Non-Contact Measurement of River Surface Velocity and Discharge Estimation with a Low-Cost Doppler Radar Sensor

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***Abstract*—River discharge is an important variable to measure in order to predict droughts and flood occurrences. Once the cross-section geometry of the river is known, discharge can be inferred from water level and surface flow velocity measurements. Since river discharges are of particular interest during extreme weather events, when river sites cannot be safely accessed, non-contact sensing technologies are particularly appealing. To this purpose, the present work proposes a prototype of a low-cost Continuous Wave (CW) Doppler radar sensor, able to monitor the surface flow velocity of rivers. The prototype is tested at two gauged sites in central Italy, along the Tiber River. The surface flow velocity distribution across the river is monitored by means of the analysis of the received Doppler signal. The surface velocity statistics are then extracted using a novel algorithm that is optimized to run on a microprocessor platform with minimal computing power (ArduinoUNO). In particular, the radar measurements are used to initialize a 2D Entropy-based Velocity Model (EVM) that is able to estimate river discharges in any flow condition. Finally, the results concerning the observed discharge provided by the EVM prove to be comparable with those obtained with more expensive commercial solutions. The results are important since the described methodology can be extended to small-size Doppler radar sensors onboard Unmanned Aerial Vehicles (UAVs), the latter providing a method for mapping surface velocity of rivers.**

***Index Terms*—river hydraulics; discharge estimation; low-cost Doppler radar sensors; surface velocity radars; Doppler centroid estimation.**

I. INTRODUCTION

RIVER discharge is a key variable in the hydrological cycle. Discharge is not a direct measurement but is calculated by integrating information coming from measurements of surface water level, velocity, and cross-sectional flow area. The cross-section shape is assumed to be known by the available bathymetry or inferred by surface velocity distribution [1]. This can be done by exploiting the Principle Of Maximum Entropy (POME), as illustrated in [2].

Traditionally, the velocity measurement is carried out leveraging current meters or ultrasonic devices such as Acoustic Doppler Current Profilers (ADCP) or similar [3]. As an example, for direct velocity measurements by current meters, the mean flow velocity is estimated once vertical velocity profiles are sampled in any portion of the flow area.

Discharge in natural channels, instead, is assessed by using the velocity-area method or the mid-section method, of which the latter is slightly more accurate [4]. Both methods rely on measurement of stream point velocities, depths of flow, and distances across the channel between sampled verticals. The velocity is measured by current meter at one or more points along each vertical, and then a depth-averaged value is estimated. The discharge is then evaluated through the mean-section method by summing the product of the depth-averaged velocity, depth, and width between verticals. Considering more measurements, the rating curve is estimated by fitting an empirical relation to the sample of stage-discharge pairs at the river site.

The major disadvantage of the aforementioned traditional measurement techniques is that they are difficult to use and not safe for operators when flow depth can significantly change and high flow velocities and floating debris might occur [5]. Besides, streamflow measurements are most of the time limited to low flow conditions inducing high uncertainty in rating curve extrapolation for higher water levels [3], [6].

For the above motivations, it is important to use non-contact technologies for monitoring the velocity field, and thus the discharge, either with Surface Velocity Radars (SVR), [7]-[12], or using image-based techniques [13]-[16]. These methods have the advantage of avoiding danger for the operators, particularly in the presence of high flows [17]. Although image-based techniques have the advantage of yielding a large amount of data in a rather short measuring time, they present shortcomings in their efficiency, especially related to acquisition (appropriate tracers and illumination conditions) and to processing procedures (processing algorithm and cross-correlation parameters) used to obtain accurate quantitative information [13], [18]. Consequently, determining the error in estimating the surface velocity is one of the challenges in the application of image techniques.

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The maximum flow velocity of rivers, which is a variable of paramount importance, can be measured with non-contact devices as well, since its position is located in the upper portion of the flow area and often on the surface [6]. Studies based on the entropy theory [19] were used to investigate the spatial velocity distribution using field and laboratory data for different channel shapes and roughness of its boundaries [20]-[23]. Based on the entropy, it was found that the mean flow velocity can be estimated from the value of maximum velocity through a linear relationship identified by an entropic parameter [24].

In such a context, SVR can be used to monitor the spatial distribution of surface flow velocity across a river site from which the discharge can be estimated. This requires, as introduced above, that the surface velocity measured at a certain location across the river (vertical) is turned into depth-averaged velocity. In particular, a recently developed entropy-based model, starting from the measurement of the surface velocity, makes it possible to estimate the dip phenomenon (whereby the location of the maximum velocity appears below the free surface) with an accuracy comparable with the one of velocity fields obtained by using the conventional measurements by current meter [24], [25]. Such a model has also been efficiently applied to estimate the vertical velocity profiles along a curved laboratory flume [20]. Based on these findings, it is evident that non-contact devices able to sense surface flow variations across a river would provide a considerable contribution in streamflow monitoring. Moreover, the application of Unmanned Aerial Vehicle (UAV) to hydrological monitoring fosters the usage of radar technologies for real-time discharge estimation, thus generating a significant interest in sensors specifically designed for this purpose [7], [11], [26].

Radar measurement of the river surface velocity is a well established methodology and, ecently, accurate Doppler sensors and sophisticated processing algorithms have been developed, [27]-[29]. The water surface has been studied exploiting remote sensing approaches [30] and the Bragg scattering is identified as the main reflection mechanism [31], [32]. All these results have been obtained with pencil beam antennas, typically a parabolic dish or a horn-lens antenna with 2° to 10° beamwidths.

The next challenge is extensive monitoring of rivers and, to achieve this goal, the unit cost of Doppler radar sensors should be reduced by one order of magnitude (i.e. from thousands to hundreds of dollars). Since the most expensive item is the antenna, low-cost technologies (like planar technologies) have to be incorporated into the sensor design at the cost of some performance degradation. In particular, the adoption of small planar antennas implies a wider beam and, in turn, larger systematic errors.

In this paper, for the first time, we investigate the adoption of low-cost Doppler radars for river surface velocity measurements. Starting from a sensor designed in 2007 by the authors, [33], we systematically characterize it in real scenarios. The considered sensor is equipped with a planar antenna (a microstrip patch array) featuring a 9° beamwidth in azimuth and 32° beamwidth in elevation. This is a large value and a simple, yet effective, Doppler centroid estimation is adopted to compensate for systematic errors. Finally, the processing algorithm is implemented on a microcontroller with minimal computing power and memory (ArduinoUno platform), and a statistical analysis of the surface velocities is derived. These results show a residual velocity standard deviation of 0.07 m/s, a value equal to the intrinsic velocity spread used by Plant et *al.* to represent scatterer lifetime effects on sea surface [29].

II. METHODOLOGY

The river discharge estimation starting from the surface flow velocity is based on the POME, [34]. This principle is tightly linked to information theory [19] and is used as statistical inference to solve a probability matter [35], [36]. The application of the entropy theory to open channels was first proposed by Chiu, [37]-[39], who predicted the two-dimensional flow velocity distribution as a function of the maximum velocity, u_{max}, in the cross-sectional flow area. However, for practical applications the Chiu's velocity distribution is complex to apply, even for parameter estimation [39]. To develop an operational approach, the Chiu's model complexity is reduced in [6] to the 2D Entropy-based Velocity Model (EVM). The EVM has been described in many papers and will not be recalled here; the interested readers can find out more about in [40]-[43]. The reliability of such an approach has been tested at gauged sites of different rivers, providing satisfactory results for different flood conditions, using field and laboratory data [6], [20]. As a consequence, the following methodology is adopted for the instantaneous discharge assessment by means of low-cost Doppler radar sensor:

1) sampling of the surface velocity u_s across the river at a finite number of points (refer to Fig. 1 for the u_s definition): this gives information about its maximum value and its location in the flow area;
2) once u_s is measured, values are turned into depth-averaged velocity by applying EVM and the two-dimensional flow velocity can be estimated, under the assumption that the river cross-section geometry is given (by topography) and the concurrent measure of water level is taken;
3) finally, applying the velocity-area method [4], the instantaneous discharge can be evaluated.

Finally note that, in order to drastically reduce the time of sampling (i.e. first step of the operational procedure defined above), one may assume that the surface velocity u_s across the river depends on its maximum value, u_s^0, through an elliptical approximation [40], [41]. This approach will be exploited in the following of the paper and u_s^0 is assumed as occurring at the center of the river.

III. LOW-COST DOPPLER RADAR SENSOR

In order to measure the surface velocity in a non-contact way, [7], [28], [44]-[46], a low-cost Doppler radar sensor is adopted in the present study. According to Fig. 1, the antenna beam is pointed from top to bottom forming an angle β between the direction of maximum radiation (the

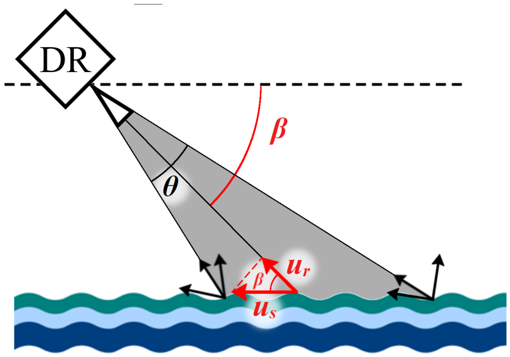


Fig. 1. Surface Velocity Radar (SVR) measurements across a river site. The Doppler sensor R is placed at a certain height above the surface and is pointed at an angle β. Because of the water surface roughness (due to waves and turbulence), a fraction of the incoming microwave signal is backscattered toward the radar. The antenna half-power beamwidth is indicated with θ. Note that the radar can be pointed either upstream or downstream direction.

electromagnetic axis of the antenna) and that of the water stream.

According to the Doppler effect, the frequency shift f_D between the signal transmitted and received by the sensor is proportional to the radial velocity u_r of the target:

$$f_D = u_r \, \frac{2\, f_0}{c_0} \tag{1}$$

where f_0 is the frequency of the transmitted signal and c_0 is the speed of light in a vacuum. The radial velocity u_r is related to the surface velocity u_s by simple trigonometry:

$$u_r = u_s \, \cos\beta \tag{2}$$

β being the angle formed by the antenna axis with the water stream velocity (see Fig. 1). As a consequence the Doppler frequency is a function of the observation angle:

$$f_D = u_s \, \frac{2\, f_0}{c_0} \, \cos\beta \tag{3}$$

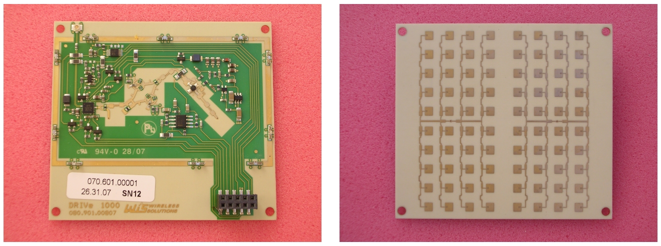
The system sensitivity is affected by the radar cross-section of the target, which, in the present case, is represented by the water surface. The Bragg scattering has been identified as the main reflection mechanism [29], [31], [32], implying that the reflection comes from the water surface roughness, as shown in Fig. 1, and that the Bragg resonance phenomenon can increase significantly the received echo [30, Vol. II, pp. 837-842].

In particular, the studies by Plant *et al.* on rivers, [27], [28], can be summarized as follows: a) when microwaves impinge on rough water surfaces at incidence angles that are not too large or too small, they are scattered by short surface waves which are a few centimeters long. This process is known as composite surface scattering in which Bragg-resonant scattering from short surface waves occurs independently of small facets on the water surface that are tilted and carried by larger scale motions, i.e. by the river stream. b) Short surface waves are produced directly by the wind and, indirectly, by longer waves, by the turbulence of the water, or by rainfall. c) In the case studied by Plant et *al.*, "wind is not driving the larger scale surface motions", [27, p. 1446]. d) Because of this complex, composite surface motion, the Doppler spectrum may be broadened since a variety of speeds are detected by the radar. e) In order to measure the river surface velocity, a Doppler spectrum center has to be identified.

Even if the above center frequency is determined in a correct way, a possible error source in the surface velocity measurements is associated to the wind. According to Plant et al., however, this error is small: about 10 cm/s for a wind blowing exactly along the direction of the antenna at 10 m/s, [28, p. 1244]. Furthermore it does not constitute, in general, a problem: "if one desired, the wind vector could be measured along with the microwave measurements and a correction could be made for the wind drift", [28].

A. *Baseline configuration*

The Doppler radar adopted in the experiments is illustrated in [33] and was originally designed for the automotive market. For completeness, a brief description of such an apparatus is reported in Appendix A. The sensor consists of a single-board circuit (i.e., it is a fully planar circuit without bulky waveguides) with the front-end electronics on one side, see Fig. 2(b), and the antennas on the other side, see Fig. 2(c). The radar operates at 24-GHz, transmits a power of 4 mW and uses two identical antennas (one for the transmitter and one for the receiver) with a gain of 13 dB and a beamwidth $\theta_a = 9°$ in azimuth (E-plane) and $\theta_e = 32°$ in elevation (H-plane).



(a) (b)

Fig. 2. Low-cost 24-GHz Doppler radar sensor adopted in the present study. Fabricated prototype: front-end electronic side, (a), and antenna side, (b). The PCB has a square shape with 8-cm side. After [33].

In order to automate the measurements, a low-cost ArduinoUno board is used. Such a platform has limited computing and memory resources (8-bit CPU operating with a 16-MHz clock, 16 MIPS, 2 kB of SRAM and 32 kB of Flash memory). Therefore, the code is designed to achieve a trade-off between numerical accuracy, memory space, and computing speed.

The baseline system is composed of: the Doppler radar, an ArduinoUno board, and a PC for data storage. The radar is powered with a 12-V battery, while the ArduinoUno is supplied via an USB cable coming from the PC. The analog Doppler radar outputs are connected to the analog pins of the ArduinoUno board. The Arduino CPU processes the data coming from the radar and, then, sends them to the PC.

The radar sensor is mounted on a base that allows two fixed inclinations β, namely 30° and 45°. This choice takes into account that small inclinations lead to a long target distance (weakening the return signal strength) and to a large antenna footprint on the river surface (large observed area). Instead, for larger inclinations, the velocity estimation error increases significantly with β, especially for beamwidths θ greater than 20°, as shown in [44] [1]. In our field experiments β is determined by measuring the base angle with respect to the horizon line with an electronic inclinometer (accuracy $\pm 1°$), and accounting for the river inclination.

IV. DATA ACQUISITION AND PROCESSING

In order to determine the surface velocity of the water stream, the analog signals available from the Doppler radar are processed as follows:

1) sampling of the In-phase/Quadrature (I/Q) channels;
2) frequency domain transformation of the sampled data;
3) determination of the Doppler centroid.

Assume that $s(t)$ is the time-domain signal to be acquired by the microprocessor. In our case this signal can be either the $i(t)$ (in-phase) or the $q(t)$ (quadrature) output of the radar sensor depicted in Fig. 2(a). The sequence $s[n]$ is obtained by sampling $s(t)$ according to:

$$s[n] = s(n\,\Delta t) \tag{4}$$

where $n = 1, \ldots, N$ is the discrete time, N is the number of samples, Δt is the sampling time, and $f_s = 1/\Delta t$ is the sampling frequency. The realizations of the Doppler power spectrum S_δ are derived applying the Wiener-Khinchin theorem:

$$S_\delta[k] = S_\delta\left(k\,\frac{f_s}{N}\right) = |\text{FFT}\,\{s[n]\}|^2 \tag{5}$$

where k is the discrete frequency and FFT is the Fast Fourier Transform operator, i.e the operator performing the frequency domain transformation. Fig. 3 shows a realization of the power density spectrum in a real scenario; in the figure $S_\delta[k]$ has been normalized to its maximum value $S_\delta^m = \max\{S_\delta[k]\}$. A Doppler spectrum smoothing algorithm can be applied at this point, as decribed in Appendix B.

As stated above, because of complex composite surface motion, the Doppler spectrum is broadened since a variety of speeds are observed by the radar. Furthermore, according to Ferrick *et al.*, [44], the Doppler spectrum is further broadened by the radar antenna beamwidth, which is particularly relevant for low-cost sensors with small antennas. Indeed, since for the given set-up the Doppler frequency is angle-dependent, see (3), a number of slightly different frequency components are produced, resulting in the Doppler spectra of Fig. 3.

The spectrum broadening due to the finite antenna beamwidth has been studied with particular reference to space-based Doppler radar measurements [47]-[49]. An important concept, called *Doppler centroid*, has emerged. It is defined as the frequency shift f_δ at the antenna beam center [50].

There are several algorithms that can be used for the accurate Doppler centroid estimation. In this work, due to the limited computing resources onboard our sensor, the approach proposed in [44] is adopted. The Doppler centroid is simply estimated as the center of the Doppler bandwidth. To determine such a bandwidth, a -6 dB threshold below the maximum is considered; this value is close to the level used in [44] [2]. With reference to Fig. 3, for example, we have:

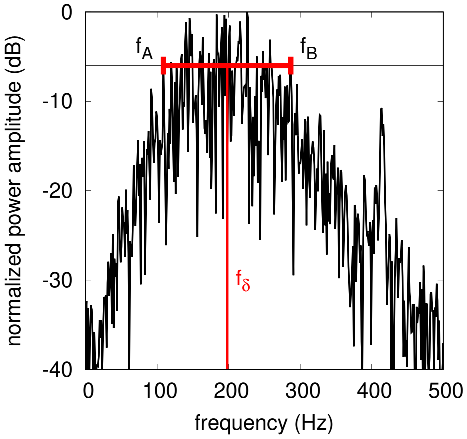


Fig. 3. A realization of the Doppler power spectrum; the signal was acquired at the Monte Molino Tiber River site with $\beta = 32°$. Because of a finite beamwidth of the radar antenna, a Doppler bandwidth is observed. The Doppler centroid f_δ, i.e. the Doppler frequency shift at the antenna beam center, can be roughly estimated as the center of the Doppler bandwidth. In this case $f_\delta = 198$ Hz. Antenna in vertical polarization with a 32° beamwidth. Data taken with a portable oscilloscope.

$$f_\delta = \frac{f_A + f_B}{2} \tag{6}$$

f_A and f_B being the lower and upper band limits. Finally, having determined f_δ along the river cross-section, the surface stream velocity u_s is calculated as:

$$u_s = \frac{c_0}{2\,f_0\,\cos\beta} f_\delta. \tag{7}$$

As a concluding remark, it is worth emphasizing that the FFT magnitude is compressed according to the logarithmic scale. With such an approach, a good dynamic range can be obtained, even with a 8-bit precision [51]. One of the challenges of the present study, indeed, is the usage of minimal computing power as this will relax the requirements for future implementations of massive-scale, Internet of Things (IoT) systems.

A. Statistical analysis

In this study, the time-varying nature of the river surface is characterized through a statistical analysis of the Doppler signals. The main goal of such a statistical analysis is to obtain, experimentally, the histograms of the surface velocity distribution, the average velocity, and the corresponding standard deviation. To this purpose, the Doppler signal is acquired multiple times. The Doppler power spectrum is computed for each realization and the corresponding velocity value is determined. Furthermore, in order to save as much memory as possible, we decided not to store the individual FFTs, but

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[1] The values reported in [44] for the 30 GHz radar experiment were $\theta = 9°$ and $\beta = 25°$.

[2] Experimentally we saw that the -6 dB threshold is safely above the noise level and, at the same time, is compatible with the Doppler bandwidth estimations for an antenna beamwidth of 32°. These estimations can be done exploiting the model reported in [44].

to implement an algorithm capable of directly calculating the velocity histograms.

To this purpose, a velocity resolution Δu is selected and, consequently, the velocity space is divided in M classes of magnitude Δu. Such a number of classes depends on the Nyquist frequency $f_s/2$, the Doppler constant $c_0/2$, f_0 and the observation angle β according to:

$$M = \text{int}\left(\frac{c_0\, f_s}{4\,\Delta u\, f_0\, \cos\beta}\right) + 1 \tag{8}$$

int( ) being the integer part function. As an example, the developed radar operates at $f_0 = 24\,\text{GHz}$ and is characterized by a Doppler constant of 160 Hz per m/s. Sampling the I/Q signals with $f_s = 1\,\text{kHz}$ and performing an $N = 512$ points FFT, the achieved frequency resolution is $f_s/N = 1.95\,\text{Hz}$. For a $\beta = 37°$ observation angle, the maximum velocity that can be detected with these system parameters is 3.9 m/s. Considering a velocity resolution $\Delta u = 0.025\,\text{m/s}$, a maximum number of $M = 157$ classes is obtained. In general, the maximum detectable velocity is given by $M\,\Delta u$ and, to increase it, one has to increase the sampling frequency and the memory (to store longer time series).

The histogram algorithm is based on two vectors of length M, namely: $hist[\,]$ and $w[\,]$. Considering N_m measurements, the former contains the velocity histograms and the latter the corresponding statistical frequencies. In order to minimize the CPU memory, the following procedure is adopted, where $p = 1, \ldots, N_m$ is the measurement counter and $j = 1, \ldots, M$ is the velocity class index:

1) initialization
    - $p = 0$
    - $hist[j] = 0$ for $j = 1, \ldots, M$
2) measurements
    - sampling & acquisition of $i(t)$ or $q(t)$
    - FFT evaluation
    - Doppler spectrum smoothing (opt.)
    - Doppler centroid f_δ estimation
    - surface velocity evaluation:

      $$u_s = \frac{c_0}{2\, f_0\, \cos\beta} f_\delta$$
3) counter increment
    - $p = p + 1$
4) histograms update
    - determination of the velocity class:

      $$\hat{\jmath} = \text{int}\left(\frac{u_s}{\Delta u}\right) + 1$$
    - histograms update:

      $$hist[\hat{\jmath}] = hist[\hat{\jmath}] + 1$$
5) repeat until
    - repeat points 2 to 4 until $p < N_m$
6) relative frequencies
    - relative frequencies for $j = 1, \ldots, M$:

      $$w[j] = hist[j]/N_m$$

In this way, a number of independent experiments are used to derive the relative statistical frequency for each velocity class that, according to the Law of Large Numbers (LLN), corresponds to a probability estimation. Using these data, both the surface velocity average $\overline{u}_s$ and variance σ_u^2 are given by:

$$\overline{u}_s = \sum_{j=1}^{M} w[j] \cdot u_s^j \tag{9}$$

$$\sigma_u^2 = \sum_{j=1}^{M} w[j] \cdot \left(u_s^j - \overline{u}_s\right)^2 \tag{10}$$

where the velocity u_s^j associated to the j-th class is given by:

$$u_s^j = (j-1)\,\Delta u + \frac{\Delta u}{2} \tag{11}$$

At this point, a new batch of measurements can be performed: the algorithm resets all variables and a new cycle starts.

V. RESULTS

In order to validate the sensor and the developed algorithm, experimental campaigns have been carried out at two gauged sites along the Tiber River, central Italy: Ponte Nuovo (Lat. 43° 0′ 37″ N, Lon. 12° 25′ 44″ E; drainage basin area 4000 km^2) and Monte Molino (Lat. 42° 48′ 9″ N, Lon. 12° 24′ 6″ E; drainage basin area 5100 km^2) sections. In both sections the surface velocity was measured with the low-cost Doppler radar sensor, as illustrated in Fig. 4.

All the experiments were carried out in no-rain and light wind conditions; the wind drift is not corrected in the results reported below.

A. Ponte Nuovo site

The surface velocity measurements were carried out on a bridge at a distance of 11.5 m from the river surface and, approximately, at the river center. The experiments were performed in low stream velocity conditions and the river surface was almost flat; only a very little ripple (between 1 and 3 cm) was observed. The Doppler signals are depicted in Fig. 5: the data were measured at the Ponte Nuovo river Tiber site on February 11, 2019. Estimating the Doppler centroid for this realization (149 Hz with a $-6\,\text{dB}$ threshold) and exploiting (7), one obtains a surface velocity of about 1.17 m/s.

The histogram plot is shown in Fig. 6 and is constructed for $N_m = 100$ realizations, with $M = 157$ velocity classes (the graph shows only the first 80 of them, the other having a zero frequency) and $\Delta u = 0.025\,\text{m/s}$. Although a tail is present at low velocities, the main peak of the histogram plot appears to be well approximated by a normal (Gaussian) distribution having a 1.18 m/s average and 0.045 m/s standard deviation.

The sensor validation is completed by comparing its acquired data with those obtained with a commercial, hand-held radar sensor, namely the Decatur SVR [52]. This is based on a 24-GHz gunn-plexer cavity, uses a horn-lens antenna with

(a) Ponte Nuovo

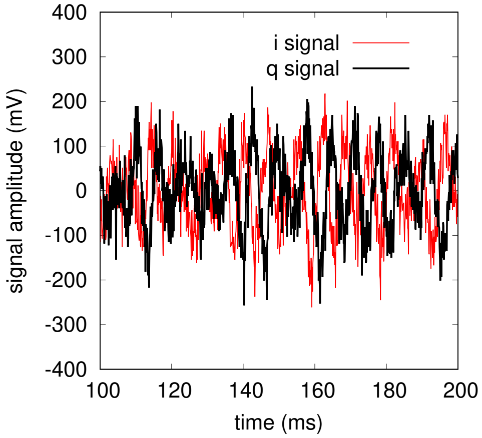
(b) Monte Molino

Fig. 4. Tiber River test sites: Ponte Nuovo, Lat. 43° 0′ 37″ N, Lon. 12° 25′ 44″ E, (a); Monte Molino, Lat. 42° 48′ 9″ N, Lon. 12° 24′ 6″ E, (b).

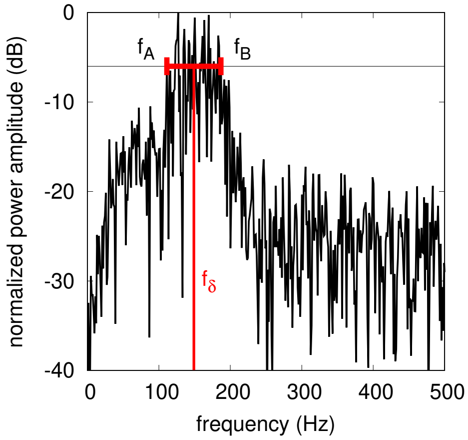
12° beamwidth and costs about 1500 $. The Decatur sensor begins measuring the surface velocity and, after some time, the average velocity over the last 10 s is returned. Then, the sensor updates the velocity every 5 s and, after 60 s, ten separate 5-s batches of velocity measurements are completed. The display indicates the average of these measurements.

The results of this comparison are summarized in Tab. I for the commercial and for the developed low-cost Doppler radar sensors, respectively. In the second case, 5 experiments, (each composed by a batch of 32 realizations, were carried out. In particular, we started in Fig. 6 using $N_m = 100$ but realized that this number could be reduced to 32 with almost the same standard deviation.

Tab. I also reports the percentage velocity error measured between the commercial (Decatur SVR) sensor and the developed sensor. The Decatur SVR is taken as the reference. To evaluate this error, a single velocity value is first determined by taking the average of averages. For the Ponte Nuovo test site such an error is -11%, thus confirming the validity of the low-cost Doppler radar described in the present contribution. Furthermore, the standard deviation of the velocity obtained with the developed sensor (and processing algorithm) is about one third of that resulting from the Decatur SVR measurements.



(a) time domain



(b) frequency domain

Fig. 5. Measurements of the surface stream velocity carried out with the low-cost 24 GHz Doppler radar. Ponte Nuovo Tiber River site; February 11, 2019. Time domain I/Q Doppler components, (a) and normalized power spectrum, (b). The observation angle is $\beta = 37°$ and $f_\delta = 149$ Hz. Antenna in vertical polarization with a 32° beamwidth. Data taken with a portable oscilloscope.

TABLE I
SURFACE VELOCITY AT PONTE NUOVO, TIBER RIVER, ITALY

sensor	batch n.	average (m/s)	std. dev. (m/s)	avg. of avg. (m/s)	error (%)
This work	1	1.18	0.06	1.16	-11
	2	1.14	0.10		
	3	1.14	0.10		
	4	1.18	0.07		
	5	1.18	0.06		
Decatur SVR	1	1.31	0.20	1.31	n.a.

This work: batches of 32 realizations, $\beta = 37°$, -6 dB threshold
Decatur SVR: batches of 10 realizations

B. Monte Molino site

A campaign of flow experiments across the Tiber River was performed also at Monte Molino hydrometric site on February 11, 2019. The surface velocity was measured using either the developed low-cost Doppler radar sensor and the Decatur SVR commercial instrument at the center of the river. The sensors were placed at 13.8 m from the water surface: Tab. II shows the

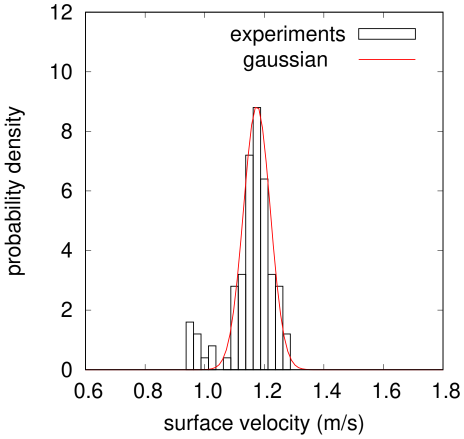


Fig. 6. Experimental results of a batch of $N_m = 100$ measurements. The surface stream velocity (u_s) probability density estimations are represented by histograms of width $\Delta u = 0.025$ m/s. The results are compared with the normal (Gaussian) distribution having a 1.18 m/s average and 0.045 m/s standard deviation.

results of these experiments. The sensor location was, again, at the river center. As it can be seen, the obtained data have an error within 3% and they can be used to estimate the velocity profile through eqn. (12).

TABLE II
SURFACE VELOCITY AT MONTE MOLINO, TIBER RIVER, ITALY

sensor	batch n.	average (m/s)	std. dev. (m/s)	avg. of avg. (m/s)	error (%)
This work	1	1.42	0.07	1.42	-3
	2	1.45	0.08		
	3	1.41	0.07		
	4	1.42	0.07		
	5	1.40	0.07		
Decatur SVR	1	1.43	0.16	1.46	n.a.
	2	1.37	0.13		
	3	1.59	0.11		

This work: batches of 32 realizations, $\beta = 32°$, -6 dB threshold
Decatur SVR: batches of 10 realizations

C. Discharge estimation

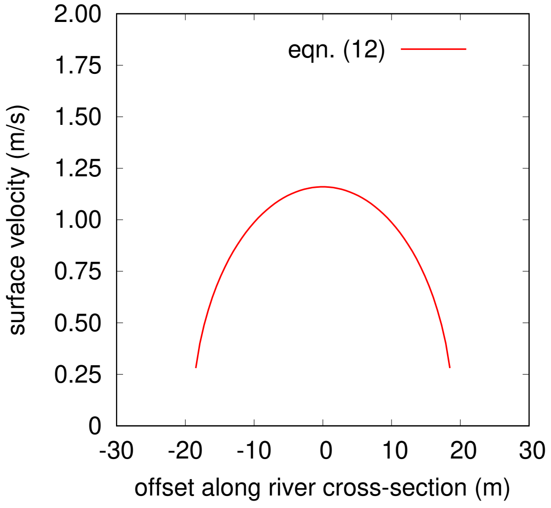
The discharges of the Ponte Nuovo and Monte Molino sections are computed using the procedure summarized in Sec. II. In particular: the maximum surface velocity u_s^0 is assumed to be located in the central strip of the cross-sectional flow area, which is a reasonable hypothesis in the case of regular and straight channels, as also found in [42], [53], [54]. For the considered river sites such a point is further discussed in Appendix C. In order to drastically reduce the time of sampling, the surface velocity is only measured at the river center. The surface velocity profile is approximated along the river cross-section according to an elliptical shape [40], [41]:

$$u_s(x) = u_s^0 \left[1 - \left(\frac{x}{x_s} \right)^2 \right]^\gamma \qquad (12)$$

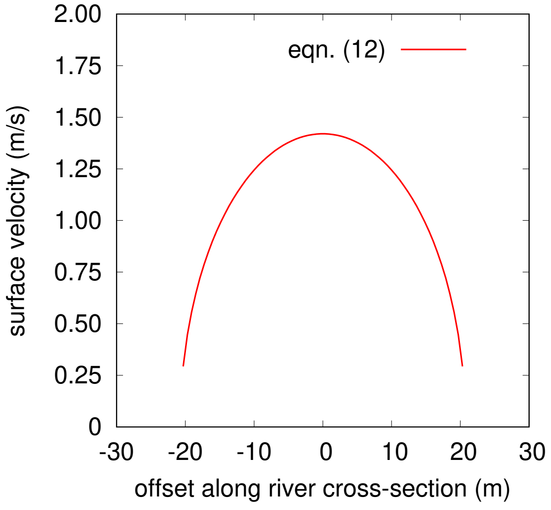
where x is the abscissa measured from the river centre (vertical where the maximum velocity is assumed) to the side walls and γ is a shape parameter. At this point, the EVM is applied and the velocity distribution over the river 2D cross-section (which can be inferred by existing topographical data and by measuring the water level) is extrapolated as in [40] with $\mu = 2.1$. Finally, by a numerical integration of such a 2D velocity profile over the cross-section, the discharge is obtained.

The two Tiber River sites considered in our experiments are gauged sites, so the water levels are continuously observed by ultrasonic sensors installed on the bridges. The surface velocity at river center, instead, is measured with the developed low-cost Doppler radar sensor and this value is taken as u_s^0.

The surface velocity behaviors for the two sites are represented in Fig. 7, where the river border x_s is at 19.05 m and 20.75 m for the Ponte Nuovo and Monte Molino sections, respectively. The measured velocities u_s^0 are those quoted in Tab. I and Tab. II, while the γ parameter is assumed equal to 0.5 (as determined in previous studies).



(a) Ponte Nuovo



(b) Monte Molino

Fig. 7. Surface speed distribution at Ponte Nuovo (a) and Monte Molino (b) Tiber River sites; measurements carried out on February 11, 2019. The distributions are inferred through eqn. (12). Ponte Nuovo parameters: $u_s^0 = 1.16$ m/s, $x_s = 19.05$ m. Monte Molino parameters: $u_s^0 = 1.42$ m/s, $x_s = 20.75$ m. In both the cases $\gamma = 0.5$.

The obtained discharges are reported in Tab. III. In particular Q_{EVM} is the discharge evaluated with EVM, A_{obs} is the cross-sectional flow area and Q_{obs} is the observed discharge (reference data). Such a value is provided by the hydrological service of the Umbria region (since the two sites are gauged sites) and is acquired at the same time as the velocity measurements.

TABLE III
COMPARISON BETWEEN OBSERVED (Q_{obs}) AND COMPUTED (Q_{EVM}) DISCHARGES

Gauged site	u_s^0 (m/s)	A_{obs} (m^2)	Q_{obs} (m^3/s)	Q_{EVM} (m^3/s)
Tiber, Ponte Nuovo	1.16	78	40	41
Tiber, Monte Molino	1.42	40	39	46

Note that the results in terms of discharge are within 18%, despite the measurements were performed for low flow, where the uncertainty on discharge is significant both for the presence of secondary currents and for the bridge piers.

VI. DISCUSSION

An analysis of the state-of-the-art for surface velocity measurements of rivers by radar sensors is reported in Tab. IV. Several outstanding studies were published in the past on this topic and accurate systems were developed. All the results shown in Tab. IV were based on Doppler radar sensors, although pulsed Doppler radars were also used for this application [28]. In all the previous studies, narrow beam antennas were used and this is in contrast with the developed Doppler radar that uses a low-cost planar antenna. Of particular relevance is the elevation beam width θ_e that, in our case, is between 2.7 to 11 times wider than in the previously published papers. On the other hand, using a proper evaluation of the Doppler centroid, the standard deviation of the measured surface velocities is comparable with the state of the art. Furthermore, the obtained 0.07 m/s residual velocity standard deviation is equal to the intrinsic velocity spread used by Plant et *al.* to represent scatterer (i.e., moving water surface) lifetime effects [29].

TABLE IV
STATE-OF-THE-ART FOR SURFACE VELOCITY RADAR SENSORS

Ref.	Type	f_0 (GHz)	Antenna $\theta_a \times \theta_e$	power (mW)	std. dev. (m/s)	mass (g)
[28]	Doppler	24	$3^\circ \times 3^\circ$	5	0.08	n.a.
[29]	Doppler	35	$4^\circ \times 4^\circ$	20	0.07	n.a.
[52]	Doppler	24	$12^\circ \times 12^\circ$	7	0.15	700
this work	Doppler	24	$9^\circ \times 32^\circ$	4	0.07	60

As a final observation it is worth noticing that, owing to the adoption of a small size planar antenna, the sensor mass can be kept well below 100 g, a feature that is attractive for applications onboard UAVs.

VII. CONCLUSIONS

This work demonstrates, through experiments at two river sites, that low-cost Doppler radar sensors can be adopted for river surface velocity measurements. In particular, the Doppler bandwidth enlargement due to planar antennas with up to 30° beamwidths in elevation does not lead to significant errors if the Doppler centroid is evaluated correctly. In terms of accuracy, the obtained results show a residual velocity standard deviation of 0.07 m/s, a value equal to the intrinsic velocity spread used by Plant et *al.* to represent sea surface lifetime effects. All the results have been validated against a reference Doppler radar (velocity) and values provided by the hydrological service of the Umbria region (discharge).

From the point of view of cost and miniaturization, target prices below 50 $ and sensor masses below 50 g could be achieved by planar technologies and System-on-Chip (SoC) microwave/mm-wave radar transceivers. Sensors of this kind could be used, in the near future, onboard UAVs.

The system is a valuable technology and meets all the requirements for monitoring surface velocities during flood events. The measurements provided by the radar sensor are essential to initialize the EVM 2D model that, in this framework, is able to estimate the discharge in a satisfactory way. These results encourage further experimental tests on different river sites with different hydraulic and geometric characteristics.

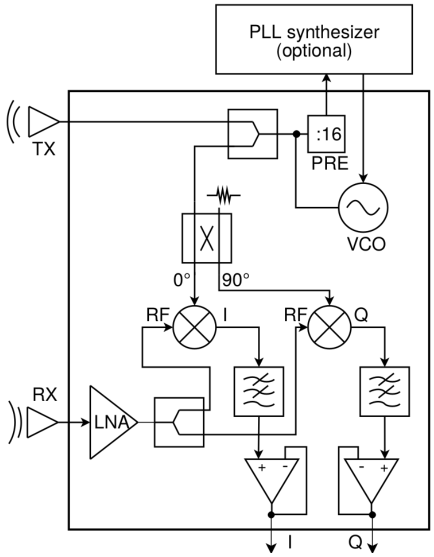
APPENDIX A
SENSOR HARDWARE

The low-cost Doppler radar architecture is illustrated in Fig. 8. A bi-static configuration with two antennas, one for the transmitter (TX) and one for the receiver (RX), is adopted to avoid circulators, thus reducing the overall sensor cost. Each antenna is a patch array composed by 10×4 elements featuring a gain of about 13 dB and a beamwidth $\theta_a = 9^\circ$ in azimuth (E-plane) and $\theta_e = 32^\circ$ in elevation (H-plane). The 24-GHz signal is generated by a commercial Voltage Controlled Oscillator (VCO) with an integrated (divided by 16) pre-scaler. The VCO output power is about 10 dBm with a phase noise of -70 dBc/Hz at 10 kHz offset from the carrier. A Wilkinson power divider with 1-dB loss splits the signal in two parts, one feeding the transmitting antenna and the other the receiving circuitry. As a consequence, the transmitted power is about 6 dBm (i.e., 4 mW).

The Local Oscillator (LO) signals needed by the I/Q mixers are provided by a 90° branch-line junction [55]. Note that only one VCO is used to implement both transmitted and LO signals: as demonstrated in [56], this is the key to detect small Doppler shifts, even in the presence of phase-noise.

The signal reflected back by the water surface, and containing the information about the radial velocity of the target itself, is first amplified by a Low Noise Amplifier (LNA) and then transferred to the RF ports of the downconversion I/Q mixers. The LNA is based on a discrete Hetro-Junction FET (in a plastic package) and exhibits a 10 dB linear gain and a 1.5 dB noise figure.

The I/Q mixers are based on a single-balanced circuit topology using a 180° rat-race junction in microstrip technology [57], [58]. To save substrate area, the two diodes and the



(a)

Fig. 8. Low-cost 24-GHz Doppler radar sensor adopted in the present study. Block diagram (a) and front-end PCB: active (electronic circuits) side (b) and antenna side(c). The PCB has a square shape with 8-cm side. After [33].

relevant radial stubs have been placed within the ring, leading to a very compact layout. A 5.5 dB state-of-the-art conversion loss has been achieved both exploiting low-barrier Schottky diodes [59] and properly matching both LO and RF ports. The LO power to optimally drive the mixer is about +1 dBm.

The IF signals of the I/Q mixers constitute the outputs of the front-end module. These signals enter a mixed-signal board for the baseband analog amplification (80 dB typical) and digital processing. The latter has been accomplished with an ArduinoUNO board (see below). Note that, because of the I/Q architecture of the front-end, the sensor can determine both the radial velocity and the motion direction.

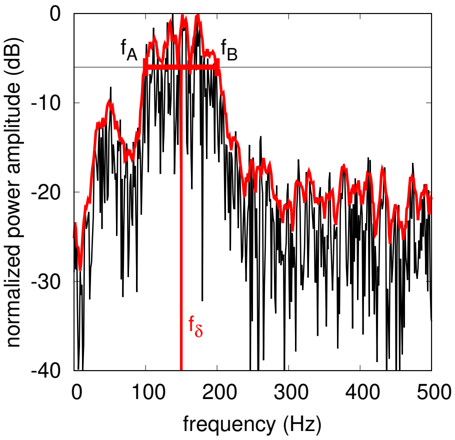
An indirect accuracy evaluation is reported, for a different context, in [33]: the experiments indicate a 2.5% absolute accuracy of the developed sensor. Finally, it is worth noticing that a further cost reduction for Doppler sensors could be attained implementing cellulose-based front-ends [60], [61], in addition to large-scale integration on silicon technology of the entire radar transceiver [62].

APPENDIX B
DOPPLER SPECTRUM SMOOTHING

In the present section, a simple moving average smoothing algorithm is applied to the measured Doppler spectra. Purpose of this study is to investigate how the recovered surface velocity (and its standard deviation) is affected by the window width and to quantify the improvements with respect to the direct, raw data usage, as proposed in Sec. IV. We tested the first, 32 realizations batch of the two Tiber River sites considered in Tab. I and Tab. II. The same -6 dB threshold was used. From the analysis of Tab. V emerges that the surface velocities obtained with the smoothing are within 3% to that determined from the raw data (no smoothing). There is a benefit in terms of standard deviation, which decreases as the moving average window width increases. An optimal value for such a parameter is within 8 and 16 samples. Since the FFT is 512 samples long, the previous window widths are in the range 1.5 to 3% of the total length. An example of Doppler spectrum before and after smoothing (and amplitude normalization) is illustrated in Fig. 9.

TABLE V
MOVING AVERAGE SMOOTHING EXPERIMENTS

window width (samples)	Ponte Nuovo		Monte Molino	
	avg. velocity (m/s)	std. dev. (m/s)	avg. velocity (m/s)	std. dev. (m/s)
1	1.18	0.06	1.42	0.07
4	1.17	0.05	1.45	0.06
6	1.18	0.04	1.46	0.06
8	1.18	0.03	1.46	0.06
16	1.17	0.03	1.44	0.05



(a) time domain

Fig. 9. Doppler spectrum without (black curve) and with (red curve) a 8 samples moving average smoothing. Once smoothed, the Doppler spectrum maximum is normalized to 0 dB. The time series was one of those measured at Ponte Nuovo site on February 11, 2019.

APPENDIX C
SURFACE VELOCITY DISTRIBUTIONS

The Tiber River sites reported in Fig. 4 have been studied for more than two decades and, for them, it can be observed that: i) the maximum velocity occurs close to the river center; ii) the velocity distribution obey to eqn. (12) quite well with $\gamma = 0.5$ (elliptical distribution). As an example, Fig. 10 shows three measurements carried-out at the Monte Molino site in May 2004, March 2006 and March 2015 respectively. The first two experiments were obtained with a current-meter over the entire cross-section while, the last one, covers only half river and was based on the developed doppler radar sensor.

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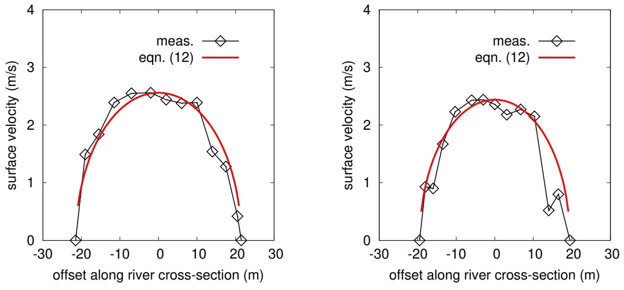
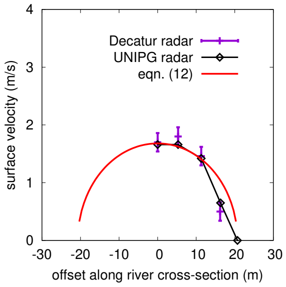


(a) May 2004 (b) March 2006



(c) March 2015

Fig. 10. Surface speed distributions at Monte Molino Tiber River site. The 2004 and 2006 experiments were carried-out with a current-meter over the entire cross-section while, the 2015 data, covers only half river section and is based on the desveloped doppler radar sensor. Eqn. (12) with $\gamma = 0.5$ provides, in all the cases, a good approximation of the measured distributions.

Ecosystems: advancement in dischaRge monitoring and understanding of Processes Relevant for ecosystem sustaInability by the development of novel technologieS with fIeld observatioNs and laboratory testinG (ENTERPRISING)".

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