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Doppler Non-contact Radar Sensors for Water Discharge Estimation: Advantages and Limitations

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The use of non-contact doppler flow radars to determine water discharge is a widespread trend in hydrometeorological surveying and monitoring. However, is it reasonable to consider such an instrument as one of the most suitable and perspective for the hydrological observation network? In-situ testing have been carrying out by authors of this article and the analysis performed in scientific papers cannot provide a single-valued positive conclusion on this issue. Obvious advantage of these radars as independent safe mode of operation seems to overweight their obvious weak points. Many "undercurrents" do not allow this method to be recognized as reliable, such as the problem of transition from surface to medium flow velocities, which consists in the data processing apparatus, reliable positioning of the device, blanking distance task and etc. All in all, this article discusses the main advantages and "vulnerabilities" of the use of such an instrument as non-contact doppler radars to determine water discharge from a scientific and practical points of view.

Keywords – water discharge, non-contact measurements, Doppler radars, non-intrusive river velocimetry

I GENERAL INFORMATION: DEVICE KIT DESCRIPTION AND OPERATION PRINCIPLES

Doppler radar flow meters were developed over 40 years ago, but have not yet gained sufficient acceptance in hydrological monitoring. This state of affairs is accompanied by a relatively high cost of instruments, as well as the complexity of the transition from measured surface flow velocities to determining water discharge.

A Doppler radar flow meter consists of a microcontroller, communications and power supply, as well as two sensors: water level (most often a radar sensor is used, but other types of level gauges can be used) and current velocity (local surface current velocity is measured). In most cases, both sensors are placed in the same housing. The current velocity sensor can be used as a separate device, but it is more correct to call such a device a velocimetry.

The radar flow meter measurement is based on the following principle. When water moves, structural relief formations appear on the surface of a turbulent flow - waves that move along with the water mass. If irradiation is performed at an acute angle to such a surface, part of the energy is reflected by inversed manner, while the other is reflected in the direction of the emitter. According to the Doppler effect, the frequency of electromagnetic oscillations of the reflected signal differs from the frequency of the irradiation signal by the value which is calculating using formula 1:

$$f_{extr.} = 2Vcos(\theta)\cos(\frac{\varphi}{\lambda}) \qquad (1)$$

Where V – velocity of movement the irradiated object;

λ – the wavelength of the emitted signal;

θ – the angle of the direction of irradiation relative to the flow surface in the vertical plane;

φ – the corresponding angle relative to the direction of flow in the horizontal plane

The mechanism of the flow meter operation. The radar flow meter transmits a signal at a constant frequency of about 24 GHz to the surface of the water at a selected angle. The miniature waves that are present on the surface reflect

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the radar waves back to the sensor. To measure the flow velocity, a wave on the water surface of at least 3 mm is required (according to the stated requirements of the vast majority of the equipment manufacturers). The reflected signal is shifted in frequency due to the Doppler effect from the movement of the water surface. Comparing the transmitted frequency with the frequency reflected from the surface, the mathematical apparatus processes the received data and converts it into local velocity.

The flowmeter is installed parallel to the stream flow on a support (for example, on a bridge pier). Installation is possible ashore, but this location does not guarantee good measurement results. The transmitter should be directed at an acute angle to the flow surface of 20-60 ° [1]. The optimum range is 30-45°. The width range of the irradiated spot should not fall to breakers, vegetation, driftwood and other interference.

II. THE INFLUENCE OF EXTERNAL ENVIRONMENTAL AND OTHER FACTORS ON THE READING OF THE DEVICE

The quality of measurements can be influenced by external environmental factors such as wind, rain, vibration, etc.

The wind speed directly over the water surface is about 2% of the wind speed measured at a height of 10 m [2]. For example, with a wind speed at the level of a air vane of 10 m/s, the wind speed above the water surface will be 20 cm/s, and assuming a logarithmic attenuation to the depth of the radar flow velocity measurement, the wind will introduce distortion the measurements by an amount equal to 11 cm/s. Such an error in measuring the flow velocity will occur only if the wind blows exactly in the direction in which the transmitter is directed. For other directions, the error will be less [3].

For *the rain* influence prevention, the most effective solution is to mount the radar so that it points upstream. When it rains, raindrops will drift away from the radar and water will flow towards the radar. Then the radar can distinguish the movement of water from the movement of a rain. Additional rain suppression can be implemented by mounting the radar under some structure (bridge, shield). You should also make sure that no rain or melt water from the bridge leak through the radar's field of view.

In some watercourses, *changes in the direction* of the current are occurring. In such cases, the radar must be configured to register both incoming and outgoing. This radar setting will not filter rain.

The structure supporting the tool (pole, bridge, fence, etc.) must be robust and vibration-free. However, some models have a built-in vibration sensor.

Most measurement inaccuracies caused by environmental factors can be eliminated by properly installing the sensor.

III. CHARACTERISTICS AND SPECIFICATION OF MANUFACTURED DEVICES

According to the up-to-date marketing research carried out by the employees of the Laboratory of Hydrological Instruments of the State Hydrological Institute [4], the average price of radar flow meters varies around two values: 3800 € and 11000 €. The minimum measurable flow velocity for 95% of radars is 0.1 m/s (some models claim 0.02 m/s). The maximum recorded flow velocity for 90% of the devices is 15 m/s. The velocity measurement error varies from (1% ± 0.025) m/s to (0.5% ± 0.02) m/s. The length of the sensing spot can vary from 0.29 to 49.2 m, the width from 0.12 to 12.8 m.

IV. CASE STUDY: INVESTIGATION OF THE APPLICABILITY OF A DOPPLER NON-CONTACT RADAR FLOW METER FOR DETERMINING WATER DISCHARGE ON THE MINOR RIVER DRAWING ON THE EXAMPLE OF POLOMET' RIVER

The research subject is the Polomet' river in the water discharge section line in the Yazhelbitsy village. The runoff observation period is 1952-2020. The length of the river to the outlet section is 52 km, the catchment area is 631 km^2, the width during the low-flow period is 15m, the mean annual water discharge is 6.7 m^3/s, the maximum is 120 m^3/s.

The scope of the research is the assessment of the accuracy of water discharge measurements on the Polomet' river with the Doppler non-contact discharge radar flowmeter RQ-24 fixed on an overpass across the river. The angle of installation of the device is 55 degrees to the water surface. The minimum recorded velocity of the current is 0.3 m/s. Velocity measurement error (1% ± 0.025) m/s.

The analysed data: water levels and current velocities for the period from March 2016 to June 2020. Discreteness of measurements for the velocity data link - 2 minutes (for the analysis they were reduced to an interval of 1 hour), for the water level data link - 1 hour.

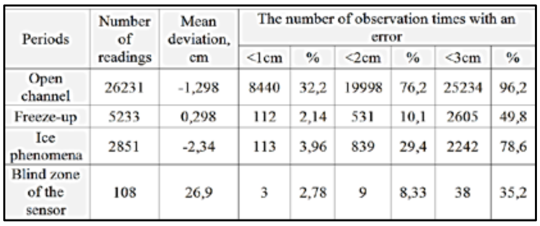
Water level data link analysis. The whole range of measured water levels was divided into 4 categories:

- with an open channel;
- with freeze-up;
- in case of ice phenomena;
- falling into the blind zone of the sensor

Radar readings were compared with reference water levels obtained from averaged data from other automated systems located at the same stream section. Data analysis for each category is shown in Table 1.

With an open channel, the radar demonstrated high measurement accuracy - less than 4% of hourly observation times have an error of more than 3 cm. For the period with ice phenomena (slush ice run, ice drift, etc.), the radar measurement accuracy was lower, but it can also be used as a reliable water level assessment device.

TABLE 1 ANALYSIS OF THE QUALITY OF THE INITIAL DATA RQ-24 ON THE WATER LEVEL DATA LINK

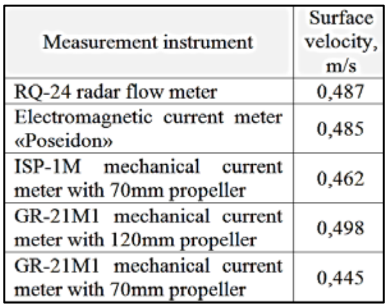


Periods	Number of readings	Mean deviation, cm	The number of observation times with an error					
			<1cm	%	<2cm	%	<3cm	%
Open channel	26231	-1,298	8440	32,2	19998	76,2	25234	96,2
Freeze-up	5233	0,298	112	2,14	531	10,1	2605	49,8
Ice phenomena	2851	-2,34	113	3,96	839	29,4	2242	78,6
Blind zone of the sensor	108	26,9	3	2,78	9	8,33	38	35,2

During freeze-up, significant deviations from the reference levels can be observed, primarily due to the measurement of snow on ice. The worst results are observed for the highest water levels falling into the blind spot of the instrument.

Estimation of the current velocity data link. The gauge section in which the radar is located is 50 meters upstream from the main one, where the water discharge is measured. Autumn 2020, single full-scale comparative field studies of the local surface flow velocity were performed with a radar flow meter and other instruments of measurement in the radar measurement cross section alignment. The comparison results confirmed the manufacturer's declared accuracy of determining the flow velocity with the RQ-24 flow meter (Table 2).

TABLE 2 SURFACE CURRENT VELOCITY COMPARATIVE MEASUREMENTS DATA AT THE RADAR SECTION



Measurement instrument	Surface velocity, m/s
RQ-24 radar flow meter	0,487
Electromagnetic current meter «Poseidon»	0,485
ISP-1M mechanical current meter with 70mm propeller	0,462
GR-21M1 mechanical current meter with 120mm propeller	0,498
GR-21M1 mechanical current meter with 70mm propeller	0,445

The water discharge calculation data link analysis. The method for calculating water discharge using a radar flow meter is based on the existence of a close relationship between the surface current velocity and the mean flow velocity. Three transition velocity indexes K_1, K_2, K_3 are distinguished depending on the width of the surface velocity measurement zone:

$$K_1 = \frac{V_{mean\ flow}}{V_{mean\ surf.}} \quad (2)$$

$$K_2 = \frac{V_{mean\ flow}}{V_{max.surf}} \quad (3)$$

$$K_3 = \frac{V_{mean\ flow}}{V_{local\ surf.}} \quad (4)$$

Where $V_{\text{mean flow}}$ – mean flow velocity, m/s;

$V_{\text{mean surf.}}$ – mean surface velocity, m/s;

$V_{\text{max.surf.}}$ – maximum surface velocity, m/s;

$V_{\text{local surf.}}$ – local surface velocity, m/s.

Since the radar flow meter measures only a certain part of the surface velocity across the width of the river, the K_3 velocity index will be used. The more correct the distribution of velocities in the stream, the closer the connection of the different transition velocity indexes with each other and more accurate mean flow velocity possible to obtain by radar. Most guiding manuals on the use of manufactured radar flow devices recommend indicating a constant value of this factor. The World Meteorological Organization (WMO) and the United States Geological Survey (USGS) recommend using the K_1 velocity index equal to 0.86 for natural channels and 0.90 for artificial channels [5, 6].

A detailed study of this issue was carried out in the 1960s by a group of scientists from the State Hydrological Institute (SHI) under the leadership of D.E. Skorodumov [7]. In his paper it is noted that according to the results of measurements at 38 gauging stations, K_1 can vary from 0.75 to 1.02. It should be noted that these studies set themselves another task - the change in the transition velocity indexes during a high-flow regime, the lower part of the amplitude of water levels fluctuations was almost not studied. However, this article also indicated that adding the lower part of the water level amplitude to the analysis increases the variation in K_1 values.

For the velocity indexes analysis at the main discharge section line, the results of 50 open channel water discharge measurements with a mechanical current meter for 2016-2020 were taken into an account (Figure 1).

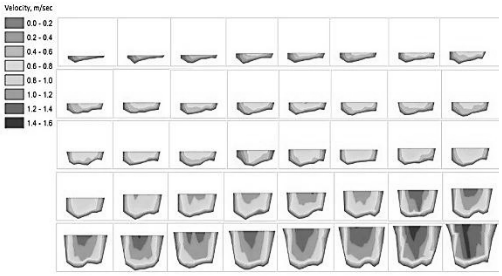


Figure 1 - Distribution of flow velocities at the main discharge section line (according to measured water discharges for 2016-2019 during open channel period)

Since the low-water bed of the river has the correct shape and relatively the same roughness across the width of the river, there is a close relationship between the transition velocity indexes. Figure 2 shows a graph of an increase in the strength of the relationship between the mean flow velocity and the surface velocity with an increase in the width of the averaging zone (based on the results of 50 measured open channel discharges). Also, with an increase in the width of the averaging zone from 1 m (the width of the averaging zone by the radar flow meter at low water level), which corresponds to the index K_3 up to 15 m (the full width of the low-water bed), which corresponds to the index K_1, the strength of the relationship, expressed in units of a pair nonlinear correlation coefficient, increases from 0.954 to 0.977. Such a slight increase in the strength of the relationship indicates the possibility of using the K_3 index instead of the K_1 index to calculate the water discharge with an acceptable error.

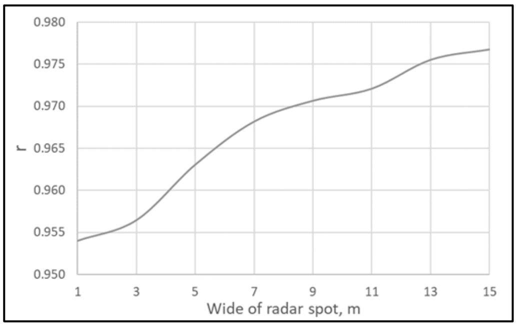


Figure 2 - Graph of an increase in the strength of the relationship between the mean flow velocity and the surface velocity with an increase in the width of the averaging zone

The distribution of the transition velocity indexes for the measured water discharges at the main discharge section line is shown in Figure 3. Thus, the transition indexes from the surface velocity to the average cannot be a constant for the entire amplitude of the water level. In the lower part of the amplitude of water levels, the value of the transition indexes decreases significantly. There is no unambiguous understanding of how these indexes will vary when water flows out to the floodplain.

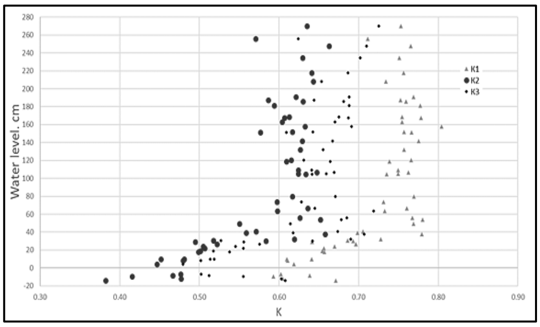


Figure 3 - Dependence of the transition velocity indexes on the water level at the main discharge section line (according to the measured water discharges)

To obtain the transition velocity index K_3 for the radar measurement section line, the following calculation algorithm was carried out:

1 The rating curve Q=f(H) is plotted for the main discharge section line. Since the section between the main discharge section line and the radar measurement section is very short (50 m) and absolutely free of inflows, the slope of the water surface is insignificant in its absolute value, so this dependence was also applied to the radar measurement section.

2 Based on the hourly resolution water level data, the water discharges at the radar measurement section were calculated with an interval of one hour.

3 Using measured cross-sectional profile at the radar measurement section, depending on the water level the water flow areas were calculated for each hour of observation.

4 Based on the data obtained, the average velocity over the entire cross-section of the radar measurement section was calculated with a resolution of 1 hour.

5 By dividing the average velocity by the surface local velocity measured by the radar, the transition velocity index K_3 was obtained (Figure 4). The analysis was performed only for the open channel period and the period with no blind-zone cases.

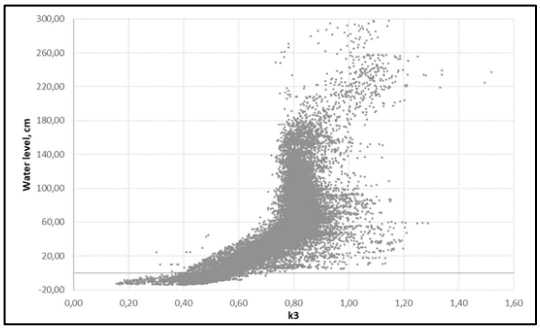


Figure 4 - Dependence of the transition velocity indexes K_3 on the water level for the radar measurement section

The nature of the distribution of points in Figures 3 and 4 is similar, which indicates the correct scheme for calculating K_3 for the radar measurement section. The scatter of points in Figure 4 is primarily due to the different channel capacity of the river at the same water level during the stages of rise and fall. Figure 5 clearly shows that the distribution of the transition velocity indexes on the rise and fall of the rainfall flood, which took place on October 13-17, 2019, is different. Figure 6 shows a complex graph of this flood, on the abscissa axis counting hours from the time of 10/13/2019 13:00. Only three parameters out of five were measured (average velocity and K_3 are calculated parameters with accordance an unambiguous curve Q = f (H). The slope, for the possibility of plotting four characteristics on one axis, is presented in relative units reduced to the variation of the surface velocity. The rise in the level, slope of the water surface and surface velocity began at 24 hours from the start of the countdown, after another 9 hours (33 hours) the values of the slope and surface velocity reached a maximum and began to decrease, while the water level continued to rise and reached its maximum only for 42 hours. From that moment on, the surface velocity began to increase and the level to fall. After approximately 62 hours of observations, the slope and surface velocity were stabilized at a quasi-constant mode, while the level continued to decline. This course of the main hydraulic elements of the flow, with some changes, is repeated on the example of other rainfall and spring floods. This suggests that at moments of intense change in river flow, the relationship between the current velocity and the water level is inverse, and not direct, which is typical for the entire amplitude of water level fluctuations.

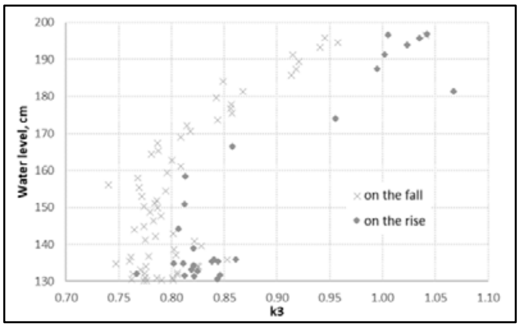


Figure 5 - Dependence of the transition velocity indexes K_3 on the water level for the radar measurement section during the rain flood on October 13-17, 2019

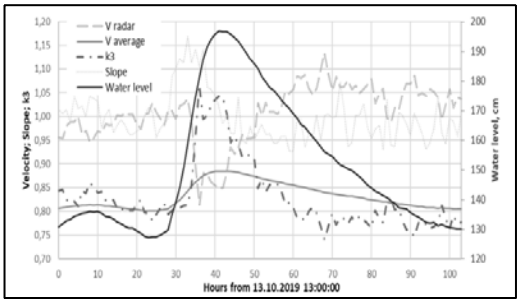


Figure 6 - Comprehensive chart of the hydraulic characteristics of the rain flood on October 13-17, 2019

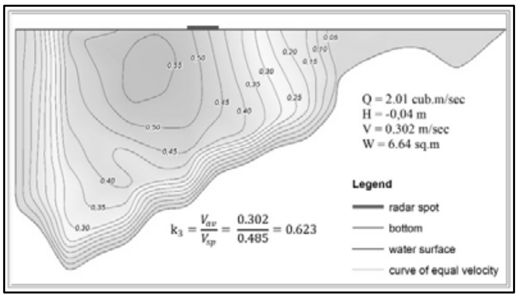
V. THE RESULTS OBTAINED

The error in determining the water discharge using a radar flow meter was calculated on the basis of 3 options:

Option 1 - with constant $K_3 = 0.623$ (Figure 7);

Option 2 - with $K_3 = f(H)$, and the water level data of the reference water level gauges;

Option 3 – with $K_3 = f(H)$, and the water level data of the radar-based water level sensor.

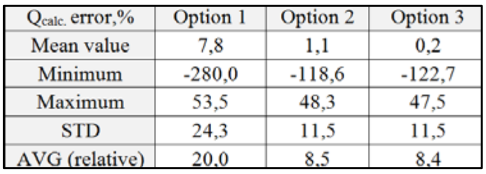


$$k_3 = \frac{V_{av}}{V_{sp}} = \frac{0.302}{0.485} = 0.623$$

Figure 7- Comprehensive chart of the hydraulic characteristics of the rain flood on October 13-17, 2019

The water discharge calculated by the rating curve Q = f (H) at the main discharge section line was taken as the true value. The results of calculating the error in calculating the water discharge are presented in Table 3.

TABLE 3 WATER DISCHARGE CALCULATION ERROR ACCORDING TO USE RQ-24 WATER FLOW RADAR



$Q_{calc.}$ error,%	Option 1	Option 2	Option 3
Mean value	7,8	1,1	0,2
Minimum	-280,0	-118,6	-122,7
Maximum	53,5	48,3	47,5
STD	24,3	11,5	11,5
AVG (relative)	20,0	8,5	8,4

The use of a constant value for the transition velocity indexes is not permitted. This leads to an overestimation of the minimum water discharge by 100-280%. The use of the dependence $K_3 = f(H)$ allows you to obtain a water flow rate with an acceptable error, but these observation are complicated and the labour inputs for the determination of this relationship are measure alike with the labour inputs for obtaining a reliable rating curve.

When water flows out to the floodplain, the value of K_3 may vary. Unfortunately, it was not possible to investigate this issue, due to the fact that most of the data at high levels of water outflow to the floodplain fell into the blind zone of the sensor and was rejected. According to the available episodic data, it is possible to assert with a sufficient degree of reliability about an even greater stratification of the $K_3 = f(H)$ dependence in the areas of rise and fall of rainfall and spring floods.

VI. CONCLUSION AND RECOMMENDATIONS

As a result of the analysis performed, the following advantages and limitations of using Doppler non-contact flow radar devices to determine the water discharge may be assessed.

Advantages:

\+ Safety and contactless measurement. To measure, hydrologist does not need to go into the water and endanger his own life;

\+ The possibility of using on mountain rivers with high slopes;

\+ The ability to measure the parameter of the mud flood flow passage velocity;

\+ The applicability even during the period of slush ice run and ice drift;

+ Using for the rating curve clarification in the periods of the variable wind- and pressure- induced backwater phenomena;

+ A wide range of measured flow velocities from 0.02 to 15 m/s;

+ Permissible error in measuring the flow velocity;

+ Continuity of measurements;

+ The ability to receive data in real time;

+ Low labour inputs for the maintenance.

Limitations (disadvantages):

- Inability to measure in freeze-up channel conditions;

- The water discharge calculation is carried out using a single complexly calculated coefficient of transition from the fictitious discharge to the true one;

- The need for more precise extra measurements of water discharge to plot the dependence of the transition velocity index on the water level, as well as to revise and upgrade the area curve;

- Changes in the averaging area of the surface velocity (radar spot) due to water level fluctuations;

- A mandatory requirement is the presence of microwaves on the surface of the water;

- The presence of a blind zone of the emitter,

- High limit of the minimum fixed velocity (for outdated devices),

- The possible influence of external factors (practically absent in modern devices).

Recommendations:

A. It is impossible to use a radar flow meter to determine the water discharge in an unexplored measuring section of the river without carrying out periodic measurements. It is necessary to obtain the relationship between the transition velocity indexes and the water level, as well as monitor the change in the profile of the river channel at the measurement section line.

B. It is recommended to use radar flow meters at the discharge section lines of mountain rivers with high steep slopes, as well as at section lines of rivers with variable backwater phenomena.

C. In order to study the distribution of current velocities in the flow at different water levels, it is recommended to create gauge sections equipped with several flow meters, in combination with immerse stationary Doppler or ultrasonic profilers (with river bank-based or bottom-based location).

D. Taking into account all the technical requirement and nuances of installation, setup, maintenance and development of transition velocity indexes, you can continuously measure the water flow with an acceptable error.

5 It is necessary to create a methodology for measuring water discharge by the "surface velocity-area" method.

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Employees of the Hydrological Instruments Laboratory of the State Hydrological Institute are open to further cooperation in the field of hydrological surveys and monitoring, share experience and improve their qualifications, keeping a dialogue with experts from all over the world. You can contact us using this email: lgpggi@yandex.ru or emails indicated in the title of the article.

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