

LOCAL REMOTE SENSING OF RIVERS

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IIHR Technical Report No. 418

Iowa Institute of Hydraulic Research
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Iowa City, Iowa 52242-1585

August 2001

TABLE OF CONTENTS

OBJECTIVE, CONTENT AND CONCLUSIONS.....	1
MOTIVATION OF THE REPORT	2
THE RIVER MONITORING PROBLEM.....	3
Variety of River Sizes and Shapes	3
Geometry of the “valley” and of the gauged section	3
Stability of the river bed.....	4
Variability of the river in time.....	4
Variety of Questions Posed	4
Improving traditional gauging stations.....	4
Modifying traditional practices	5
LOCAL REMOTE SENSING OF RIVER SURFACE VELOCITY.....	5
Visible and IR Imagery	5
PIV method	5
Advantages and drawbacks of the video imagery	6
Doppler Radar	6
Electromagnetic detection of water surfaces.....	7
Conventional mono-static radar	9
Bi-static radar	10
Advantages and drawbacks of Doppler radar technology	12
LOCAL REMOTE SENSING OF BATHYMETRY.....	12
GPR	12
LIDAR.....	14
LOCAL REMOTE SENSING OF STAGE.....	14
KEY RESEARCH ISSUES.....	14
Waves and Roughness Structures at the River Surface.....	14
Inversion of the Data and Assimilation in Hydro-Dynamics Models	14
BIBLIOGRAPHY	15
APPENDICES	16
1: HYDRO21 Committee	16
2: Proof-of-concept experiments to date	16
3: Conventional river monitoring methods.....	19

	Water velocity	19
	Measurement of Water Levels	21
	Dye dilution methods	22
	Rating-curves.....	22
4:	Instruments and methods for aircraft and satellite remote sensing	23
	Altimetry	23
	SAR Imagers	24
	Trajectory analysis	25
5:	Radar altimeters embarked on satellites	26
6:	Visit to USGS Water Resources Division in Menlo Park (California)	26
7:	Visit to CODAR Company in Palo Alto (California).....	27
8:	Visit to the Applied Physics Laboratory of the University of Washington (Washington).....	27
9:	Question on river waves to RiverList members	28
10 :	Some research teams and projects.....	30
11 :	Some manufacturers and engineering companies	31
12:	USGS Documentation on river discharge measurement	32
13:	Illinois USGS Documentation on ADCP	32
14 :	General considerations about wind waves	33

LIST OF FIGURES

Figure		Page
1	Classification of river channel types and controlling variables after Mollard.....	3
2	Apparent velocities identified by the PIV method in the Iowa River.....	5
3	Bi-static radar SeaSond®e by Codar in operation on a beach.....	7
4	L-band radar return from a wave tank as a function of the frequency.....	8
5	L-band radar returns from sea surface	9
6	Sketch showing the mono-static radar protocol chosen for rivers.....	10
7	Sketch illustration of the bi-static configuration.....	11
8	HF-radar return from ocean surface according to Barrick et al. 1974.....	11
9	Installation of a GPR under a helicopter during the Cowlitz River experiment in May 2001-08-24	12
10	GPR raw image of a Skagit River section according to Haeni et al. 2000	13
11	Cowlitz River Experiment on May 1, 2001-08-24	19
12	SonTek ADCP probe with converging beams on the bank of the Cowlitz River on the 1 st of May 2001.....	20

OBJECTIVE, CONTENT AND CONCLUSIONS

This report aims at giving a synthetic view of developing local (i.e. not from space) non-contact (i.e. not direct) measurement of river discharges.

This report considers the measurement of hydraulic parameters in river channels. It ignores the monitoring of water quality related parameters like temperature or pH as well as the questions related to the presence of ice. A first section lists the variety of situations and the variety of objectives encountered in river monitoring. Even if it is well known, this diversity is good to recall since it constitutes a true specificity of hydrology compared to atmospheric or ocean sciences where more homogeneous media simplify exploration strategies. The two following sections are devoted to the core of the subject: the local remote sensing techniques used to date for the measurement of river surface velocities and river depths. Basically, most of the reported attempts concern the light/IR and the microwave/HF parts of the electro-magnetic spectrum and not at all sound technologies. Regarding surface velocities, the alternatives are visible or IR imagery and Doppler radar. Regarding water depth, radar technology seems preferred to LIDAR when this measurement is needed (unstable river bed). The last section addresses briefly some key research issues. The report is completed with a reference section and appendices regarding current research efforts in the area, a brief review of conventional river measurement methods and satellite remote sensing of rivers and a summary of my last year activity on the topic.

Following this study, I share the conclusion of the USGS/HYDRO21 Committee that non-contact methods are the river gauging techniques of the future. In effect, it seems obvious that the knowledge of rivers can greatly benefit from remote sensing technologies such as those used for investigation of oceans or atmosphere. We are at a very exciting moment for this field of investigation. Some keen pioneers are proud to show the real potential of different methods through carefully selected examples. However, the problem is very complex and will certainly require patience and efforts to be solved. I would like to provide herein some complementary conclusions and recommendations.

Due to their indirect nature and potential to revolutionise current practices, remote sensing techniques are always difficult to implement. Indirect nature calls for a strict control of the multiple sources of uncertainties. Innovative capabilities call for a good capacity to renew the way the problems are posed. To my opinion, the techniques explored to date are still closely inspired by the current in-situ practice. For instance the debate between point and bulk measurement is not yet considered.

Due to the variety of situations and objectives in river monitoring, the above statement will be even more true. Depending on the geology and the climate, rivers exhibit a tremendous variability of shapes and behaviours over a wide range of spatial and temporal scales. From simple water balance considerations to more complex ecological considerations, the objectives of river monitoring evolve and dictate new measurement requirements. From this respect, the local remote sensing solution for rivers will be diverse.

As for all remote sensing projects, two conditions need to be fulfilled for the success of this domain:

- 1) Constitution of a research community grouping applied physicists, hydrologists and fluid mechanics. The successful use of sophisticated sensors relies on a good understanding of

their physics and of the physics of the measured phenomenon. The constitution of such a community takes time and needs support.

- 2) Early implication of practitioners of river management and of technologic development companies. Sensors need to be tailored and tested according to specific needs.

MOTIVATION OF THE REPORT

The river discharge is the single parameter traditionally measured as a bulk indicator of river dynamics. The discharge measurement method used today little evolved since the XIXth century. It relies on the concept of stage-discharge relationship. The stage-discharge relationship (or *rating-curve*) assumes a univocal link between the level of the water in the river and the discharge. The discharges are measured occasionally by exploring the stream velocity field with a *current-meter* in a cross section of the river. This manipulation is called *river gauging*. The stages are measured on a continuous basis with a *stage-meter* or *limnimeter*. The stage-discharge relationship is used to derive continuous series of discharges from continuous series of stages. This method applied to networks of thousands of stations across the world provided much valuable data with respect to their accuracy and homogeneity. The accuracy first stems from the good validity of the rating curve concept which appears to be valid when the gauging section is well chosen, i.e. with a stable and simple geometry. The accuracy is also due to the measurement principles used – the sensors are simple and in the river (direct measurements). The sensors used little evolved in time, which explains the homogeneity of the data in time and space. This classic technology is considered as indispensable for perennial series of data and as a reference for any kind of new device.

Nevertheless, the hazards and costs related to this measurement technique of river discharge and on the other hand the evolution of the questions posed about rivers, lead to ask the question of the modernisation of river monitoring methods.

The hazards essentially relate to high water periods. During floods, floating objects and water turbulence make all type of direct measurement of the stream velocity extremely risky for the instruments but also for the involved technical staff. In reason of this risk and also of the difficulty to have staff present along the river during the flooding (specially in case of flash floods), only 20% of the French rivers are gauged for discharge values exceeding the 10 year return period.

The costs are related to the gauging station itself which must be stable enough to endure floods (the Paillon river at Nice, 800km², demolished three times its gauging station since 1942). The costs are also due to the need to have teams present along rivers at a priori unexpected times, with a non negligible possibility of simultaneous high waters on different rivers over a region. These costs push the organisation in charge of river monitoring to reduce the number of gauging stations and they make impossible the installation of ephemeral stations for purposes of research or specific studies.

The questions posed about rivers call either a diversification of the measurement types or denser networks. The solid transport and water quality related issues, as well as the aquatic life conditions call for a detailed knowledge of the water velocity field. The validation of numerical models of river stream-flow necessitates more parameters than the global discharge. The detailed knowledge of rain distribution in space and time that is now available from weather radar

detection, suggests that denser river monitoring networks would help the prediction of storm floods. The monitoring of pollution shocks also needs denser river monitoring networks.

Thus, it appears that the measurement of river flow needs to be modernised and complemented. This is well perceived by the organisation in charge of river monitoring in the United States (See for instance the activity of the HYDRO21 Committee of the USGS in Appendix 10) as well as by the National Electricity Board in France (Personal communication of C. Lallement, 2001 from EDF).

THE RIVER MONITORING PROBLEM

The question of river monitoring is complex basically because of the wide variety of river sizes and shapes, from small upstream rills to estuaries, and because of the wide variety of questions posed, from the traditional sizing of hydraulic works to more recent concerns about river ecology. The following lines do not pretend to give an exhaustive view of the problem. They simply list in an almost random manner a series of items reflecting the above mention complexity of the problem. They try to figure out the changes one could expect moving from traditional to non-contact gauging techniques.

Variety of River Sizes and Shapes

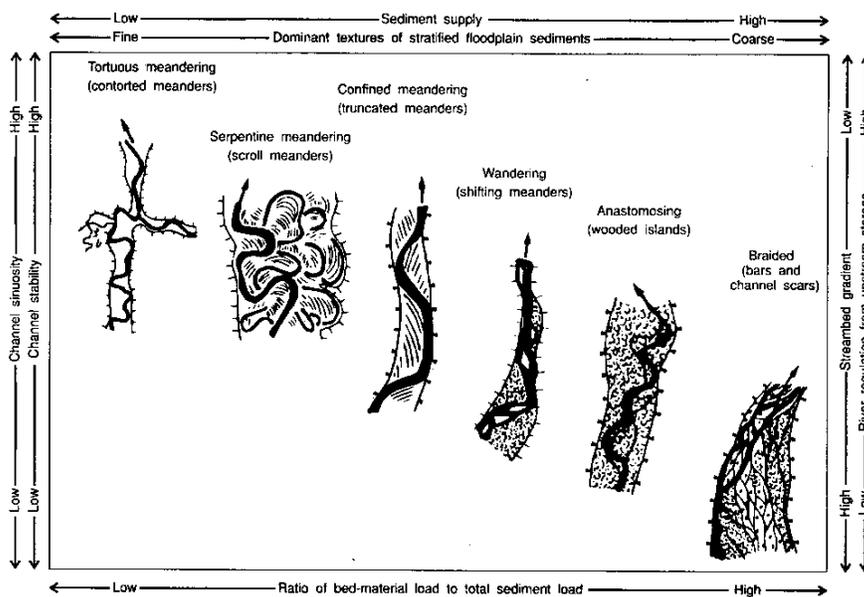


Figure 1: Classification of river channel types and controlling variables after Mollard.

Rivers are very diverse in space depending on the level considered from upstream rills to the downstream estuaries and depending on the type of interaction between the climate and the geology controls the river. The Figure 1, extracted from the Handbook of Hydrology p.8.7 illustrates the very different

shapes rivers present according to major features such as sediment characteristics and topography.

As far as discharge measurement is concerned the most important factors are probably the following:

Geometry of the “valley” and of the gauged section

The geometry of the gauged section is of primary importance respect to the validity of the rating-curve. The plausibility of a univocal relationship between level and discharge is higher when the gauged section has a simple hydraulic behaviour. This is why gauging sites have to avoid complex geometry such as pronounced meanders, breaded channels, marked sills etc... The accessibility constrain frequently leads to establish gauging sections at bridge level which are not always free of undesirable effects on the flow. Non-contact methods can alleviate this type of constrain, making the choice of a gauging section more focussed on the river section than on accessibility.

The geometry of the valley itself enters into play again with the accessibility question. In deep mountainous valleys, the only convenient access to rivers is given by bridges. Non contact methods should substantially change this constrain.

Stability of the river bed

The stability of the river bed is a second important validity condition for the rating curve. Again the advantage of remote-sensing methods could be to allow gauging in places with poor accessibility but better bed stability (search for natural sills stabilising the river bed for instance).

Variability of the river in time

Rivers are also diverse in time according to climate fluctuations. In quickly varying rivers, one of the most constraining aspects of gauging is to perform the entire measurement at a constant level or discharge. This is true for all type of flow but specially for high flows. The drastic reduction of the gauging time provided by remote-sensing should completely change this point. Even in a quickly rising or descending river one can reasonably expect from non-contact methods the capability to continuously gauge and thus to change this adverse situation for traditional methods into a favourable one to rapidly explore a large portion of the rating-curve.

Variety of Questions Posed

When new monitoring techniques appear, it is always difficult to figure out the way they will modify the questions traditionally posed.

At present, the way river monitoring is organised is deeply marked by the gauging methodology. The only variable which is routinely monitored is the level, setting the gauging station and establishing the rating-curve represents a considerable investment. The consequence is that the flexibility of the gauging networks is very weak (moving stations is almost impossible) and that possibilities like i) temporary densification of the gauging network for a specific study or ii) redeployment of an existing network according to new management objectives appear to be unfeasible.

The use of remote sensing techniques for river survey can be seen either as a way to improve traditional gauging techniques or as a way to change this traditional practice.

Improving traditional gauging stations

For practical reasons of continuity and reliability of the produced data, the non-contact methods must be used in complement of contact methods. They can provide the following improvements at sites already equipped with a gauging station:

- continuous monitoring of the surface velocity field needed for a better management of water quality problems,

- reduction of the cost and risk associated to the identification of the rating curve,
- design of a new non-contact station finding the appropriate combination of measurement able to provide at least a comparable accuracy.

Modifying traditional practices

The deep motivation for changing the present practice would definitely be to go from the concept of precise point control to the concept of space distributed runoff monitoring. The question is then to find a new compromise between costs, accuracy of measurement and spatial density of measurements. These aspects still certainly belong to the research domain.

LOCAL REMOTE SENSING OF RIVER SURFACE VELOCITY

Essentially two non-contact methods have been tested to measure the water velocity at the river surface. The first relies on the digital images in visible or infrared (IR) that can be taken using video or picture cameras. It can be considered as a passive detection methods since the natural emission of the river surface is used. The second relies on radar detection using wavelengths from microwaves to radio waves. It is an active detection method. Other methods could be based on LIDAR or SODAR techniques – they have not been experimented.

In any case it can be noted that the identified velocity is a “surface” velocity that needs to be extended to the vertical profile in order to produce a discharge measurement. This extension can be done in a simple manner like in classical gauging techniques where the profile is assumed to have a given shape (power law in general). It can also be done in a more comprehensive way by assimilation to a flow model (see for instance Sulzer et al., 2000 or Bradley et al., 2001).

The access to the 3D velocity field using a non-contact method seems to be out of reach for the existing technology.

Visible and IR Imagery

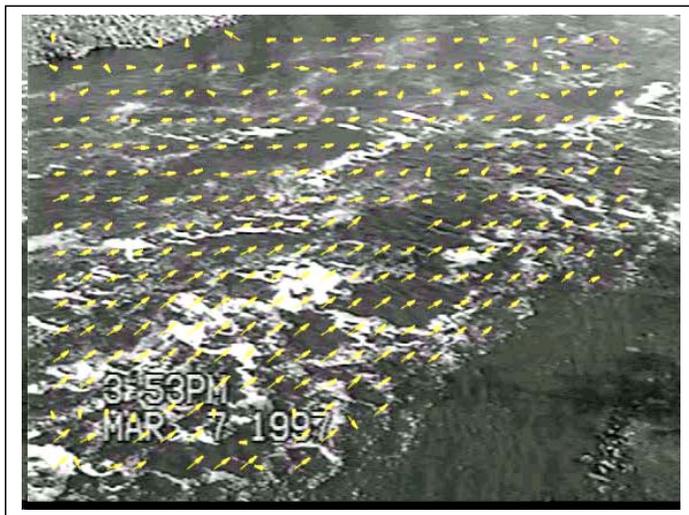


Figure 2: Apparent velocities identified by the PIV method in the Iowa River (IIHR document).

PIV method

In experimental fluid mechanics, the use of images to measure fluid particle velocity is a well established technique known as Particle Image Velocimetry (PIV). Different books describe the theory and application of the PIV method (see for instance Raffel et al., 1998). The principle of measurement is to use a visible light video camera (as opposed to IR video camera) with appropriate lighting conditions in order to image natural tracers present in the water at two successive instants and then to process these images in order to derive the

displacement of the tracers. The processing essentially includes two steps: i) the geometrical transformation allowing to go from the picture plan to the physical plan and ii) the correlation analysis allowing to identify the tracers displacement. At the early stage of the method, the two successive instants were recorded on the same image thanks to successive light flash during the same camera aperture. The improvement of film cameras and the arrival of video cameras led to the use of two distinct images, which simplifies and improves the correlation analysis. The lighting improvement thanks to laser sources also dramatically refined the possibilities of the method.

In rivers, the application of the PIV method is still limited to i) some pilot experiments (on the Iowa River on March 97 as shown on the Figure 2 and latter in Bradley et al., 2001) and ii) some pilot applications (different river gauging stations equipped with video cameras in Japan – M. Muste, personal communication).

Advantages and drawbacks of the video imagery

The advantages of the method:

- The low cost and the transportability of the sensor. Digital cameras (picture or video) are of the order of 1000 cost units (€ or \$) and easy to plug to portable microcomputers. The ensemble can be easily moved and installed.
- The apparent simplicity of the principle. The optics of a camera is pretty simple to model and thus the issues related to image geometry are probably simple to solve. The interaction between the light source (natural or artificial) and the river surface that gives the detected values is probably less simple to understand.
- The possibility to analyse visually the pictures before processing allows a better identification of the state of the river (type of flow, type of available targets...).
- The retrieval of the detailed 2D velocity field (no assumption is made about the main flow direction compared to “active” methods).

The drawbacks of the method:

- The need of light (day light – passive detection or artificial light – active detection) and the need of clear air at the river surface (absence of fog or any type of water emulsion due to the turbulence of the river flow and diffracting light) are certainly crucial limitations of the method in rugged conditions.
- The need of “tracers” is also a serious issue. Artificial seeding using “environmental friendly” tracers can be a solution but in some sense sticks the method to contact methods. Non-seeded PIV deserve more attention in two senses: i) depending on river conditions and the scale of interest, many “structures” advected by the river current can serve as tracers (fluid turbulence structure, wind waves, floating bodies), and ii) time integration can help in having a reasonable description of the surface velocity speed with low density of natural tracers.
- The data processing is not yet clearly formalised and many questions remain pending. In spite it is intuitively easy to understand the cross-correlation method and in spite it is used in many different fields, I did not find the exact meaning of the optimisation achieved by this method. The method looks for a maximal coefficient of correlation that corresponds to maximising the explained variance of one image by the other – the link with the “optimality” of the derived displacement is not obvious.

Doppler Radar

The most popular examples of radar detection of water bodies come from the use of Synthetic Aperture Radar (SAR) and Radar Altimeters on satellites. They concern both non-Doppler radar systems. They are both very well described in different books on remote sensing (see for instance Ulaby et al., 1986). They are briefly reviewed in Appendix 4.

The Doppler capability of measuring radial velocities of targets has been used over oceans in the perspective of measuring currents (Barrick et al., 1974 for UHF, Plant and Keller, 1990 for microwaves). At present two antenna configurations used for ocean currents have been adapted and tested on rivers. In the following we recall some basic principles on the electromagnetic detection of water surfaces and we describe the mono-static and bi-static configurations tested in rivers (see illustration in Figure 3).



Figure 3: Bi-static radar SeaSonde® by Codar in operation on a beach.

Electromagnetic detection of water surfaces

Only periodic waves have been the object of a clear analysis in terms of radar detection. This analysis relies on the so-called Bragg scattering effect by analogy with the X-ray resonance in minerals. It applies well to wind generated waves over large bodies of water like seas or lakes. According to the Bragg theory, a periodic surface with a wavelength Λ (capital letter for water related variables) is known to reflect EM waves of length λ (the radar wavelength, denoted with a low-case letter) if the following relationship is satisfied:

$$\lambda = 2\Lambda \cos \Phi$$

where Φ is the grazing angle (i.e. the angle between the EM wave propagation line and the water surface) and provided the surface is slightly rough (slopes < 1 , height of the water waves $< \Lambda$). Given a radar wavelength and a grazing angle, only one water

wavelength can be distinguished by a radar according to the Bragg theory.

This relationship means that for the typically used frequencies (microwaves in X-band and over to LF waves) the following water wavelengths (in cm) are detected:

	Φ	10°	30°	45°	60°
10 GHz $\lambda_{\text{radar}}=3\text{cm}$	X	1.52	1.73	2.12	3.0
300 MHz $\lambda_{\text{radar}}=1\text{m}$	UHF	51.0	58.0	71.0	100.0

Note that the concerned waves are essentially gravity waves (the theoretical wavelength limit between capillary and gravity waves being around 1.7cm). Such waves appear to be very common on sea surfaces exposed to wind (see Appendix 15 for elementary considerations on wind generation of waves).

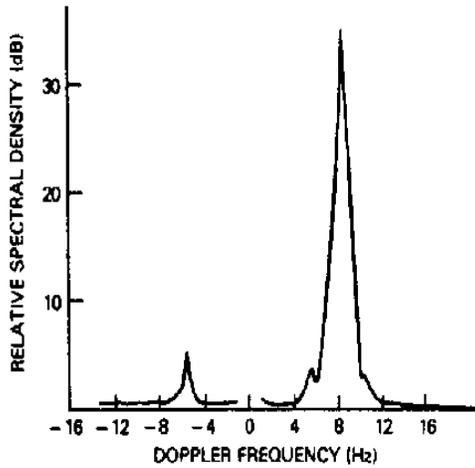


Figure 4: L-band radar return from a wave tank as a function of the frequency.

If the radar is able to measure the frequency spectrum of the return signal (Doppler or coherent radar), the frequency difference between the transmitted and the received signal will indicate the apparent velocity of the detected water wave family *in the direction of the propagation of the radar signal* (antenna axis for a classic parabolic antenna). The shift ΔF will satisfy the following relationship:

$$\Delta F = V_A / \lambda \cos \Phi$$

The question is then to establish what is this apparent wave velocity V_A . It reflects in fact both the phase velocity V_P of the waves and their group velocity V_G that depends on the wind advection and on the underlying current. The frequency shift can thus be reformulated as:

$$\Delta F = (V_P + V_G) / \lambda \cos \Phi$$

For a radar wavelength and grazing angle, the targeted wave family in the direction of the radar signal propagation comprises advancing and receding waves that are assumed to propagate in opposite directions at their theoretical phase velocity. In absence of group velocity, these waves give two signal peaks at symmetric frequency shifts:

$$\Delta F = \pm V_P / \lambda \cos \Phi$$

The group velocity acting in the same direction on the processing and the receding waves will shift the two symmetric peaks the same way, leading to a signal spectrum which is no more symmetrical respect to 0 as on Figure 4 extracted from Plant and Keller, 1990. At L-band ($\lambda = 16\text{cm}$) and for the chosen grazing angle $\Phi = 36^\circ$, the targeted waves have a wavelength of $\lambda = 6.47\text{cm}$. Note that the advancing wave peak (positive shift of +8Hz) provides a stronger return since it corresponds to more developed waves. Note also that the shift due to the group velocity is of about 1Hz in the same direction as the processing waves and that the phase velocity is of about 7Hz. This shift corresponds to a phase velocity $V_P = 90\text{cm.s}^{-1}$ close to the expected theoretical phase velocity. The 1Hz shift corresponds to a 13cm.s^{-1} group velocity that is to be connected to the 20cm.s^{-1} wind imposed at the surface.

In natural conditions, the received echoes are naturally more complex than from controlled experiments. See for instance the Figure 5 corresponding to sea echoes at C-band (Plant and Keller, 1990) obtained with a wind direction almost perpendicular to the antenna axis and a current of ca 60cm.s^{-1} . Among the possible reasons for the wider dispersion of the received spectrum, one can put forward the following ones:

- The water waves detected by the radar are carried by larger waves that modifies the grazing angle. Thus the radar detects a set of wave families instead of a precise one as expected. These families have different velocities, producing thus different Doppler shifts,
- The water waves do not travel at their theoretical speed which are established under ideal conditions (single family of waves present a the free surface...),

- The back-scattered signal comes from other elements than the waves of the expected wavelength like the crest of breaking waves or some surfaces from which specular reflection occurs (vertical incidence).

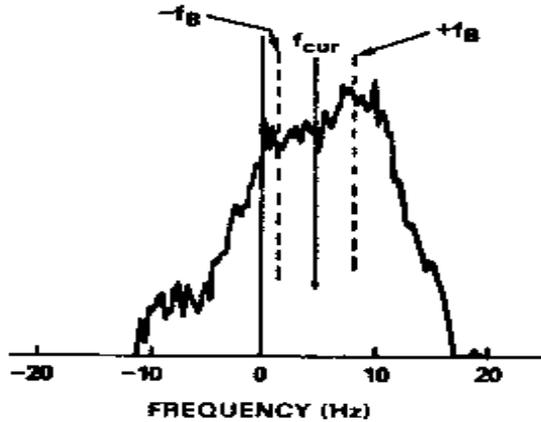


Figure 5: L-band radar returns from sea surface

The back-scattering properties of rivers are much less known (no publication to my best knowledge and no information from a web investigation related in Appendix 13). The roughness of their surface at scales corresponding to the used electromagnetic wavelengths (i.e. from 1cm to 10m roughly) should come from the following sources (see E. Mosselman, personal communication in Appendix 13):

- Periodic waves (from wind and reflections on the banks, from raindrops, from boats or helicopters),
- Instabilities due to high flow velocities (supercritical flow)
- Coherent structures (upwellings, turbulent bowls, eddies)
- Floating objects (debris, foam)

According to the proof-of-concept experiments described below, back-scattered signal is always well above the detection threshold of the radar used at X-, K- and HF-bands.

Conventional mono-static radar

The first configuration tested in rivers to date is very basic in radar technology – it consists in using a parabolic antenna to both transmit and receive a pulsed signal. The size of the antenna is typically 1m in diameter which provides a half-power angular resolution of typically 2° at X-band and less at K-bands. The size of the foot print of the beam on the river surface depends on the ratio between the height of the radar and the considered range according to the following formula:

$$S_m = \Pi \frac{h_r}{\sin^2 \Phi} r \sin \theta = \frac{r^3}{h_r} \Pi \sin \theta$$

where r is the radial distance to the radar, h_r is the height of the radar above the river surface and θ is the beam angle.

The radar equation for a point target shows that the received power decreases in r^4 , reaching a minimum on the opposite bank of the river:

$$P_r = \frac{P_t G \lambda^2 \sigma_m}{(4\Pi)^3 r^4 L_p^2 L_s}$$

where G is the antenna gain and L_p and L_s are losses respectively due to the propagation and to the system. It can be noted that the required transmitted power P_t is very low (a few tens of Watts).

This antenna is mounted on a pedestal able to point at chosen azimuth and elevation angles (negative elevations are called depression). Given the signal sampling operated, the range resolution is typically 10m.

In rivers, the scanning strategy is simple (see Figure 6).

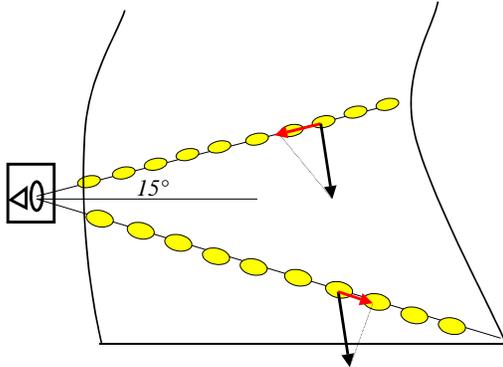


Figure 6: Sketch showing the mono-static radar protocol chosen for rivers

The antenna is successively pointed 15° upstream and 15° downstream in order to determine from the measured range velocities the actual velocity in the river. One must notice that *an assumption must be made about the river velocity* – it is either assumed constant over the two radar spots or parallel to the axis of the river. The first hypothesis becomes stronger at increasing range.

This configuration was tested in the Skagit River and the Shenandoah River Experiments described in Appendix 2. The possibility to mount two radar systems of this type on the two

sides of an helicopter and to point at a 45° incidence on the waves created by the propeller at the surface of the river was explored during different experiments conducted in the Columbia river basin (refer to the Cowlitz River Experiment mentioned Appendix 2). In this configuration, the symmetry of the setting allows to deduce directly the river current from the addition of the measured speeds if one makes the *assumption that the current is perpendicular to the helicopter flight*. Note that given the need to detect close to the helicopter, the transmission and the reception cannot be done with the same antenna (switch delay), thus a couple of antennas is used.

In addition to these already tested configurations, the possibility to use a series of small antennas across the river (for instance fixed to a bridge) will be tested in the next future by the Applied Physics Laboratory in Seattle (W. Plant, personal communication).

Bi-static radar

Generally speaking bi-static configurations are seldom used in radar detection since they imply the use of distinct antennas for emission and reception at locations significantly separated in space. The directionality of the system depends on the number of receiving antennas. The main advantage is the possibility to explore globally the separation space with a rather homogeneous resolution. This is why this type of configuration was essentially used for fence detection.

In oceanography this configuration was used to globally detect the sea state at distances parallel to the coast.

In rivers a bi-static radar installed on the two banks of a river detects basically the mean projected velocity of the resonant water wave over a couple of elliptical cross-sections of the river situated upstream and downstream of the antenna line (see sketch).

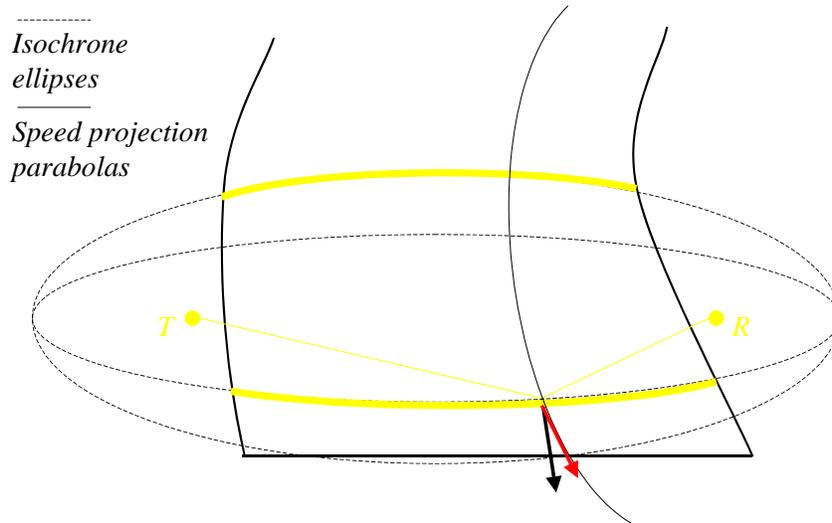


Figure 7: Sketch illustration of the bi-static configuration

In this configuration the speed of the target is projected on parabolas orthogonal to the isochrone ellipses. With more than one receiving antenna or with a more sophisticated receiving antenna, the combined analysis of the received signals by an appropriate software (for instance MUSIC® by CODAR) can lead to establish a profile of speed projections on parabolas perpendicular to the isochrone ellipses across the river.

The bi-static radar equation for a point target shows that the received power is more uniformly distributed across the river with a minimum at equal distances from the antennas:

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma_b}{(4\pi)^3 D_t^2 D_r^2 L_p(t) L_p(r) L_s}$$

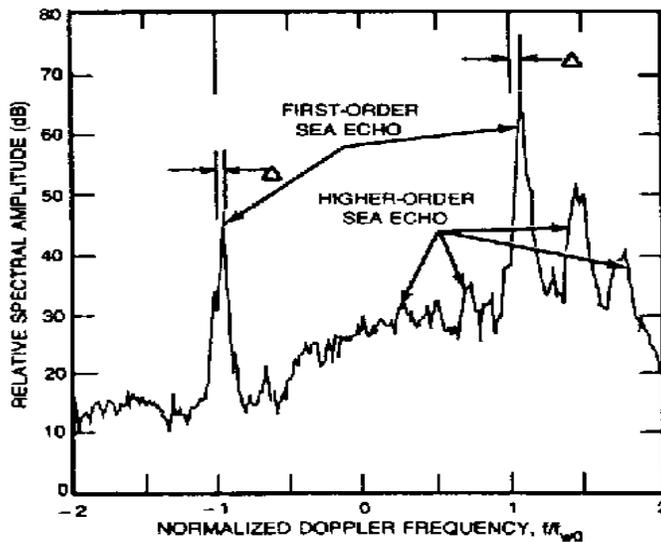


Figure 8: HF-radar return from ocean surface according to Barrick et al. 1974

where the subscripts t and r stand for the transmitter and the receiver. Note that the back-scattering cross-section is also specific of the configuration. The received power P_r is minimal when the product of the squared distances from the target to the receiver and the transmitter is maximal, i.e. when the distances are equal.

The signal spectrum received from a bi-static system is comparable to the one seen for the mono-static one. The Figure 8 shows the spectrum obtained at 9.4 MHz (i.e. $\lambda=30\text{cm}$) from the ocean.

The two advancing and receding wave peaks are clearly visible. The shift Δ due to the group velocity appears to be very small on this example.

Advantages and drawbacks of Doppler radar technology

The two methods (mono- and bi-static) rely on the same principle and therefore present globally the same advantages and drawbacks.

The advantages of the method:

- The active detection allows to be more specific about the targeted structures. The Bragg theory provides a serious support to this specificity. To date, all the experiments made report a good level of signal returned by the river surfaces explored. Regarding this issue, the use of radio waves presents the advantage to make a clearer choice than micro-waves in the sense that the responding waves are more likely to be wind induced.
- The active detection also makes these methods independent of lighting conditions and insensitive to any kind of water emulsion present at the river surface (W. Plant personal communication, 2001).
- The integration capability of this type of technique, which could also be mentioned as a drawback, can be seen as an advantage if it is well used.

The drawbacks of the method:

- The decomposition of the group velocity into wind and current effects is far from being straightforward.
- The measurement of projected speeds needs to make strong assumptions on the flow direction.
- The river surfaces contain probably more than periodic waves and as such need further investigations in term of back-scattering properties.
- The delivered signal cannot be “intuitively” analysed. In particular, when the targets are not periodic waves, no theoretical scheme is offered to “read” the signal.
- The cost of these systems is more around 10000 cost units even if for this type of instruments costs are always difficult to assess (Codar sells its RiverSonde® for 10000\$). Bi-static antennas needing less power and longer wavelength using less complex receivers (no frequency conversion?) are likely to moderate the costs.

LOCAL REMOTE SENSING OF BATHYMETRY



Figure 9: Installation of a GPR under a helicopter during the Cowlitz River experiment in May 2001

Two non-contact active methods exist and have been tested to measure river bathymetry. The first relies on radar detection using wavelengths able to penetrate the river down to the bottom (LF). The second relies on LIDAR technology.

GPR

A Ground Penetrating Radar is a LF Radar (60-300 MHz). These EM waves are able to penetrate river waters meeting certain characteristics of conductivity and sediment load. With a conductivity of more than 1000 microSiemens/cm, the radar energy can be rapidly absorbed and no signal will be returned. With sediment loads of more than 10000 mg^l⁻¹ it is also known that radar penetration in rivers becomes difficult (Spicer et al., 1997).

Initially, GPR were used in rivers to monitor erosion around bridge piers – delineation of refilled scour holes (Haeni et al., 2000).

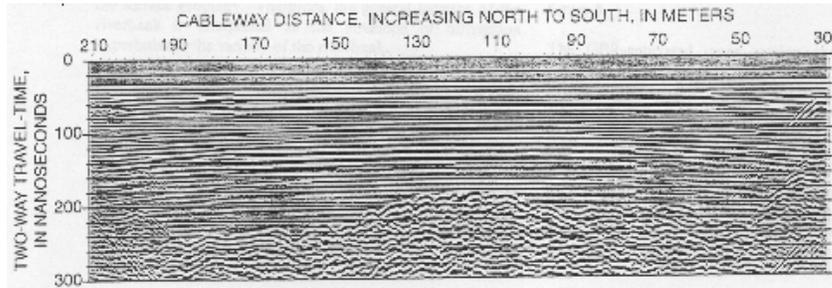


Figure 10: GPR raw image of a Skagit River section according to Haeni et al. 2000

A GPR pointing vertically toward the river surface can broadly distinguish the air, the water and the sediments forming the bottom of the river (see Figure 10). The raw image obtained of the returned signal intensity as a

function of the travelling time mixes different frequencies and different travelling velocities when the penetrated medium is complex like impure water or sediments. For instance, in the experiments reported by the USGS, after propagation in the river, a 100 MHz transmitted signal is received at a frequency centred at about 150 MHz. The signal analysis is not straightforward—noise filtering out of the desired frequency band (less than 50MHz), removal of spurious horizontal bands due to the reflection of the radar signal on nearby obstacles (cable-way, bridge). Once the boundaries of interest (surface and bottom of the river) are identified from the filtered image, the travelling times actually measured by the instrument need to be converted into distances assuming appropriate wave velocities in the different mediums (essentially in the river, since in the air, the velocity of 0.3 mns^{-1} is well established). At present, too little experience is available to say if the wave velocity fluctuates much in rivers and what are the controlling parameters. In impure water the travel velocity of waves is taken equal to 0.04 m.ns^{-1} in average for rivers of south-western Washington State after comparing weight-sounded depth and radar travel times (Spicer et al., 1997) – note that this signal speed in fresh water is roughly one order of magnitude below the speed in air (0.033mns^{-1} versus 0.3mns^{-1} according to general figures).

The radar can be operated from a bridge or suspended to a cable car or a helicopter. In the Skagit River experiment, it was moved across the river thanks to a cable car with a 0.33 ms^{-1} , which means that it took 10 minutes to cross this 200m river.

The measurement errors are not analysed in detail but I can imagine that the following steps represent major sources of uncertainty:

- Determination of the propagation speed in the water,
- Identification of the horizontal and lateral boundaries (like for the ADCP technique, the river banks are detected by the side lobes of the radar creating spurious structure resembling to a bank more than 20 m from the real bank in the case of the Skagit River experiment),
- Uncontrolled movements of the sensor due for instance to the wind (in the case of a cable-car) or to mechanical vibrations can result in geometrical errors related to the antenna pointing and to the 3D locating of the sensor,

The advantage of the GPR method is definitely its ability to monitor the bottom of the river and even better to provide information on the “structure” of the sediments by penetrating apparently several meters in them.

The following drawbacks:

- need to be suspended over the river with associated constrains and errors,
- cost of the instrument,
- complex signal processing,

make the GPR method suited only for occasional explorations (like in the Cowlitz River helicopter configuration). This is somewhat contradictory to the advantage expected from the method in the sense that the monitoring of moving river beds should be continuous in time – at least during flood conditions when the bed movements are the more likely to occur.

LIDAR

A LIDAR (Light Detection and Ranging) is a radar using laser pulses. The propagation of these waves obeys the classical optical laws (reflection, refraction...).

The only example of use of a lidar to monitor river bathymetry is given by the SHOALS project (see Appendix 9). According to the visited web-site, SHOALS (a USACE system) operates on a Bell 212 helicopter or a fixed wing Twin Otter aircraft. Under normal operating conditions – an altitude of 200 meters and a speed of 60 or 120 knots – the system can survey up to 8-32 square kilometers in one hour, collecting depth soundings on a 4 meter horizontal grid. Using a differential or kinematic global positioning system, SHOALS references each depth measurement to a horizontal position accurate to 3 meters and a vertical position accurate to 15 centimeters.

Again, I did not find information about the reliability of the method that obviously depends on i) the lidar capability to detect the bottom of the river and ii) the precision of the aircraft navigation. I did not identify any attempt to use ground based lidars for river depth measurement.

LOCAL REMOTE SENSING OF STAGE

Acoustic and optic devices are commercialised for the measurement of the water levels.

KEY RESEARCH ISSUES

Given my present understanding of the question, the key fundamental research issues related to the non-contact measurement of river discharge using the above techniques are the two following ones.

Waves and roughness structures at the river surface

Both the video and the radar technique make more or less explicit assumptions on the structure of the river surfaces. Apparently very few is known for the moment concerning this structure both in simple geometrical terms – what is the 2D spectrum of river surfaces? – and in hydro-dynamical terms – what are the internal (flow turbulence, surface instabilities...) and the external (natural or helicopter wind) processes that control the river surface topography?

Inversion of the data and assimilation in hydro-dynamics models

All the above mentioned techniques give indirectly access to different state variables (stage, depth, surface velocity) of the 3D river flow. The assessment of the river discharge from the surface velocity measurements poses the twofold classical problem of i) the inversion of the data under a local model representing the measurement principle and the local structure of the medium and ii) the assimilation of the identified variables in a global model representing the river dynamics in order to derive coherent estimations of the flow velocity field or more globally of the river discharge.

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APPENDICES

Appendix 1: HYDRO21 Committee

HYDRO21 Committee (6 USGS experts J.E. Costa, R.T. Cheng, F.P. Haeni, N.B. Melcher, E.M. Thurman, E. Hayes) is a USGS initiative aiming at changing the paradigm of river gauging in the Water Resource Division. USGS runs 7000 gauging stations across the US for a budget of 80 M\$ (i.e. 10% of the total budget of the Division). The gauging methods used at present for discharge measurement rely on mechanical (propellers), chemical (dye) or acoustic (ADCP) principles of measurement. They all necessitate the contact with the river with problems associated to the human involvement (extensive labour, hazardous situations). The goal of the Committee is to define alternative non-contact methods. To my best knowledge this committee is the only organised attempt at present to modernise river gauging methods.

The working method of the Committee is i) to make an inventory of possible technologies and ii) to conduct proof-of-the-concept experiments i.e. to gauge a river with simultaneously a variety of methods including direct classical water velocity and depth measurements. These experiments are limited to a single day of measurement, i.e. a single discharge.

To date, the interim conclusions of the Committee are i) non-contact methods will be the gauging methods in a near future, ii) implementation of these techniques will be incremental and tailored to specific circumstances, iii) all technologies deserve to be further tested and technology firms need up-front support.

Appendix 2: Proof-of-concept experiments to date

The wording proof-of-concept is taken from the HYDRO21 documents in order to designate pilot experiments designed to show the feasibility of non-contact gauging methods.

The list provided below is probably non exhaustive.

One can notice that all these experiments deal only with one river discharge, which always make the results difficult to interpret. Without doubting about the good faith of the authors, it is for instance surprising that the difference between classical and non-contact methods is generally less than the error of a few percent attributed to the classical gauging techniques.

Connecticut River near Haddam (Connecticut), November 9, 1993 (experiment mentioned in Haeni et al., 2000)

A GSSI SIR-10 GPR is operated by USGS to monitor the streambed of the river. Profiles across the river (up to 10m deep and 126 microSiemens/cm water conductivity) using 80-, 100- and 120 MHz antennas 1 m above the river surface.

Mount Saint Helens (Washington), 1996 (Spicer et al., 1997)

The cross-sectional area of four streams were determined using a similar GSSI SIR-10 GPR operated from bridges or cable-ways. The water conductivity ranged from 32 to 262 microSiemens/cm and the river depths up to 5m.

Clear Creek at Oxford (Iowa), October 17, 1997 (see Bradley et al., 2001)

A small 150 km² watershed was gauged with a classical current meter and by the seeded PIV method during low flow conditions – less than 0.2 m³s⁻¹. The video camera was settled on a bridge in order to minimise the optical deformation of the river surface. The water depth along the gauged cross-section and over the modelled river portion was measured manually. A linear hydraulic model (called cinematic) and a minimisation algorithm were used to convert surface velocities into a discharge. The resulting value is remarkably similar to the result the traditional method yields – less than 1% difference.

Skagit River at Mount Vernon (Washington) April 21, 1999 (see Costa et al., 2000)

This 8000 km² basin, was gauged at Mount Vernon (183m wide by 3m deep channel confined between levees) for a moderate discharge of 520m³s⁻¹. The water depth was measured by a Mala Geoscience GPR suspended to the cable-car of the station. A regional value of the radar signal velocity in the river water (conductivity of 70 microSiemens/cm) was taken to convert the travelling times into water depth (0.04 mns⁻¹). The surface velocity was measured using the X-band Doppler radar of the University of Washington mounted on a van (i.e. standing approximately 9m above the river level). Surface velocities in the range of 1-1.5 ms⁻¹ were observed to be fairly constant during the hour the experiment lasted. ADP probes as well as current meters (Price current meter at 0.2 and 0.8) were used to provide comparison values of the discharge. The difference between the non-contact method and the current meter method is less than 0.2%, which is remarkable if one thinks that the current meter method is known to only provide a 2 to 5% accuracy. In other words, this result is surprisingly good and a wider range of measurements must be done in order to provide a statistics.

The conclusion of the Skagit River experiment was that both the surface velocity and the depth were detectable by radar. A single radar with a selectable range of frequencies installed on the river bank should be able to measure both the depth and the surface velocity. The concept was tested on the Shenandoah River

South Fork Shenandoah River at Front Royal, Virginia (8-9 March 2000) (unpublished results to date – indications found on R.T. Cheng website)

The South Fork of the Shenandoah River, a tributary of Potomac River, is in North Virginia. The 8-9 March 2000 the following instruments have been operated :

- The variable frequency mono-static radar of Metratek, Inc., designed to measure both the river depth and the surface velocity.
- Acoustic Doppler Velocity profiles,
- The surface velocities were monitored with ADV, floaters and current meter,
- An ADCP (but the river was too low) and a conventional device (Pygmy current meter at .2 and .8) established the references discharge.

I understand (R. Cheng, personal communication) that the detection of the river bottom from the mono-static radar was hardly possible. This means that only the current detection should be possible from the bank as demonstrated during the Skagit River experiment.

Delta Mendota Canal and American River (5-7 June 2000) (unpublished results to date – indications found on R.T. Cheng website)

Situated in California (Delta Mendota is considered at Tracy and American River flows in the Sacramento county), these watercourses have been instrumented as follows :

- The bi-static radar CODAR RiverSonde™ (one antenna on each side of the stream), designed to measure both the river surface velocity and the river depth (using the hypothetical delayed transmission of the signal reflected from the bottom of the river).
- The surface velocities were monitored with an optical current meter, a video system and a “hand radar gun”,
- An ADCP on boat at fixed positions and conventional devices (Price AA and Pygmy current meters at 0.2 and 0.8) established the references discharge.

The Delta Mendota canal near Tracy (CA) is a trapezoid, concrete lined channel of 25m wide. The current-meter indicated a flow rate about $1500 \text{ m}^3\text{s}^{-1}$, the ADCP gave about $1700 \text{ m}^3\text{s}^{-1}$ (i.e. 13% more) and the measured values given by the RiverSonde™ ($1250 \text{ m}^3\text{s}^{-1}$ i.e. 17% less) and the image method (tennis balls tracked by a video camera - $1400 \text{ m}^3\text{s}^{-1}$ i.e. 7% less) were lower. The flow velocities were of the order of 0.3 to 0.7 ms^{-1} in the canal section.

I understand (R. Barrick, personal communication) that the detection of the river bottom from the bi-static radar was unsuccessful. This experiment thus shows that HF waves and a bi-static configuration work.

Cowlitz River near Kelso (Washington) September 13,2000 and May 1, 2001 (unpublished results to date)

The objective of these experiments was to test if airborne radar can measure the river depth, stage and surface velocity. An helicopter was equipped with i) a GPR pointing at vertical incidence in order to detect both the surface and the bottom of the river and ii) two mono-static Doppler radar pointing at oblique incidence (45°) symmetrically on both sides of the helicopter (actually these radar are bi-static since they have distinct transmitting and receiving antennas in order to be able to measure at short range (few tens of meters). The idea is that the helicopter propeller creates a circular wind field and associated waves. When the helicopter moves across the river, the radar systems will measure the sum of the velocity of the created waves (with opposite signs and equal norm on the two sides of the helicopter) plus the velocity of the river current parallel to the river axis (or at least perpendicular to the helicopter flight line). The addition of the two measured speeds should give access to the river flow if the natural wind is negligible compared to the one generated by the helicopter.

On September 2000, while the traditional flow rate was $130 \text{ m}^3\text{s}^{-1}$, the helicopter device indicated successively 170 and $90 \text{ m}^3\text{s}^{-1}$ in two runs, which represents $\pm 30\%$. The results of May are still not analysed – the preliminary computed surface velocities were correct.



Figure 11: Cowlitz River Experiment on May 1, 2001

The main difficulties encountered with this type of setting are linked to the helicopter flight. In order to operate correctly the radar systems, the helicopter need to fly at very low altitude (different trials from 3 up to 15m) – the unshielded version of the GPR (i.e. with strong back lobes susceptible to reflect on the helicopter structure) apparently works up to 15m, the resolution of the side Doppler radar systems anyway is directly related to the height of the helicopter and prevent to go higher than some tens of meters. At these low altitudes and given the fact the

advancing speed must be kept very low, the helicopter piloting is tricky and very sensitive to the wind. The passes over the river are hardly straight and the helicopter is often poorly aligned with the cross section. In consequence, corrections are to be made to Doppler velocity measurements.

Appendix 3: Conventional river monitoring methods

The monitoring methods operationally in practice today provide a continuous assessment of the river discharge thanks to, on the one hand, a continuous measurement of the river stage and, on the other hand, the use of a stage-discharge relationship. Their measurement principles are simple and well described in many books and technical manuals (see for instance Holmes, 1999). Their accuracy is seldom considered and should be looked at carefully. To our best knowledge, the last paper devoted to this question is by Pelletier in 1988 and it does not really provide a complete assessment of river measurement practices, in particular it does not deal with the rating-curve accuracy.

In this Appendix, the river gauging methods in use operationally are reviewed. I distinguish the measurement of water depth and velocity, the bulk measurement of the discharge using dye methods and the rating-curve question. Nothing precise is said about the infrastructure of river gauging stations in spite of the importance of this point when we have in mind the use of remote sensing methods. The choice of gauging sites is often drastically guided by constrains of staff “accessibility” and of resistance to floods. With remote techniques, these constrains could change substantially.

Water velocity

Electromagnetic and Hydraulic Flow Sensors

The more widespread current-meters directly measure the water velocity using propellers of different types (see Ott or Price Company for instance in Europe and in the US). Some devices rely on the measurement of the electromagnetic field resulting from the particles moving with the fluid around the probe.

Acoustic Doppler Velocimetry

Acoustic Doppler Velocimetry uses an immersed acoustic probe to measure current velocities. Initially designed for oceanography studies of currents from moving ships or from moored devices, this technology started to be applied to large rivers in the late 1980's (Gordon, 1989;



Figure 12: SonTek ADCP probe with converging beams on the bank of the Cowlitz River on the 1st of May 2001.

<http://il.water.usgs.gov/adcp/>). The instruments rely on the Doppler SODAR principle – short acoustic pulses are transmitted in a narrow beam at frequencies of 75 to 1200 kHz and the back-scattered signal is analysed in frequency in order to determine the relative velocity between the instrument and the scattering elements (fine sediments as well as zoo-plankton, which dominant size is roughly 1/6 of the wavelength). They are generally used in down-looking position and are known under various acronyms such as ADCP (Acoustic Doppler Current Profiler) or ADP (Acoustic Doppler Profiler). Recent attempts to use them in side-looking position are reported (see IEEE 6th Working Conference on Current Measurement in San Diego, Ca, March 1999). In order to derive a 3D current and the instrument velocity, four beams are used. They are symmetrically set around the vertical with a 30° tilt angle. Assuming that between the beams the velocity field is uniform – an assumption that becomes strong as the range increases, the 3D current is deduced from its projections on three beams, the fourth one being used either to check the others or to derive the boat movement.

New ADCP probes exist with converging instead of diverging beams (see Figure 12). The advantage is to obtain a point measurement (at the focal point) instead of an average measurement over the area covered by the beams that again enlarges with range. The drawback is conversely to obtain this measurement at a single depth, which obliges to move the sensor vertically in order to get a velocity profile for instance.

The measurement errors are the following:

- i) Calibration of the instrument
- ii) Bias and random errors

The first moment of the Doppler frequency is computed by the auto-covariance method. The theoretical error for a perfect instrument is as follows (Gordon, 1989):

$$\sigma = kF^{-1}D^{-1}N^{-2}$$

where σ is the standard deviation of the measured velocity (in ms^{-1}), k is a constant ($1.6 \cdot 10^5 \text{ m}^2\text{s}^{-2}$), F is the SODAR frequency, D is the resolution in range (m) and N the number of averaged pulses. The accuracy thus varies inversely to these three parameters. It must be kept in mind that higher frequencies have lower exploration ranges (25 m for 12000 kHz). Gordon, 1989 proposed to multiply by 1.5 this theoretical error in order to cope for actual processing imperfections.

The bias is estimated to be less than 1 cm s^{-1} .

- iii) **Blind range and side lobe effects on the river bed**
The time to switch from transmission to reception makes the sensor unable to provide any measurement up to a distance of the order of 1m. This distance must be added to the depth to which the sensor is immersed to determine the depth up to which the sensor is blind at the water surface.
The presence of side lobes makes detection of the river bed corrupts the velocity measurement over the last 15% of the river depth.
- iv) **Moving bottom error**
The bottom speed measured by the sensor is used a) to describe the boat trajectory and b) to correct accordingly the above measured current speeds assuming the river bed is motionless. If the river bed is mobile, this procedure underestimates the high discharges by up to 30% for the Amazon river for instance (see Callede et al., 2000). For this river the drift due to the moving river bed is about 200m as the river width is 2300m. The bottom speed is shown to be proportional to the river discharge above a threshold of $10^5 \text{ m}^3 \text{ s}^{-1}$.
- v) **Pitch and roll effect**
The movements of the platform carrying the sensor modify substantially the geometry of the measurement. These movements are less sensitive in rivers than in the sea.

The main advantage of ADCP is the rapidity of the measurement procedure that needs little mechanical manipulation.

The main drawbacks of ADCP are the following:

- i) The probe must be in the water and thus a moving platform is needed. The most common solution is to use a boat, but then the safety of the embarked personnel becomes a critical issue at least with high waters. Tethered and remotely controlled mini catamarans are currently used by USGS services after preliminary field tests in Indiana and Kentucky. Comparable systems are also proposed by companies like Son Tek (San Diego, CA).
- ii) The probe is blind over the last 15% of the water depth and on the river edges due to reflections of the side lobes of the beam on the river bed. In order to at least measure the size of the blind area along the river shore on both banks, the USGS procedure strongly recommends to use a reliable complementary instrument such as a tag-line or a laser- or optical- range finder. The “eyeball” method is strongly discouraged as introducing unacceptable errors.

Ultrasonic Veloci-Meter (UVM)

UVM stations consist in a continuous transmitter and a receiver installed on the two sides of the river at a significant angle with the river axis. This device allows to measure the mean current across a river reach after appropriate calibration with conventional gauging.

Measurement of Water Levels

Float and pressure devices

The two more widespread river level sensors rely on i) the direct measurement of the water level with a float in a stilling well connected to the river or ii) the measurement of the water pressure at a given depth of the water column which is related to the water level under hydrostatic equilibrium assumption. The most performing pressure probes rely on the continuous production of bubbles in balance with the water pressure at the outlet of an immersed pipe.

The advantage of the float method is the simplicity of the measurement principle and thus its good reliability. The main drawbacks are the installation and maintenance of the well that control the quality of measurement.

The advantage of the pressure method is an easier connection to the river (a simple pipe can replace the well). The main drawbacks are related to the indirect nature of the measurement which can be in error when the pressure distribution in the river differs from hydrostatic equilibrium.

Radar, acoustic and optic measurement of water levels

Using radio frequencies around 25 GHz it is possible to detect locally the water level with a good precision (1 cm with 1 mm resolution according to the specifications of Ott Kalesto Radar Sensor® – a 5 kg/5 mW radar designed for river level measurement). SODAR as well as LIDAR measuring water level are also available on the sensor market and routinely used in hydrometry (in urban drainage system for instance).

The main advantages compared to the conventional level measuring systems seen before is the lightness of the installation which does not require a stilling well or an inlet pipe. This type of remote sensor remains efficient in rivers densely loaded with sediments or debris. It is also easy to move these probes in relation with changes in the water cross section.

Dye dilution methods

The place of these methods is singular in the sense that i) they rely on a chemical principle instead of a physical principle and ii) they measure globally the river discharge.

Injecting a known tracer (which does not need to be a dye like the terminology “Dye dilution” wrongly suggests) in the river and measuring its concentration downstream after a sufficient mixing allows to gauge discharge in rivers where the above methods are impractical (like small streams or mountain tracts). The injection can be massive (“slug injection”) or at constant rate.

The advantages of these methods are that they allow i) to gauge channels with very complex geometry and ii) a tractable analysis of the measurement error contrary to the methods relying on the velocity field identification (C. Lallement, EDF, personal communication).

Their main drawbacks are i) the difficulty to assess how far from the injection point a *sufficient* mixing is obtained and ii) the need for steady conditions in the river (see Noppenev and Kranenburg, 1989).

Rating-curves

The establishment of the stage-discharge relationship is at the heart of all the traditional river monitoring process. They allow to convert the continuous level measurements into discharge values. They probably constitute one of the most powerful diagnosis tool for gauging stations, in the sense that their shape and dispersion is the signature of the hydraulic behaviour of the section, of its stability and of the quality of the discharge measurements done. EDF (the French Electricity Board) developed a software for the analysis of rating curves (C. Lallement, personal communication).

The accuracy of the rating curves is obviously better for “ordinary” discharges for at least two reasons: i) the gauging operations are more frequent for these more frequent discharges and ii) the gauging methods work better for moderate flows than for too low or too high flows. It is worthy

to note that the time taken by traditional gauging manipulations is certainly a determinant factor contributing to the inaccuracy for high flows that are often far from steady conditions.

The time and efforts needed to establish and maintain these curves is certainly one of the most important cost element in the total measurement process. This investment curbs the development and the evolution of river gauging networks. It takes time and efforts to establish the ratio-curves essentially for high waters since it is difficult for the gauging teams to be along the river at the right moment. It takes time and efforts to maintain ratio-curves of unstable rivers since each major flood invalidates the current ratio curve by modifying the flow conditions.

Appendix 4: Instruments and methods for aircraft and satellite remote sensing.

This part of the question of river monitoring certainly deserves a serious research effort. It is shyly considered as capital for the future in a foot note of the NASA Report “Earth Science Enterprise Post-2002 Mission” in the following words:

Measuring River and Lake Stages from Space

A difficulty facing hydrologists and water resource managers world-wide is the unavailability of timely stream-flow discharge data. Existing techniques are fairly primitive point measurements of stage from which discharge is obtained, presuming a stable stage-discharge relationship is available. Many times these observations are not available for political reasons. Nowadays knowledge of stream-flow world-wide is of strategic interest since, like soil moisture, it is a surrogate of agricultural potential, among other things. Ultimately NASA and the US should move to estimate river discharges from space. The technology needs further definition. Questions of resolution, accuracy of necessary targeting of the signal, and how to infer the necessary stage-discharge relationship remain.

In this Appendix, I simply mention the detection methods used from air- or space-crafts that could be or are also used for local remote sensing of rivers. For instance I do not mention the works relying on passive microwave techniques (high resolution radiometers). A recent key reference for this type of work is for instance Vörösmarty et al., 1996.

Altimetry

Radar altimeters measure the distance between the satellite and the earth surface below with an accuracy which tremendously improved over the last decades thanks to the concurrent improvement of the altimeters and of the satellite trajectory monitoring.

Radar altimeters are K-band nadir pointing radar instruments designed for determining the delay of echo from the Earth’s surface with high accuracy (less than 1ns for RA-2, the new generation altimeter of ENVISAT). They also measure the power and the shape of the reflected signal. The signal is modulated in frequency in order to improve the range resolution. They have been embarked on different satellite missions starting in the early 70’s with Skylab, Seasat and Geosat. At present, missions primarily devoted to ocean topography like TOPEX/Poseidon (a NASA/CNES mission, 1992-present) and Jason in the future, coexist with “all surface” missions like ERS-1 and -2, and ENVISAT (2001-).

ERS as well as TOPEX/POSEIDON data have been used for river detection. TOPEX/POSEIDON for instance counts two altimeters: the NASA Radar Altimeter (NRA) operates at 5.3 (C) and 13.6 (K) GHz and the CNES Solid State Altimeter (SSALT) operates at 13.6 (K) GHz – this light prototype only works one tenth of the time sharing the same antenna.

With an orbit altitude of 1334 km and a coverage extending up to 66° of latitude in both hemispheres, this satellite has a repeat period of 10 days and the sampling rate is of 0.1 s representing one measurement each 580 m. The NRA pulse duration is 3ns and the signal is “chirped” i.e. modulated in frequency (this corresponds to 0.47 m according to Birkett, 1998 which for me is strange since I expected less 0.45m). A real time tracking procedure “adjusts” or “locks” in real time a range window to the topography. The fine tracking mode counts 128 range bins, which gives a window width of 60m (960m for the coarse mode).

It is difficult to feature the accuracy and even the exact meaning of such measurements over continental surfaces. The same sources of uncertainty as for ocean measurements exist, namely the satellite trajectory (10 cm accuracy on the altitude or less), the propagation conditions between the satellite and the surface (delays due to electrons in the ionosphere and water molecules in the troposphere) and the surface roughness which determines the shape and strength of the surface echo (the series of range bins is also called waveform which is misleading for a measurement pertaining to ocean). The footprint size depends on the surface roughness as well (200 m to 2 km over the ocean). Given the main objective of the mission, many correction algorithms pertain to ocean wave fields. The accuracy of measurement established for oceans is certainly not true for continental water. When vegetation, ground and water are present in the beam, the radar echoes become more complicated. Flat areas with calm waters and no vegetation will produce echoes narrower than ocean echoes. Vegetated or mountainous areas will produce wider echoes. Continental surfaces are typically 10 to 1000 more reflective than oceans ($\sigma_0=20$ to 40 dB instead of typically 10 dB for oceans), thus the signal strength is supposed to be much more variable. These two factors – more complex waveforms and more fluctuating signal strength, can put in trouble the sensor software which always tries in real time to adjust to the signal strength and to identify the appropriate range window (which basically means to recognise the ground altitude).

The few validations of the measurement of river level apply to large rivers (Amazon being the favourite, Zambezi and Paraguay wetlands) and lakes (Ontario). The rms error reduced from 0.2 to 1.2 m (Koblinsky et al., 1992 with Geosat) to 0.11m (Birkett, 1998 with Topex).

The main advantage of satellite measurements is their availability all over the planet.

The main drawbacks of satellite altimetry are:

- i) The resolution in time and space of these measurements make them suitable for the long waves of the largest rivers of the world. In addition it must be kept in mind that satellite orbit processing takes time (one month for TOPEX) preventing the real time availability of the data.
- ii) The complexity of continental surface returns (the so-called waveforms) puts in trouble the altimeter and the downstream processing system that is “ocean oriented”.

SAR Imagers

SAR systems are “electronically scanning” C-band radar instruments operating at a fix grazing angle. They merely measure the back-scattering cross-section of the surface in different polarisation modes. Over seas the back-scattering cross section is related to the waves and can globally inform about the sea surface state. It can be used in an indirect manner to assess the wind speed near the surface. A precise theory can be established for gravity waves relating the generating wind speed and fetch to the back-scattering cross section under restrictive hypotheses. SAR data have also been used to monitor continental water bodies and in particular flooded areas (Bates et al., 1997, 2000) or braided river, which present the particularity to have a discharge

which depends more on the width of the river than on its level (Nykanen, 1998). The water surfaces being less rough than the surrounding lands, they appear as much darker on SAR images.

SAR Imagers They have been embarked successively on ERS-1 (1991-1999) and -2 (1995-), on RadarSat and on ENVISAT (2001-) in order to “actively” remote sense the Earth surface from polar orbits.

The complexity of these systems comes from their antennas. Synthetic Aperture Radar use the speed of the spacecraft, a very high pulse repetition frequency (PRF over 1/1700 for ERS) and a more or less sophisticated antenna in order to reach, after intensive signal processing, a spatial resolution (30 m for ERS) corresponding to a much bigger classical radar antenna (4km² compared to the 10x1m² of the real antenna). The passive wave-guide slot array antenna of ERS-1 (AMI instrument) will give place to an active phased array antenna on ENVISAT (ASAR instrument), providing distinct transmitting/receiving beams and elevation scanning capability. AMI will also feature i) digital waveform generation able to “chirp” the pulses for range resolution improvement and ii) polarisation diversity.

Trajectory analysis

The analysis of satellite trajectories informs about the global gravimetry field. The fluctuations of this field primarily depends on the internal Earth dynamics but also on the dynamics of the fluid envelopes like the atmosphere, the oceans and the continental waters. Modern satellite positioning systems like DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) reached a precision corresponding to a few centimetres of water over areas of typically 40,000km². This system is thus potentially able to monitor the large wave propagation on large river such as the Amazon River.

The DORIS system comprises radar systems on-board different satellites and an at-ground network of 50 beacons covering the world. DORIS on-board first flew on SPOT-2 (1990) and then on TOPEX-POSEIDON (1992). It will be in the future on SPOT-4 and -5 and on Jason.

The system simply operates frequent measurements of the craft position relative to the tracked beacon and of the craft radial velocity (each 10s) with a very high accuracy (respectively 5cm and 0.4 mms⁻¹). Actually the velocity measured by the embarked receiver according to the Doppler shift is a projection of the craft velocity along the beacon-antenna direction (radial velocity). As the receiver is doubled, it can track two transmissions simultaneously. The accuracy is obtained thanks to the Ultra Stable Oscillators of both the transmitting beacon and the receiver, that keep a precise phase reference with a stability of 5×10^{-13} over 10 to 100 seconds. In order to correct for tropo- and iono-spheric effects, two very different wavelengths are simultaneously used - 2036.25 MHz and 401.25 MHz (VHF). The VHF being strongly affected by the ionosphere. The radial velocities are assimilated in a dynamic model of the satellite trajectory. The resulting accuracy is better than 5cm in altitude.

Appendix 5: Radar altimeters embarked on satellites

	Skylab	GEOS 3	SeaSat	Geosat	ERS-1	TOPEX/Poseidon	ERS-2	Envisat	Jason
Launch	1973	1974	1978	1984	1991	1992	1995	2001	1999
Altitude (km)	435	840	800	800	800	1300	800	800	1300
RF power (W)	2000	2000	2000	20	50	20 / 5	50	50	?
Beam width (deg)	1.5	2.6	1.6	2.1	1.3	1.1	1.3	1.3	?
Footprint (km)	8	3.6	1.7	1.7	1.7	2.2	1.7	1.7	?
Pulse width (ns)	100	12.5	3	3	3	3	3	3	3
Second Frequency (GHz)						5.3/-		3.2	
PRF (Hz)	100	100	1020	1020	1020	4000 /1700	1020	1800	?
Second PRF (Hz)						1220		450	
Tracker Algorithm	2 gate	3 gate	split gate	split gate	SMLE	split SMLE	gate/ SMLE	MFT MLE	/ ?
Noise (cm)	> 100	60	10	4	4	2 / 2	4	2	?

Appendix 6: Visit to USGS Water Resources Division in Menlo Park (California)

JDC received by Dr. R.T. Cheng on December 19, 2000.

USGS is a Federal Scientific Organisation created at the beginning of the 19th century. USGS employs 80000 persons and is divided into different divisions like Geology or Mapping. The Water Resources Division counts 4500 persons and is divided into different Program Groups of 5-6 researchers and technicians. Dr. Cheng is Chief of the BRR Group.

The main focus of the group over the past years is the monitoring of the San Francisco Bay. The Bay includes the deltas of the Sacramento River and the San Joaquin River and is submitted to the influence of coastal currents and tides. The group is involved in the development of ADCP measurement for coastal currents using moving and moored sensors. Such data are assimilated in a numerical model in order to monitor the bay circulation in nearly real time respecting the measured currents.

Since 1998, the Group is involved in the HYDRO21 Committee action about river gauging.

At the moment of the visit the conclusions of Dr. Cheng about non-contact river gauging were:

- i) the concept of non-contact river gauging is proved with different principles (mono and bi-static radar, video imagery),
- ii) the constrains of these different methods are seen – UHF radar (bi-static) needs wind, micro-waves (mono-static) needs turbulence and video imagery needs seeding,
- iii) after having tested the capabilities of ground based sensors we have to look at the possible use of an helicopter platform.

Appendix 7: Visit to CODAR Company in Palo Alto (California)

JDC received by Dr. Donald Barrick (Director) and Laura Pederson (Sale Engineer) on December 21, 2000.

CODAR (Coastal Ocean Dynamics Application Radar) is a small privately owned company specialised in UHF systems for detecting ocean waves. The company is represented in France by Mesuris.

The company basically develops bi-static radar systems at 300 MHz (developed on Unix and MacIntosh workstations) in order to map coastal currents. They experienced in July and August 1999 a bi-static system in the San Francisco Bay. In response to the USGS demand concerning river monitoring, the company recently developed the CODAR RiverSonde™ tested on June 5-8, 2000 during the Delta Mendota Canal and American River experiments.

At the moment of the visit, the technical point of view of Dr. Barrick can be summarised as follows:

- i) UHF detection of river current relies on the detection of long gravity waves (10m) for which the wave dispersion theory is valid. Such waves are almost always present on river surfaces. UHF is preferable to microwave which mixes too many wave types.
- ii) In the bi-static configuration the received power depends uniformly on the square of the cumulated distances from the target to the antennas (compared to mono-static antennas for which the received power depends on the 7th power of the distance from the target to the antenna). The bi-static UHF can use very low radiation power (1 Watt peak power) and has a more even resolution in space compared to microwaves.
- iii) The measured first-order Bragg-scatter signal from the river surface appears to be as expected from the theory while the echoes expected from the river bottom have not been seen so far.

The commercial view point of Dr. Barrick is that UHF allows to design lower cost systems than microwaves. The cost of a RiverSonde™ unit should be less than 5000 US\$ compared to more than 10000 US\$ for a classical microwave mono-static radar.

Appendix 8: Visit to the Applied Physics Laboratory of the University of Washington (Washington)

JDC received by Dr. W. Plant (Principal Research Scientist at APL) on May 4, 2001.

APL is a laboratory of the University of Washington mostly involved in marine science with a longstanding expertise in sound physics.

Dr. Plant team developed wave remote sensors using microwaves first at the Naval Research Laboratory and then at APL. This rather unique expertise has recently been applied to rivers in the framework of different proof of the concept experiments conducted by the HYDRO21 Committee.

At the moment of my visit, the projects of Dr. Plant were essentially i) the improvement of the helicopter side looking Doppler radar that needs to evolve toward a more compact and handy system and ii) the development of sets of smaller microwave sensors that could operate on a more permanent way from bridges.

Appendix 9: Question on river waves to RiverList members

On January 23, 2001 I sent the following message to all the RiverList members, a Web initiative of IAHR:

Dear Listers,

I am interested in problems of remote sensing of river discharge through surface microwave observations.

The active microwave sensing of rivers relies on Bragg back-scattering of electromagnetic waves by river waves at the centimetric to the decimetric scale. The radar detection of river currents thus necessitates a good knowledge of the river wave spectra.

I seek publications or sources of experience dealing with the observation, the theory and the modeling of river waves at the above mentioned wavelengths.

Anticipated thanks.

Only two answers (among five to date) coming both from the Netherlands really addressed the question.

Fred Havinga, a PhD student of the Delft University of Technology (Faculty of Civil Engineering and Geosciences, Hydraulic and Offshore Engineering Section, P.O. Box 5048, 2600 GA Delft, The Netherlands) is involve in a research concerning shear waves during floods. These shear waves are mainly due to the difference in water velocities between the deep main channel and the shallow floodplain. In the river Waal that he is studying, the depth averaged velocity during a flood of 1998 was:

main channel : $u = 1.80$ m/s

flood plain: $u = 0.80$ m/s

These waves are expected to be about 100 meters large. It's however very hard to detect them and photos are very scarce. In the laboratory he found wavelengths of about 4-6 meters (scaling 1:100), which leads to wave lengths of more than 100 meters in rivers. A Dutch technologic institute (TNO) made some photos during high water. In case of no wind waves the difference of velocities in main channel and floodplain can be distinguished, though the vortices (shear waves) not.

Erik Mosselman, a research engineer of Delft Hydraulics (Inland Water Systems WL | Delft Hydraulics, P.O. Box 177, 2600 MH Delft, The Netherlands, Phone: +31 15 285 8569, Fax: +31 15 285 8582, E-mail: erik.mosselman@wldelft.nl, home page: www.wldelft.nl) gave a very rich answer that is reproduced in detail below.

“As far as I know, there is hardly any literature about water surface topography (or spectra) in rivers. Yet many practitioners in the field "read" the water surface to obtain information about navigability, water depth, currents, etc. Thus observation of water surface topography by means of microwave remote sensing must have a great potential. The following inventory of water surface phenomena was made a few years ago by Maarten van der Wal and me:

(1) Roughness of water surface:

(1.1) Wind waves (height, direction and refraction), from which it is possible to derive:
- flow pattern

- bed topography

This is a great success in coastal waters and shallow seas, but application to rivers faces problems, see Mosselman & Wensink (1993).

(1.2) Ship waves and wakes (incl. refraction).

Also these waves may provide information about bed topography.

(1.3) Water surface instability due to high flow velocities.

Presumably these waves are related to the Froude number. They carry information about zones of high flow velocities and information about flow lines.

(2) Coherent structures:

(2.1) Turbulent bowls (upwelling is observed as a more or less circular area with a smooth water surface). These provide information about local upwelling and downwelling. The spatial arrangement of zones of upwelling and downwelling may provide information about the size of bedforms.

(2.2) Mixing interfaces, providing information about mixing and about flow directions.

(2.3) Eddies, providing information about flow velocity gradients (indicating, for instance, submerged channel margins).

(2.4) Stripes: stripes observed on radar images were found to comply with flow lines.

(3) Floating debris (driftwood, water hyacinths, banana trees):

They may have a distinct reflection of microwaves, and their patterns may provide information on flow velocities, flow lines and mixing interfaces.

We have been trying to carry out research on this topic ourselves, but we have not managed to get it launched. That is why we are pleased that somebody else is taking it up. Some of our ideas included:

- to make video recordings of the water surface from a survey boat on a day when a radar satellite (like ERS) observed the same area.

- to carry out flume experiments of various flow conditions, with a radar sensor mounted above the flume (in particular in view of the water surface instability due to high flow velocities).

It may also be useful to know that EGIS has several radar satellite images of the large rivers in Bangladesh: the Jamuna (= Brahmaputra) and the Ganges. Address:

EGIS

House 49, Road 27, Banani

Dhaka

Bangladesh

Tel +880 2 881570, +880 2 881571, +880 2 881572

Fax +880 2 883128

Director: R. Koudstaal

E-mail address of director: rkdstaal@cegisbd.com

Your research has our greatest interest, and we would highly appreciate if you could keep us informed. Good luck with it !

Reference: Mosselman, E. & G.J. Wensink (1993), River bathymetry observation with radar remote sensing. Proceedings International Workshop on Morphological Behaviour of the Major Rivers in Bangladesh, Government of Bangladesh and Commission of the European Communities, Dhaka, November 1993, pp.243-250."

Appendix 10 : Some research teams and projects

Europe :

HR Wallingford (UK) <http://www.hrwallingford.co.uk/>
Acoustic Doppler Velocimetry (using Nortek instruments)

University of Bristol (UK) <http://www.cen.bris.ac.uk/welcome.html>
School of Geographical Sciences and Water and Environmental Management Research Centre
Prof. P. Bates' team is involved in flood plain inundation. Use of LIDAR data for characterising topography and vegetation and of RADARSAT SAR imagery for inundation extent (Bates et al., 2000).

Northern America :

University of Iowa, Institute of Hydraulics Research, Iowa City (Iowa)
<http://www.iuhr.uiowa.edu/>

IIHR is a research laboratory in fluid mechanics and environmental sciences. They initially developed PIV tools for in-door experiments in fluids and are presently extending their application to rivers.

University of Washington, Applied Meteorology Laboratory – Seattle (Washington)
<http://www.apl.washington.edu/>

APL is involved in remote sensing of the ocean. They show interest for river discharge measurement using mono-static radar systems and participated to different USGS proof-of-concept experiments.

USACE Coastal and Hydraulics Laboratory – Vicksburg (Mississippi) <http://chl.wes.army.mil/>
This laboratory of the Waterways Experiment Station (research facility of the US ACE – <http://www.wes.army.mil/>) develops a project on measuring hydrodynamics and sedimentation distribution at Old River Control Complex, on the Mississippi River. An ADCP probe and a Price current-meter have been simultaneously used to monitor velocity fields in the river (<http://chl.wes.army.mil/research/field/oldriver/>).

US Army Corps of Engineers – Mobile District (Alabama) <http://shoals.sam.usace.army.mil/>
The Mobile District operates the Scanning Hydrographic Operational Airborne Lidar Survey system which performs hydrometric and topographic surveys. SHOALS operates on a Bell 212 helicopter or a fixed wing Twin Otter plane. Under normal operating conditions – an altitude of 200 meters and a speed of 60 or 120 knots – the system can survey up to 8-32 square kilometres in one hour, collecting depth soundings on a 4 meter horizontal grid. Using a differential or kinematic global positioning system, SHOALS references each depth measurement to a horizontal position accurate to 3 meters and a vertical position accurate to 15 centimetres. SHOALS uses kinematic GPS to produce topographic maps. “Recently”, SHOALS surveyed an upland dredge disposal site located in Mobile, AL. SHOALS is the only airborne lidar survey system in the world providing both hydrographic and topographic surveys.

USGS Water Resource Division (Menlo Park, California) <http://sfports.wr.usgs.gov/>
R.T. Cheng's Group is involved in coastal science and since 1999 it is one of the components of the HYDRO21 committee.

USGS Water Resources of Illinois (Urbana, Illinois) <http://il.water.usgs.gov/>

The USGS currently uses Acoustic Doppler Current Profiler instruments to monitor rivers, estuaries and coastal waters. At present more than 80 instruments are used. Illinois Water Resources Division is active in co-ordinating ADCP use and projects throughout USGS Districts (<http://il.water.usgs.gov/adcp/>). Training courses as well as technical workshops are regularly organised to improve the use of ADCP technology for stream-flow measurement.

Joint Airborne Lidar Bathymetry Technical Center of Expertise

<http://www.sam.usace.army.mil/op/shoals/pages/jalbtex.htm>

This project in LIDAR bathymetry is a joint project of the **US Army Corps of Engineers** (Mobile and Vicksburg Districts), of the **US Naval Meteorology and Oceanography Command** and of the **Naval Oceanographic Office**. It is essentially build around the SHOALS system.

Appendix 11 : Some manufacturers and engineering companies

Europe :

Nortek AS <http://www.nortek-as.com/>

Norwegian Company building **ADCP** (AWAC – acoustic wave and current profiler, Aquadopp Profiler – IIIrd generation profiler for shallow water) and related software.

Ott – Hydrometrie <http://www.ott-hydrometry.de/>

German company specialised in hydrometry. They provide a large range of **classical gauging products** including water level meters (bubble sensors, radar) and current meters (hydraulic, electromagnetic).

Northern America :

CODAR Ocean Sensors <http://www.codaros.com/>

American company specialised in **HF Radar** measurement of sea surface currents – the SeaSonde® System. A set of mast antennas (bi-static radar) and an appropriate signal processing allows a measurement of radial current velocities at a resolution of typically 1km up to a 50 km range. They design for Offshore applications a reduced size comparable system (range of 2km).

Optech <http://www.optech.on.ca/>

Optech is a Canadian company specialised in electro-optic instrumentation – **LIDAR** essentially, for application in atmospheric monitoring, terrestrial surveying, measurement control and hydrographic surveying. The company is associated to the SHOALS project.

RD Instruments – Acoustic Doppler Solutions (San Diego, CA and La Gaudie, Alpes Maritimes, France)

American company specialised in **ADCP** probes for applications to oceans, lakes and rivers. The central and most diffused instrument for shallow waters at frequencies from 300 to 1200 kHz is the Workhorse Sentinel <http://www.rdinstruments.com/sen.html>.

Son Tek (San Diego, CA and representatives in many European Countries) <http://www.sontek.com/>

American company specialised in **sonic probes** for applications to oceans, lakes and rivers. The company proposes a wide range of instrument types : acoustic Doppler current profilers (ADP, ADCP), velocimeters (ADV), water velocity sensors (Argonaut current meters), Doppler velocity logs (DVL). It developed recently a Mini ADP Surveyor Catamaran.

Appendix 12: USGS Documentation on river discharge measurement

(<http://water.usgs.gov/osw/pubs/twri.html>).

General field and office procedures for indirect measurements, by M.A. Benson and Tate Dalrymple, 1967, 30 pages.

Measurement of peak discharge by the slope-area method, by Tate Dalrymple and M.A. Benson, 1967, 12 pages. ERRATA SHEET

Measurement of peak discharge at culverts by indirect methods, by G.L. Bodhai, 1968, 60 pages. ERRATA SHEET

Measurement of peak discharge at width contractions by indirect methods, by H.S. Matthai, 1967, 44 pages. ERRATA SHEET

Measurement of peak discharge at dams by indirect methods by Harry Hulsing, 1967, 29 pages. ERRATA SHEET

General procedure for gaging streams, by R.W. Carter and Jacob Davidian, 1968, 13 pages.

Stage measurements at gaging stations, by T.J. Buchanan and W.P. Somers, 1968, 28 pages.

Discharge measurements at gaging stations, by T.J. Buchanan and W.P. Somers, 1969, 65 pages.

Measurement of time of travel and dispersion in streams by dye tracing, by E.F. Hubbard, F.A. Kilpatrick, L.A. Martens, and J.F. Wilson, Jr., 1981, 44 pages.

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Measurement of discharge by moving boat method, by G.F. Smoot and C.E. Novak, 1969, 22 pages.

Fluorometric procedures for dye tracing, Revised, by J.F. Wilson, Jr., E.D. Cobb, and F.A. Kilpatrick, 1986, 34 pages.

Computation of continuous records of stream-flow, by E.J. Kennedy, 1983, 53 pages.

Use of flumes in measuring discharge, by F.A. Kilpatrick, and V.R. Schneider, 1983, 46 pages. ERRATA SHEET

Computation of water-surface profiles in open channels, by Jacob Davidian, 1984, 48 pages.

Measurement of discharge using tracers, by F.A. Kilpatrick and E.D. Cobb, 1985, 52 pages.

Acoustic velocity meter systems, by Antonius Laenen, 1985, 38 pages.

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Computation of fluvial-sediment discharge, by George Porterfield, 1972, 66 pages.

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Appendix 13: Illinois USGS Documentation on ADCP

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Appendix 14 : General considerations about wind waves

In very general terms (see for instance Phillips, 1957 for a detailed analysis), the wind applies to the water surface a field of pressure which is fluctuating in time and space. These pressure fluctuations result from the turbulence of the wind flow over the surface. They depend on the wind direction (anisotropy). They have different scales, corresponding to the various sizes of the turbulent structures. At a given moment a wind turbulence scale in one direction is able to enter in resonance with a water waves of equal wavelengths advancing or recessing in the same direction. A wind turbulence scale will thus amplify a family of waves of comparable scale. In the wind direction, the activated wavelengths are longer than at an angle. A limiting angle exists over which the wind effect disappears. The wind velocity and the fetch (i.e. the length on which the wind field is applied) determines the maximum scale up to which wave families are solicited. In front of this growth mechanism different dissipation mechanisms contribute to modify the water wave spectrum. Viscosity transfers energy from small water waves to larger ones and breaking dissipates the energy of large waves. As a global result, wave fields remain a complex combination of different families of waves even if under steady wind conditions some equilibrium conditions should theoretically been reached with a dominant family of waves. At the initial stage of development of wind generated waves, very small waves are generated after only a few seconds of wind over surfaces that can be small too. These waves span over the range of capillary waves (<1.73cm) and gravity waves (>1.73cm) – this distinction marking the respective importance of surface tension forces that are significant in capillary waves and almost negligible respect to gravity forces in gravity waves. In terms of shape, capillary waves exhibit more pronounced height to wavelength ratios (a maximum ratio of 3 to 4 compared to 1 to 7 for gravity waves). The phase velocity of waves is known to increase with the wavelength for gravity waves according to:

$V_g = \sqrt{g\Lambda / 2\pi}$ where Λ is the water wavelength, and it is known to increase with decreasing wavelengths for capillary waves according to:

$V_c = \sqrt{\tau 2\pi / \rho\Lambda}$ where τ is the surface tension and ρ the water density.