s - v$). In this case, the basic operation of a Doppler radar consists in (Plant et al. 2005): (1) rapidly record many velocity data (e.g. ≈ 1,000 data in less than one second), (2) identify the two largest peaks in the histogram of the velocity data. and (3) estimate the mean velocity of the water surface (V_s) as the midpoint between these two peaks.

Composite surface theory (for microwave radar)

Unfortunately, the histogram of the velocity data recorded by a microwave radar -compared to a HF radar- does not always clearly show two peaks. This is due to the fact that the signal of a microwave radar is backscattered by rather small (*gravity - capillary*) water waves, which can be *bounded* to larger (*gravity*) waves: in this case, the small waves does not tend to travel exactly at their own (phase) velocity, but rather at the (phase) velocity of the larger ones; this phenomenon is known as the *composite surface theory* (e.g. Hasselmann et al 1985, Plant & Keller 1990; Plant et al 2005; Chapron et al. 2005). The existence of bounded water waves has been demonstrated in the laboratory and through numerical simulations (e.g., Dias & Kharif 1999): it has been shown that there are often small (gravity - capillary) water waves on the top and/or in the forward part of larger (gravity) waves. Other reasons for explaining why the histogram of the velocities recorded by a microwave radar has a rather complicated shape -and is therefore difficult to process- are given by Plant et al. (2005) and Chapron et al. (2005).

How large can be the dispersion of the velocity data recorded by a microwave Doppler radar around the mean velocity of the surface ? At least, this will depend on the (phase) velocity of the (gravity - capillary) water waves that backscatter the radar signal. When an open channel is deep (i.e., its water depth h is large enough so that $\Lambda << 2\ \pi\ h$), the (phase) velocity of a (gravity - capillary) water wave is (e.g., **Equation 3.1** in Dias & Kharif 1999):

$$v = \sqrt{\frac{g\,\Lambda}{2\,\pi} + \frac{2\,\pi\,\sigma_w}{\rho_w\,\Lambda}} \qquad (7)$$

where g is the acceleration of gravity (≈ 9.8 m s^{-2}), ρ_w is the density of water (≈ 1000 kg m^{-3}), σ_w is the superficial tension of water ($\approx 73 \times 10^{-3}$ N m^{-1}) and Λ is the wavelength (m). For the studied handheld radar, it is expected that $\Lambda_0 = 0.5 \times \lambda / \sin(\theta) \approx 6$ mm (considering $\theta \approx 45^{\circ}$), which would give: $v \approx 0.1$ m/s. However, recent studies about the use of Doppler radar in rivers suggest that the dispersion of the radar data can be much larger. For instance, in case of a radar operating at a frequency close to that of the tested handheld radar (K band: $f_o = 24$ GHz, which gives: $\lambda = 12.5$ mm) and with a moderate incidence angle ($\theta = 45^{\circ}$, which gives: $\Lambda_0 = 8.8$ mm), half of the distance between the Bragg peaks was typically: $\delta f \approx 50$ Hz; this means that the water waves producing the backscattering were traveling at a phase velocity of: $v = c\, \delta f / f_o \approx 0.6$ m/s (which would corresponds to water waves with: $\Lambda = 23$ mm). In this case, it can be concluded that the water waves (ripples, Λ_0) producing the radar backscattering were transported by water waves (capillary waves, Λ) $\approx$ three times larger.

Stokes drift

Considering a deep channel (i.e., its water depth h is large enough so that $\Lambda_0 << 2\, \pi\, h$) and rather large water waves (i.e., gravity waves: $\Lambda >> 17$ mm), the Stokes drift at the water surface is (adapted from **Equation 1** of Monnismith & Fong 2004):

$$U_s = \rho_w \, a^2 \left(\frac{2 \, g \, \pi}{\Lambda} \right)^{3/2} \qquad (8)$$

where a is the wave amplitude (m). The formula shows that the Stokes drift can be significant when the water waves are large, as in the ocean. On the opposite, it is not expected to be larger than ≈ 0.1 m/s in open channels (i.e., an estimation obtained considering that water waves in open channel have a wavelength $\Lambda < 1$ m; in this case, their amplitude is expected to be $a < 0.05 \times \Lambda = 50$ mm, in order to respect the classical condition for non-breaking waves; see Monismith & Long 2004).

For fully developed waves on the ocean, the Stokes drift can be also expressed empirically as (Chapron et al. 2005): $U_s \approx 0.0125 \times W_{10}$, where W_{10} (m/s) is the wind speed measured at a height of 10 m above this surface

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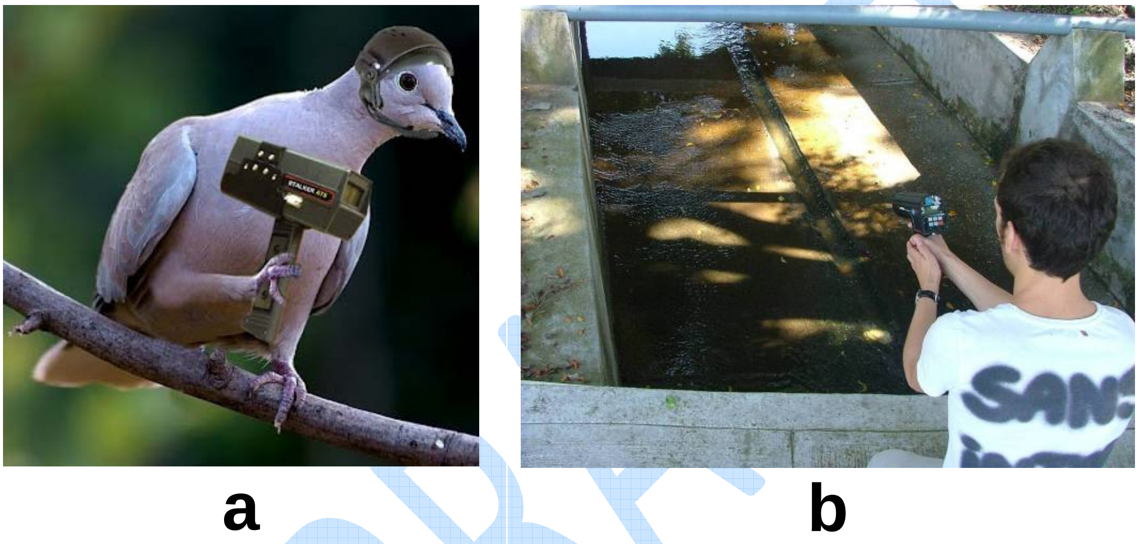

Pendiente !

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Figure 1. Some views of the tested handheld radar used (a) in the field over an irrigation channel and (b) in the laboratory over the plane part of a spillway. To take a measurement, a user orientated in the main stream direction shoot the water surface, press a trigger and wait for a few seconds; a trigonometric correction (Equation 2) is necessary for estimating the velocity at the water surface.

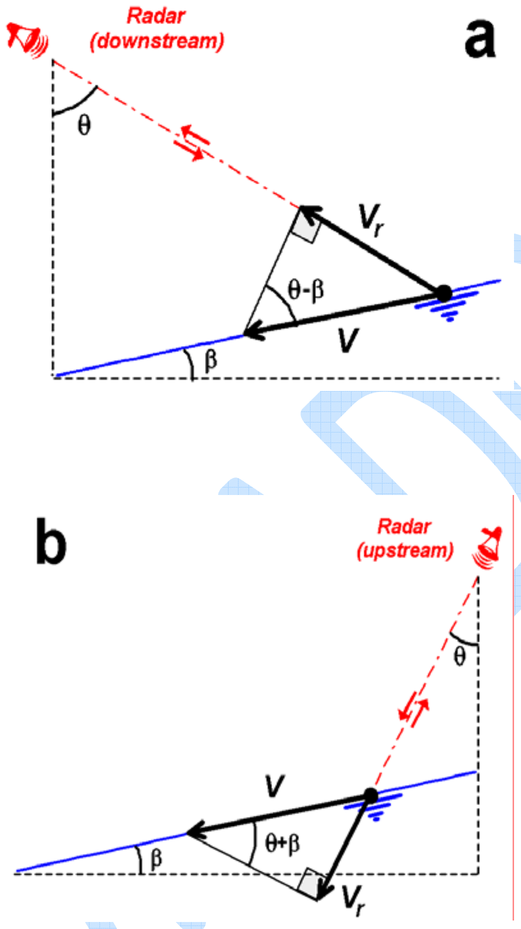


Figure 2. Diagram of how the handheld Doppler radar is used to determine the velocity at the surface of water: (a) radar looking upstream, (b) radar looking downstream. The radar incidence angle (θ) is relative to the vertical. The water surface is assumed to be a plane; this plane is usually horizontal (β = 0), but it can be also inclined (β ≠ 0) in some cases (e.g. over a spillway).

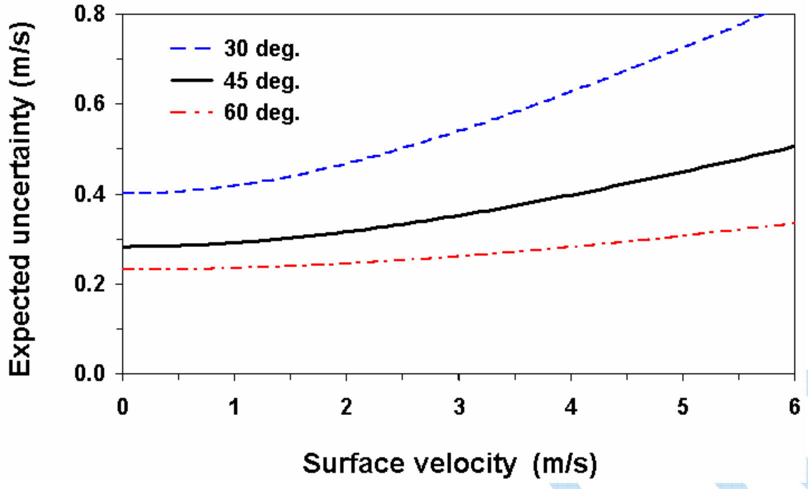


Figure 3. Expected uncertainty of a handheld Doppler radar, as a function of the surface velocity (V_s) and for three angles of incidence (θ). Computations are based on Equation 3, with $U(V_r) = 0.2$ m/s and $U(\theta) = 0.07$ rad ($4\ ^{o}$); these values are considered as realistic for the tested radar, at a confidence interval of: $p = 0.95$.

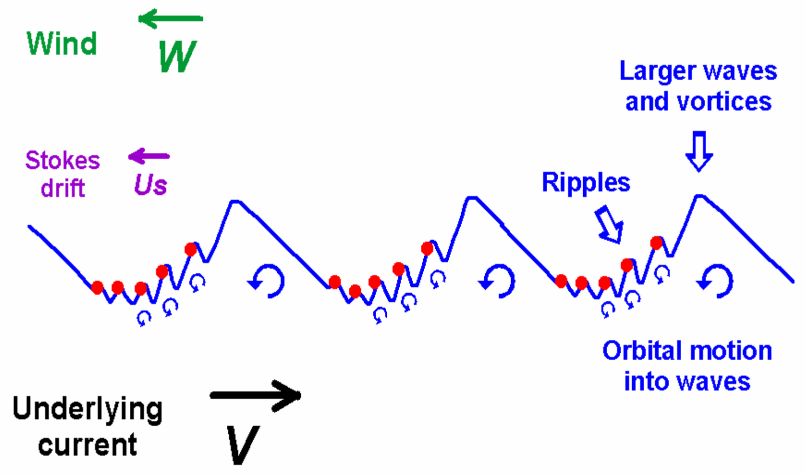


Figure 4. Diagram of how a (microwave) Doppler radar "sees" a water surface. Rather small water waves ("ripples"; points on the diagram) backscatter most of the microwave radar signal (due to the "Bragg effect"). Many of these small waves are bounded to large (gravity) water waves and vortices. Although the large waves tends to move in several directions at their own (phase) velocity, on the average they are advected by the underlying current and/or by the wind (the "Stokes drift" is expected to be small in open channels).

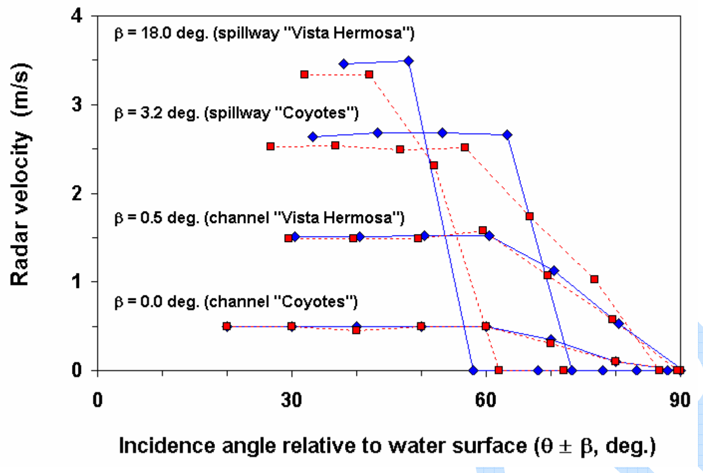


Figure 5. Effect of the incidence angle (relative to the water surface) on the response of the tested handheld radar. The tests were performed on four laboratory channels, with different slopes (β). The measurements were performed with the radar looking upstream (squares) and downstream (diamonds).

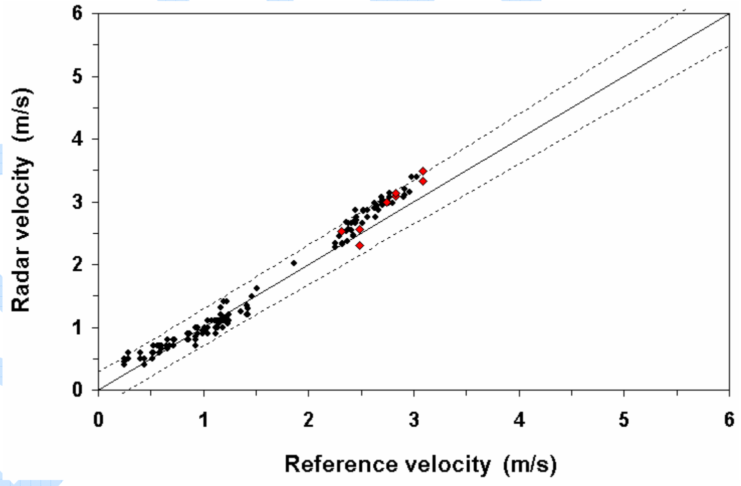
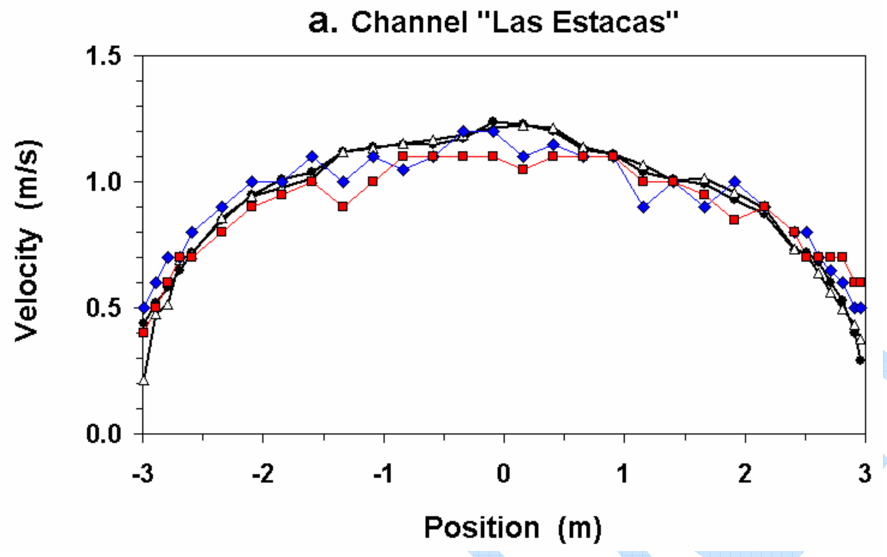


Figure 6. Verification of the tested handheld radar. The data were obtained on several laboratory and real channels (see Table 1). The reference velocity was obtained with an electromagnetic velocimeter locate at ≈ 3 cm below the water surface. The dash lines show the expected difference between the reference and the radar velocities (see text).



(b) Chilatan TA

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(c) Lateral 13+200

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Figure 7. Horizontal velocity profiles obtained with the tested handheld radar looking upstream (diamonds) and downstream (squares), as well as with an electromagnetic velocimeter (bold line) located at ≈ 3 cm below the water surface.

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Figure 8. Systematic difference in the velocity data with the tested handheld radar looking upstream and downstream, as a function of water velocity.

Table 1. Sites where the handheld radar has been tested.

Place	#	Site	Channel walls	Length (m)	Width (m)	Water level (m)	Slope (deg.)	Water velocity (m/s)	Froude (*Fr*)	Nezu (κ)	Reference technique	Data	Note
Lab	1	Channel, "Canal Largo"	Glass	50	1.0	0.2 - 0.5	0.0	0.2 - 1.5			(1)	10	
	2	Channel, "Coyotes"	Cement	10	1.0	0.2 - 0.5	0.0	0.2 - 0.6			(1)	8	
	3	Spillway, "Coyotes"	Cement	8	0.5	0.1 - 0.3	0.5	1.2 - 1.6			(1)	4	
	4	Channel, "Vista Hermosa"	Acrylic	4	0.5	0.1 - 0.3	0.5	1.2 - 1.6			(1)	4	
	5	Spillway, "Vista Hermosa"	Acrylic	6	0.5	0.1 - 0.3	0.5	1.2 - 1.6			(1)	4	
	6	Spillway, "Naranjos "	Acrylic	4	0.5	0.1 - 0.3	0.5	1.2 - 1.6			(1)	4	
	7	Spillway, "XXX"	Acrylic	6	0.5	0.1 - 0.3	0.5	1.2 - 1.6			(1)	4	
	8	Spillway, "Huapachic"	Acrylic	6	0.5	0.1 - 0.3	0.5	1.2 - 1.6			(1) (3)	4	
Field	9	Channel, "Las Estacas CP I (Mor.)"	Concrete	> 50	3	1.0 - 2.0	0.0	1.2 - 1.6			(2)	10	
	10	Channel, "Las Estacas CP II (Mor.)"	Concrete	> 200	8	1.0 - 2.0	0.0	1.2 - 1.6			(2)	10	
	11	Channel, "Lateral 13+200" (Mich.)	Concrete	> 400	4	1.0 - 2.0	0.0	4.0 - 5.0			(2)	10	
	12	Channel, "Chilatan TA" (Mich.)	Concrete	> 500	16	1.0 - 2.0	0.0	4.0 - 5.0			(2)	10	
	13	Channel, "Atuto" (Mich.)	Masonry	> 200	6	1.0 - 2.0	0.0	1.0 - 1.5			(2)	10	
	14	Channel, "Rapida" (Pue.)	Concrete	> 500	6	0.5 - 1.0	40.0	5.0 - 6.0			(2)	10	
	15	River, "Apatlaco" (Mor.)	Stones	> 500	20	4.0 - 6.0	0.0	1.5 - 2.5			(2)	10	
	16	Residual water (e.g. Tuxpan) ?	Cement	> 200	5	1.5 - 2.5	0.0	1.5 - 2.5			(2)	10	
	17	Residual water (e.g. with foam) ?											

(1) Electromagnetic velocimeter (FloMate, Marsh Bratney, XXX)
(2) Acoustic Doppler Velocimeter (FlowTracker, Sontek, XXX)
(3) LSPIV (Muste et al 2008)