THE APPLICATION OF DOPPLER VELOCITY METERS IN THE MEASUREMENT OF OPEN CHANNEL DISCHARGES

UK Günther • A Rooseboom

WRC Report No 980/5/00

Water Research Commission

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by

U K Günther & A Rooseboom

SIGMA BETA
CONSULTING CIVIL ENGINEERS

WRC Report No. 980/5/00
ISBN: 1 86845 667 6

February 2002

PREFACE

This report is one of five which were produced under Water Research Commission contract No. 980, and which are listed below.

The first three reports contain results which may be regarded as conclusive, whilst the last two contain the results of exploratory research which may serve as the basis of further research.

WRC Report No.980/1/00
The rating of compound sharp-crested weirs under modular and non-modular flow conditions.

WRC Report No. 980/2/00
The rating of sluicing flumes in combination with sharp-crested and Crump weirs under modular and non-modular flow conditions.

WRC Report No.980/3/00
Discharge measurements in terms of pressure differences at bridge piers.

WRC Report No.980/4/00
Flow gauging in rivers by means of natural controls.

WRC Report No.980/5/00
The application of Doppler velocity meters in the measurement of open channel discharges.

EXECUTIVE SUMMARY

This report deals with the use of Doppler meters to measure flow velocities and hence discharges in streams. The Doppler meter measures the shift in frequency of an acoustic wave, which it emits and then becomes reflected by a moving particle. The reading is converted into a velocity by dividing the shifted frequency by a calibration constant. The particles that reflect the signal need to follow the flow sufficiently closely so that their velocity may be assumed equal to the flow velocity.

A previous study on the use of the Doppler meter at a Crump weir (Du Toit and Venter, 1999) indicated that velocities measured with a Doppler meter showed a distinct relationship with recorded water levels. However, the wide scatter of the observed frequencies in this study, necessitated further tests on the use of the Doppler meter at measuring structures as well as calibration tests on the instrument in the hydraulic laboratory of the University of Stellenbosch.

The main objective of this investigation was to establish the relationship between measured Doppler velocities at a Crump weir and the approach velocities in the stream. The instrument was to be tested in both modular and non-modular flow ranges. In addition, the instrument had to be calibrated in the hydraulic laboratory under varying flow conditions, such as very low flow velocities and different sediment concentrations. The placement of the probe at different depths of the flow was also investigated to comment on the accuracy of the Doppler readings at these depths. The results of these tests should serve as guidelines for any additional tests required for use of this instrument in open channel discharge measurements.

The Doppler meter used for this study was supplied and manufactured in Stellenbosch by **Flotron**, and is being marketed as **DFM-P-067**. It was calibrated in the laboratory in a channel with limited width and hence non-two-dimensional flow conditions. Conclusions were drawn on the calibration

constant that was established. The calibration of the instrument requires the division of the cross-sectional flow area into a number of sub-divisions over which the flow was integrated. The calibration constant of **1460** established in this study differs by approximately 6 percent from the theoretical constant value of **1375**.

The sensitivity of the Doppler meter to different sediment concentrations was also investigated. For the instrument to read a shifted frequency, it is essential that suspended particles that follow the water movement sufficiently closely are present in the stream. It was observed that readings of the instrument in "sediment-free" water differed only by 3.6% from the readings taken in water containing sediments. The instrument was thus not very sensitive to different sediment concentrations. It was also found that the angle at which the probe was placed in the water had no effect on the accuracy of the observed Doppler velocity. It was furthermore found that the Doppler meter worked reliably at all depths, including levels very close to the channel floor and levels just below the water surface. One drawback of the apparatus was the minimum velocity that it can measure accurately. This minimum velocity of 0.046 m/s does not compare well with that for other commercially available Doppler meters. The Argonaut-Acoustic Doppler meter for example can measure velocities as low as 0.0001m/s, meaning that the DFM-P-067 measures a minimum velocity 460 times swifter than the minimum velocity of the Argonaut-Acoustic Doppler meter.

After the Doppler meter had been calibrated, it was tested at a Crump weir in the laboratory to determine the relationship between the Doppler velocities, measured at the weir's crest, and the velocities in the approach channel. These tests were performed for both modular and non-modular flow conditions.

The report concludes that, within the flow range in which the instrument was tested, there is a linear relationship between the two velocities mentioned. It is likely that the results obtained in the modular flow range can be used to extrapolate for high flows, especially for submergence ratios less than 0.93.

The wide scatter of results obtained in the previous study was due to the readings not being averaged. The Doppler meter does not measure a point velocity but an average velocity within the acoustic field that it emits. This acoustic field is very small and depends on the geometry of the probe.

Finally it is recommended that the linear relationship in the non-modular flow range be investigated further in a larger model, where the submergence ratio can be better controlled. The Doppler meter should in future also be calibrated in a wide channel in which two-dimensional flow conditions are approached and these results should be compared to the results obtained in this study. Every instrument is expected to have its own calibration constant, and depending on its application, it can either be calibrated at a weir or in the laboratory. The calibration of the instrument at a Crump weir should allow for a wider range of flows, and also very low flow velocities.

At the end of this report guidelines were drawn up that are based on the results and conclusions obtained in this investigation. They may serve as an aid for measurements that could be carried out with this instrument in open channels.

Acknowledgements

The authors wish to thank the following members of the Steering Committee for their appreciated contributions to the project:

Mr D S van der Merwe (Chairman)

Mr H Maaren

Prof A H M Görgens

Prof G G S Pegram

Dr M J Shand

Mr S van Biljon

Mr J van Heerden

Dr P Wessels

Miss U Wium (Secretary)

A special word of thanks is also due to Mr K Vosloo of Flotron for providing the instrument used in this project.

CONTENTS

LIST OF SYMBOLS

c	ultrasonic propagation velocity of sound
$f_{d/D}$	Doppler shift frequency
f_{Di}	Doppler frequency read for block Nr (i)
$f_{S/R}$	frequency the source (Doppler meter) emits [S] and receives [R]
h	water level relative to crest level of Crump weir
h_0	water depth at gauge point (flume) under modular flow conditions
h_v	water depth at gauge point (flume) under non-modular flow conditions
H_{wf}	energy level in approach channel of Crump weir for modular flow
L	width of Crump weir in laboratory
K	Doppler constant to convert Doppler shift frequency into velocity
Q_{wf}	discharge over Crump weir for modular flow
Q_{ws}	discharge over Crump weir for non-modular flow
t	tail water level relative to weir invert
v_{app}	approach velocity in the approach channel upstream of weir
v_{Dopp}	velocity measured with Doppler meter at Crump crest level
$v_{R/S}$	velocity of received [R] and emitted [S] wave
v_{wf}	approach velocity at Crump weir under modular flow conditions
v_W	approach velocity as calculated from the discharge over the weir (DWA)
v	Doppler velocity relative to measured water level (Du Toit, Venter, 1999)
x	horizontal dimension in the 600mm wide channel
y	vertical distance in the 600mm wide channel / flow depth in approach channel of Crump weir

$\lambda_{R/S}$	wavelength of received [R] and emitted [S] wave

LIST OF ACRONYMS

DWAF	Department of Water Affairs and Forestry
WRC	Water Research Commission

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1. INTRODUCTION

Most parts of South Africa experience relatively low rainfall when compared to other regions world-wide. In fact, South Africa is rated as one of the twenty most water stressed countries in the world, receiving an annual average rainfall of less than 500 mm compared to the global average of 860 mm (Bhagwan and McKenzie, 1999). This, together with the high annual evaporation rates in the region, result in a low unit runoff for the country as a whole, 44 mm/annum compared to the global average of 330 mm/annum. Not only is the rainfall low but also unevenly distributed throughout the country, with more than 65% of the country receiving less than 500 mm per annum. Most regions also experience a pronounced wet and dry season making the runoff extremely variable from season to season and from rain event to rain event.

This, together with the fact that South Africa's water demand is growing due to a rising population, calls for the accurate estimation of all the available water resources. The South African National Water Act of 1998 also stipulates that a minimum quantity of water should be retained in an aquatic system to sustain the aquatic environment. It is therefore of utmost importance to be able to measure the flow at gauging stations as accurately as possible for accurate estimation of all the water resources. This is necessary to allocate water to different sectors of the economy and at the same time to sustain our aquatic environment.

In South Africa the network of flow measuring stations consists mainly of compound weirs, in addition to a number of measurements being taken at dam spillways and a number of sites where the velocity area method is being applied (Rooseboom and Lotriet, 1995). The first weirs to measure flow were built in the former Transvaal in 1904 (Wessels, 1996). Up to the mid 70's the majority of weirs constructed were of the sharp-crested type. The first Crump weir was built in the Great Fish River and started to operate in 1977 (Wessels, 1996). By 1995 approximately 25 % of gauging weirs operational in the country were compound Crump weirs.

The measurement of flows at both compound and sharp-crested weirs has undergone extensive research, funded by the Water Research Commission (WRC) in the past. Various methods were proposed to measure flows more accurately. All of these projects involved the principle of measuring the stage some distance upstream of the crest of the weir and hence calibrating the weirs by the appropriate formulae developed for the specific weirs and/or to make corrections to the discharge coefficients. The method to measure flow being investigated here is relatively new. It makes use of a Doppler velocity meter, also extensively used in medicine to measure the flow of blood in arteries (Atkinson and Woodcock, 1982). Acoustic or Doppler meters offer a new technology in the field of hydraulics, which is well suited to difficult flow measuring sites where traditional gauging structures (weirs and flumes) are not practical. For example, sites with backwater problems caused by downstream gates or tides (Vermeyen, 1999).

The Doppler velocity meter was to be used to establish a possible relationship between the flow velocity over the Crump crest and the velocity in the approach channel. This was also to be investigated in the non-modular flow range. It was anticipated that this method would yield satisfactory results for the accurate measurement of non-modular or drowned flows. In addition to this, the accuracy of the Doppler meter was tested for alternative applications and these results should serve as guidelines for the application of this apparatus.

2 AIMS AND OBJECTIVES OF THIS STUDY

The Doppler meter studies were initiated to establish whether Doppler meters could be used to measure discharges at gauging weirs, which become submerged. As the Doppler meter can also be used to measure local velocities in natural streams as well as canals, additional tests were performed to test its applicability and accuracy under varying flow conditions. The opportunity was also used to do comparative tests when the results of stream gauging on other WRC projects by means of an electronic flow meter seemed to be unreliable.

In 1999 the study of the use of a locally manufactured Doppler meter was conducted at a Crump weir in the Jonkershoek River (du Toit, Venter, 1999). The results proved to be promising and a relationship between the discharge over the structure and the water depth was established with the aid of the velocities measured by the Doppler meter. One drawback of the study was the wide scatter of the Doppler frequencies that were observed for the same flow depths and hence flow rates.

An aim of this project was to find reasons for the scatter in the observed values of the previous study. This was to be done by testing the instrument in the laboratory against different variables, such as the sediment concentration in the water and the angle of the probe relative to the horizontal. In addition to these tests, the performance of the apparatus was also tested under varying flow conditions, such as the minimum velocity it could measure accurately in the laboratory.

The frequency measured with a Doppler meter is converted into a velocity reading by dividing the measured frequency by a constant. The theoretical derivation of the constant followed and the apparatus was then calibrated in the laboratory. The Doppler meter used for the previous study had not been calibrated and a constant of value **1100** was used. This constant is used by the manufacturer of the instrument for measuring velocities in pipes. Conclusions on the calibration results were then drawn from the results obtained in this study.

Following on calibration tests in the laboratory, the main objective of this study was to test the Doppler meter on a Crump weir in the laboratory. It was anticipated that a continuous relationship over all flow depths could be obtained to relate the measured Doppler velocity at Crump crest level to the velocity in the approach channel. These tests were to be performed first in the modular flow range of the weir and then extended to include tests in the non-modular flow range. The sensitivity of the flow meter to the curved flow lines that prevail in the region of the crest, for both modular and non-modular flow conditions, could then be established.

Finally conclusions and recommendations were drawn on the applicability of the instrument, especially when used to measure the crest velocity at a Crump weir under modular and non-modular flow conditions. The results of all these tests were then used to provide guidelines for future work to be carried out with this instrument.

3 CRUMP WEIRS AND THEIR APPLICATION IN SOUTH AFRICAN RIVERS

3.1 INTRODUCTION

This chapter on the Crump weir, has been included as it is envisaged that the technique of using the Doppler meter would ultimately simplify drowned discharge measurements at weirs. An understanding of the present technique is necessary for any new development and simplifications in the discharge measurements at both sharp-crested and Crump weirs.

This study however only deals with Crump weirs as the first part of this research had been carried out on the Jonkershoek River near Stellenbosch which is equipped with a Crump weir. The tests carried out in the laboratory were also performed on the Crump weir in combination with the Doppler meter.

3.2 HISTORY OF THE CRUMP WEIR

In 1952 E.S. Crump published a paper in which he proposed a new type of gauging weir (Ackers et al, 1978). This new structure had a triangular profile with upstream and downstream slopes of 1:2 and 1:5 respectively. The development of this type of weir was a significant step forward in the field of flow measurement due to its constant discharge coefficient and high modular flow limit.

The upstream slope of 1:2 was chosen as the steepest slope that would most effectively prevent sediment built-up in the vicinity of the crest and thus not alter the upstream pool depth significantly (Ackers et al, 1978). This is achieved by reducing the dead water region that occurs upstream of broad-crested weirs. The downstream slope of 1:5 in turn was chosen so that a stable hydraulic jump would be formed. In the modular flow range this hydraulic jump would traverse the downstream face depending on the discharge and/or the tailwater level and thus satisfactory energy dissipation would occur. The modular limit is also a function of the downstream slope and the smaller the slope, the higher the modular limit. The 1:5 slope was chosen so as to keep construction costs at a minimum. Another attribute of these weirs is the ease with which they are constructed.

Sharp-crested weirs have been used to gauge flows in South African rivers since the turn of the previous century (1904). As mentioned earlier, by 1995 about one quarter of all weirs in South Africa consisted of Crump weirs and the first Crump weir became operational in 1977 (Wessels, 1996). This type of weir together with the sharp-crested weir make up the majority of flow gauging stations being used in this country.

The Crump weir became very popular because of its robustness and its ease of construction. In South Africa minor floods are often experienced after rain storms and after a long dry season a lot of debris and big tree stumps tend to be transported down rivers. Any sharp edges on a weir structure are therefore at risk of being damaged by these objects. The Crump weir with its relatively smooth geometry, especially when compared to the sharp-crested weir, offers a better option. This type of weir is also less sensitive to non-modular flow conditions than the sharp-crested weir.

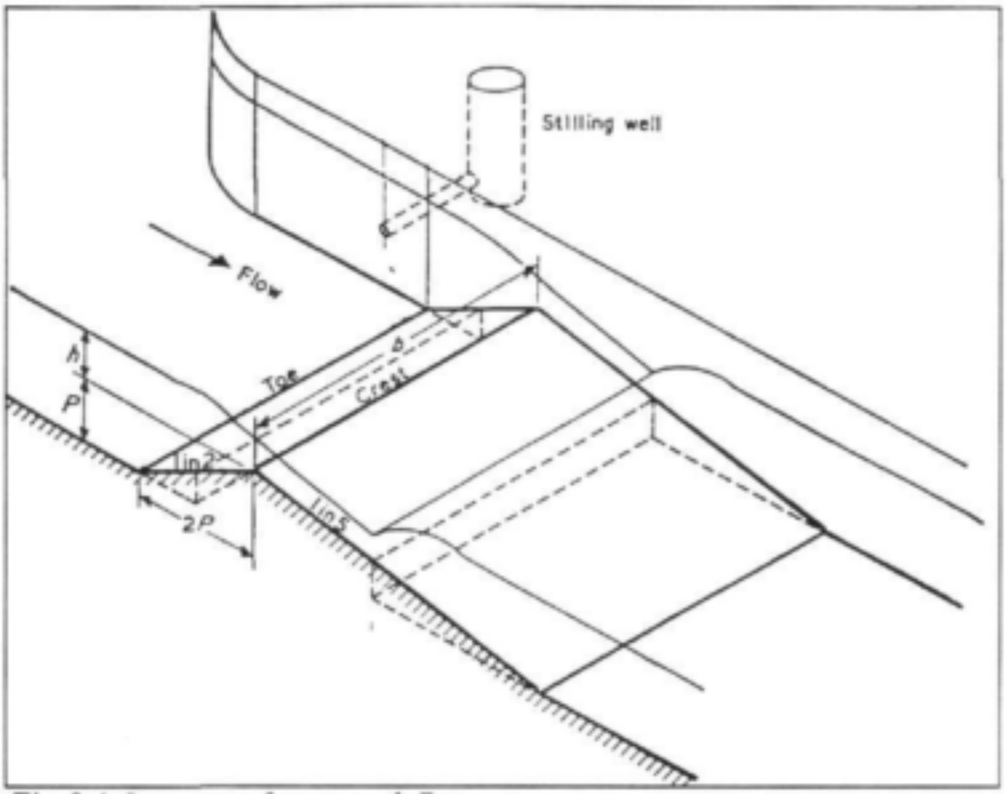


Fig.3.1 *Lay-out of a typical Crump weir.*

3.3 COMPOUND CRUMP WEIRS

By definition a compound weir is a weir in which the crest level is varied in steps across a river section. Compound weirs are used to increase the range of flow conditions that can be accurately gauged by these structures. Low flows only pass over the lowest section of the weir and as the flow increases, the flow progressively occurs over more crests. As in the case of the V-notch weir, this ensures that flows can be measured relatively accurately over a wide range of discharges without an excessive increase of the water level upstream of the weir for higher flows. By ensuring that the water level will be sufficiently high upstream to be measured accurately, the accuracy of low flow measurements is increased. In South Africa, where we experience great variations in the flow of most rivers due to wet and dry cycles, this is obviously the preferred option for a weir type and more than 95 % of all sharp-crested and Crump weirs in South Africa are of this type (Rossouw et al, 1995).

The British Standards (BSI, 1984), require dividing walls between the different crests of a compound weir. These dividing walls serve to separate the flow over each crest thereby ensuring uniform flow condition upstream of each crest. The water level should also be measured at a distance 4 times the design head upstream of each crest for the sharp-crested weir and 2 times the design head upstream of the crests for the Crump weir. For practical reasons however most compound weirs in South Africa lack dividing walls. As mentioned elsewhere, the rivers in this region carry a high proportion of debris and this gets entangled in front of the dividing walls thereby hindering free flow through the sections of the compound structure. This has an adverse effect on accurate flow measurement. Most structures also measure the head only upstream of the lowest crest and for both weir types this is done at a distance 4 times the design head upstream of the crest. The BSI specifies that weirs lacking dividing walls should be calibrated in-situ. An extensive study to overcome the lack of dividing walls has been carried out in South Africa (Rossouw, et al, 1995) and appropriate discharge coefficients for use without dividing walls were proposed. The compound Crump weir that was used in the previous study with the Doppler meter also lacked dividing walls.

3.4 WATER LEVEL RECORDING

In order to obtain continuous records of river stage, the Department of Water Affairs and Forestry, (DWAF), equips its gauging stations with autographic water level recorders (du Toit and Venter, 1999). Such a recorder consists of a drum with graph paper wrapped around. The drum is driven by a clock mechanism and rotates at either one revolution per week or one revolution per month. A float, with a counterweight system, follows the rise or fall of the water within a stilling well and this in turn is recorded on the graph paper with a pen. Records are collected weekly or monthly. In South Africa the inlet to the stilling well is located at a distance of 4 H_{max} upstream of the crest of the weir. As mentioned earlier, this is done for both sharp-crested and Crump weirs and is usually done upstream of the lowest crest of a compound structure. This is also the case for the compound Crump weir in the Jonkershoek River.

3.5 EXISTING FORMULAE USED FOR THE CRUMP WEIR

3.5.1 MODULAR FLOW CONDITIONS

The purpose at most gauging structures in South Africa is to develop a relationship between the overflow depth (h) and the discharge (Q) by calibrating the in situ structure with the developed theory. Presently only the overflow depth is measured and converted into discharge.

Every discharge formula, including those for compound structures, is based on the theory of a single notch weir. For the Crump weir the discharge formula is derived from energy principles and the assumptions of a broad-crested weir. It can be shown, (Rossouw et al, 1995) that the discharge over a Crump weir is given by

$$Q = C_D \frac{2}{3} L \sqrt{\frac{2}{3} g} H^{\frac{3}{2}} \qquad \text{.............................3.1}$$

This is identical to the equation

$$Q = \left(\frac{2}{3}\right)^{\frac{3}{2}} C_D C_V \sqrt{g} L h^{\frac{3}{2}} \qquad \text{.............................3.2}$$

given in the British Standards [BSI(1984)]

where

Q is the discharge over the weir in m^3/s

C_D is the discharge coefficient to compensate for energy losses (non-dimensional)

C_V is the coefficient allowing for the effect of the approach velocity, (non-dimensional)

H is the total or energy head, in metres (m)

L is the width of the weir, in metres (m)

g is the gravitational acceleration, in metres per second squared (m/s^2)

h is the measured head, i.e. the water level upstream of the weir, in metres (m).

Limitations on the applicability of this formula are also given in the BSI(1984) and are as follows:

i. $h > 0.03$ m for a crest section of smooth metal or equivalent
ii. $h > 0.06$ m for a crest section of fine concrete or equivalent
iii. $P > 0.06$ m (where P is the upstream pool depth)
iv. $L > 0.3$ m
v. $h/P < 3.5$
vi. $L/h > 2.0$

The discharge coefficient in the formula has to compensate for small energy losses between adjacent sections over the weir. Since the flow lines over a Crump weir are not horizontal and parallel but convex, the pressures at

measuring points thus become lower than hydrostatic. This has the effect of increasing the discharge coefficient to values larger than unity.
The discharge coefficient is given by

$$C_D = 1.163\left(1 - \frac{0.0003}{h}\right)^{\frac{3}{2}} \quad \text{.............................3.3}$$

To calculate the discharge over a Crump weir, a first approximation of the energy head will be the water level or head as measured relative to the crest level. An iteration or loop calculation of the energy level is then applied until the discharge, as calculated with equation 3.1, remains constant.

3.5.2 NON-MODULAR FLOW CONDITIONS

The threshold, when flow changes from modular to non-modular flow, is known as the modular limit. This limit is defined as being the submergence ratio H_2/H_1 which produces a 1-percentage reduction from the equivalent modular flow. Here subscript 2 stands for the downstream end of the weir and subscript 1 for the upstream end of the weir. The ratio of these two heights at the modular limit is equal to 0.75 (Ackers et al, 1978). When this point is reached non-modular or drowned flow conditions are encountered. In the non-modular flow range the discharge is dependent upon both the upstream and the downstream water levels, i.e. the tailwater starts effecting the discharge over the weir. This has the result of reducing the discharge that would occur for the same upstream water level in the modular flow range. The equation for the modular flow range thus has to be adapted by a factor that takes the downstream water level into account.

Ackers et al quote this reduction factor to be

$$f = 1.035\left[0.817 - \left(\frac{H_2}{H_1}\right)^4\right]^{0.0647} \qquad \text{......} 3.4$$

for $0.75 \leq \dfrac{H_2}{H_1} \leq 0.93$

and

$$f = 8.686 - 8.403\frac{H_2}{H_1} \qquad \text{......} 3.5$$

for $0.93 < \dfrac{H_2}{H_1} \leq 0.985$

where subscript 1 refers to the upstream side of the weir and subscript 2 to the downstream side.

This correction factor is the same as in BSI(1984) but there the factor is given as the product of C_V*f. The British Standards also specify that crest tappings should be provided on the downstream side of the crest of a Crump weir to measure the head at that section for non-modular flow conditions. The formula for the reduction factor is given in terms of the pressure in the separation pocket behind the crest, expressed as the head of the fluid relative to the crest, and the upstream water level. The values in the formula above thus change slightly. Since most Crump weirs in South Africa do not provide for this we will only consider the formula given above. It is also worth noting that the Department of Water Affairs and Forestry uses all the equations as given above.

3.6 PROBLEMS CAUSED BY UPSTREAM SEDIMENTATION IN THE CALIBRATION OF WEIRS

Sedimentation is a big problem in many parts of South Africa with concentrations rarely being lower than 0.001% by mass. Typical values for flood conditions fall in the range between 0.001% and 3% (Rooseboom, 1992). In the summer rainfall areas, bed sediments mainly consist of fine sediments and in the winter rainfall areas of cobbles.

The report "River Discharge Measurement in South African Rivers: The Development of Improved Measuring Techniques, 1995" by Rooseboom and Lotriet highlights the problems experienced due to sedimentation. A brief summary follows. From the formula quoted above (3.1) it becomes clear that the calibration formula for flow over a weir relies on an accurate estimate of the upstream pool depth. Since the weir creates a relatively calm pool with lower flow velocities upstream, sediments tend to be deposited here. This causes uncertainty about the pool depth at any given time and therefore periodic surveys of the pool depth should be carried out. Most pools will however approach an equilibrium pool depth and this should be kept in mind when a new weir is constructed.

When pools become too shallow, the control section that the weir creates in the river may shift upstream making the weir ineffective as an accurate gauging station. Sediments may also block-up the head measuring equipment rendering it ineffective.

Attempts to solve the problems associated with sediments have not been entirely successful. Various structures have been proposed to alleviate the problem and it can be mentioned here that the Crump weir is less sensitive to variations in its pool depth than for example the sharp-crested weir.

The position of the probe of a Doppler meter, when installed into the upstream face of a Crump weir, should therefore be close to the crest level to prevent it from being silted up. If the probe gets covered by sediments or floating debris, no or inaccurate readings may result. The tests with the Doppler meter at a Crump weir in the laboratory, will thus be performed at Crump crest level, a position that is most likely to be used in the prototype.

4 THE DOPPLER METER

4.1 BACKGROUND

The Doppler meter and the Doppler shift are named after the Austrian physicist Christian Johann Doppler (1803-1853), who discovered what is known as the Doppler effect in 1842 when he was professor at the State Technical Academy in Prague. The discovery was tested and confirmed in 1845 in Holland, using a steam locomotive to haul an open carriage carrying several trumpeters. This showed that when the locomotive travelled towards the stationary observers, the observed noise from the trumpeters was louder than when the locomotive travelled away from the observers. The reason for this is that sound waves get "squashed" together for the first case and likewise, when the locomotive travelled away from the observers, the noise heard from the trumpets was softer because the sound waves became "expanded" between the observers and the carriage. In other words, the frequency of the sound waves gets "squashed" or "expanded".

The technique of using the Doppler shift of *laser light* to determine velocities was first demonstrated in 1964 by Yeh and Cummis (Drain, 1980), who observed the shift of light scattered from particles carried in water. Measurements of flow velocities in gases also followed soon. Lasers produce a very intense monochromatic light (a beam of particles where all particles have the same energy and hence the same wavelength) that is very suitable for this type of measurement.

There are two types of ultrasonic flowmeters: "transit time" and "Doppler" (Pipeline and Gas Journal, July 2000). Both types depend on the fact that the flowing stream affects the travel time of the ultrasonic wave. Both instruments contain sending and receiving transducers. For transit time flowmeters, a transducer sends an ultrasonic wave across the flowing stream to the receiving transducer. By altering between sending and receiving ultrasonic signals, and by measuring the travel time of these signals across the pipe, the transducers constantly calculate the velocity of the flowing stream.

Ultrasonic Doppler flowmeters also make use of an ultrasonic wave, but they utilize entrained air or particles that move with the stream. A description of the principle of the Doppler shift frequency, that is used to convert the Doppler shifted frequency into a velocity, follows.

In any form of wave propagation, frequency changes can occur due to the movement of the source, receiver or the propagating medium. These shifts are generally called "Doppler" shifts. The Doppler shift, also well known in acoustics, is due to the relative motion of source and receiver. In recent years this principle has been expanded to include Doppler meters that rely on the interaction between an incident *sound wave* and a moving reflecting target. Sound wave theory describes the propagation of mechanical vibrational disturbances. These vibrations travel through media in the form of sinusoidal waves, which obey the laws of reflection, refraction, diffraction and dispersion.

In its most basic form, the Doppler principle states that if a receiver (R) moves relative to a source (S) of sound waves, then the frequency detected by the receiver is not the same as that transmitted by the source (Doppler Ultrasound and its use in Clinical Measurement, 1982). The most simple Doppler device is the continuous-wave flowmeter, which was first used in 1975 to monitor blood velocity non-invasively in a particular blood vessel. The derivation of the Doppler shift, that was to be used in this study, follows.

4.2 BASIC PRINCIPLES OF THE DOPPLER SHIFT

We will first provide an expression for a moving receiver, then one for a moving source and then combine the two to establish the Doppler relationship (Doppler Ultrasound and its use in Clinical Measurement, 1982).

4.2.1 MOVING RECEIVER

Suppose firstly that the receiver and the source are both stationary as in Figure 4.1a, and consider the arrival times of the peaks of the sound wave at the receiver. The rate at which the peaks are detected as the travelling sound wave hits the receiver is simply equal to the rate at which they were transmitted, in other words the frequency of the source, f_S.

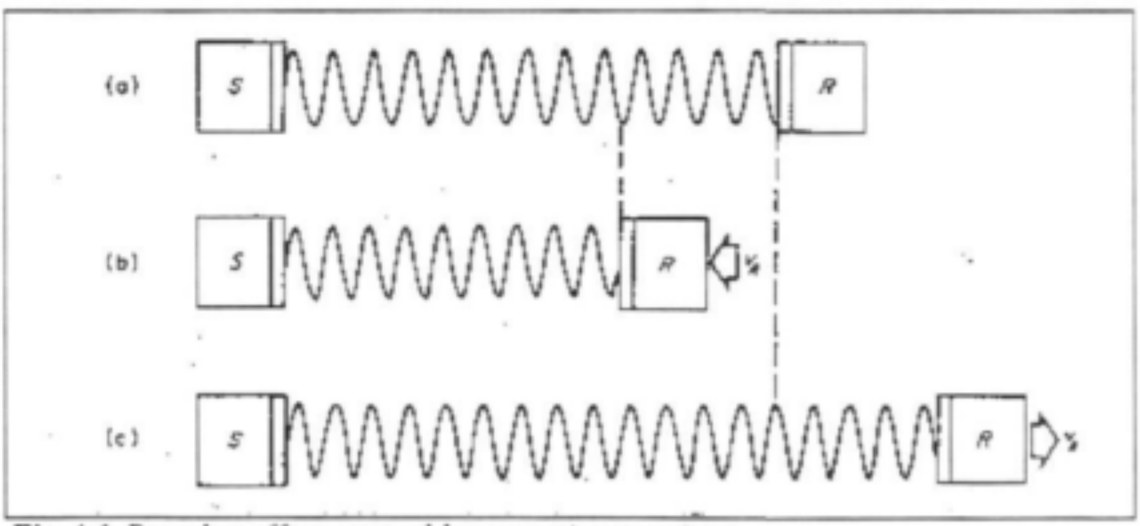


Fig.4.1 *Doppler effect caused by a moving receiver.*

If the receiver now begins to move in the direction of the source (Figure 4.1b), then the number of peaks detected will correspond to the number transmitted plus the extra number of peaks intercepted. The frequency as seen by the receiver has thus increased. Likewise, if the receiver moves away from the source (Figure 4.1c), then the peaks that would have been detected had the receiver been stationary, are not detected. The peak detection rate is therefore lower than the source frequency and has thus decreased. Mathematically, suppose the receiver, R, moves at a velocity v_R in the direction of the source S, which emits a frequency f_S into a medium where the ultrasonic propagation velocity is c. Now from wave theory, the distance between successive peaks in the travelling wave is

$$c / f_S = \lambda_S,$$

the ultrasonic wavelength. In unit time the receiver moves a distance v_R and intercepts an extra number of peaks v_R / λ_S. The received frequency f_R equals the *total* number of peaks detected per unit time and is therefore given by

$$f_R = f_S + \frac{v_R}{\lambda_S} \quad \text{..............................4.1}$$

or, since $\lambda_S = c / f_S$

$$f_R = f_S + \frac{v_R}{c} f_S \quad \text{..............................4.2}$$

The Doppler frequency shift, f_d, is defined as the difference between the received, f_R, and transmitted frequency, f_S, giving the conventional Doppler expression

$$f_d = \frac{v_R}{c} f_S \quad \text{..............................4.3}$$

4.2.2 MOVING SOURCE

If the source is moving then the Doppler effect needs to be explained in a slightly different way. Consider Figure 4.2a, which shows that when both the receiver and the source are stationary, the peak-to-peak distance is by definition the ultrasonic wavelength, λ_S. Now, when the source is moving in the same direction as the wave, i.e. in the direction of the receiver, successive peaks will be spaced closer by an amount equal to the distance $\Delta\lambda$ that the source has been able to move between the transmission of the two peaks (Figure 4.2b). The stationary receiver thus detects a higher frequency than that transmitted by the source. Likewise, if the source moves away form the receiver, then the spacing increases by $\Delta\lambda$ and the frequency at the receiver appears to be lower than that transmitted by the source (Figure 4.2c).

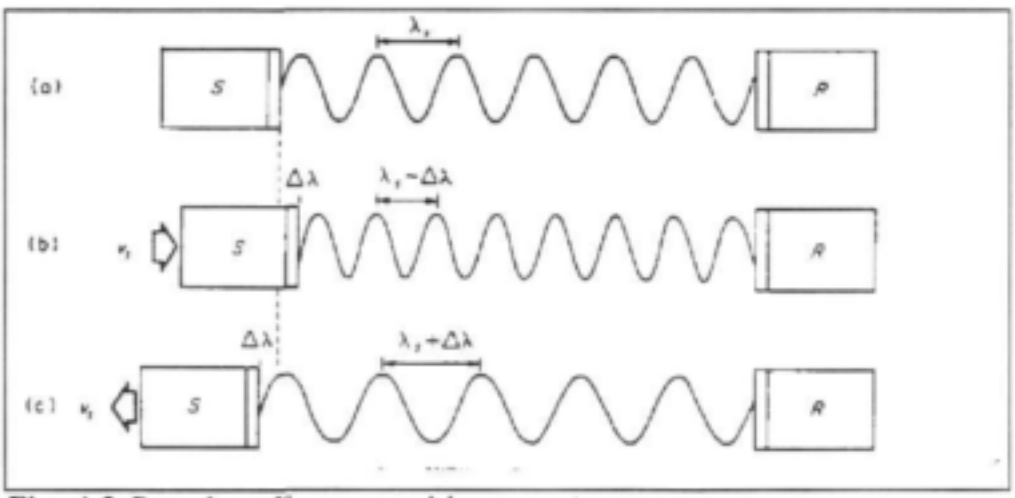


Fig. 4.2 *Doppler effect caused by a moving source.*

Now, mathematically, if v_S is the velocity of the source S **in the direction** of propagation, then in time interval $1/f_S$ between peaks, i.e. the period, the source will move a distance $\Delta\lambda$ given by

$$\Delta\lambda = v_S \frac{1}{f_S} \qquad \text{..............................4.4}$$

The wavelength λ_R of the travelling wave, which is eventually detected at the receiver and bearing in mind the discussion above is thus given by

$$\lambda_R = \lambda_S - \Delta\lambda \qquad \text{..............................4.5}$$

Rewriting this, with $\lambda_s = {}^{c}/_{f_s}$ and substituting for $\Delta\lambda$, we obtain

$$\frac{c}{f_R} = \frac{c}{f_S} - \frac{v_S}{f_S} \qquad \text{..............................4.6}$$

Rearranging this to

$$f_R = \frac{c}{c - v_S} f_S \qquad \text{..............................4.7}$$

Divide this expression by c,

$$f_R = \frac{1}{1 - {}^{v_S}/_{c}} f_S \qquad \text{..............................4.8}$$

Now, recognising that this can be rewritten as an expansion of the form

$$\frac{1}{1-x} = 1 + x + x^2 + x^3 .... + x^n \qquad \text{..............................4.9}$$

with the term v_S/c being very small we can omit all the higher order terms producing

$$f_R = f_S + \frac{v_S}{c} f_S \text{..............................} 4.10$$

The Doppler shift frequency $f_D = f_R - f_S$ is then given by

$$f_D = \frac{v_S}{c} f_S \text{..............................} 4.11$$

4.2.3 REFLECTION OR ECHO

The above analysis considered first the receiver to be moving and then the source to be moving. This can now be combined and extended to describe reflection of ultrasound from a moving target by combining equations 4.3 and 4.11.

Consider a moving target, which is assumed to be a moving receiver in our case. This target will, from equation 4.2, receive a frequency f_R. This target will then behave as a moving transmitter or source of the frequency by echoing it back to the "source" which is the receiver now. The target will thus radiate **an already Doppler shifted frequency f'_R**, which is then detected by a stationary receiver. This frequency f'_R seen by this receiver (the original source) will thus be given by equation 4.10, namely

$$f'_R = f_R + \frac{v_S}{c} f_R \text{..............................} 4.12$$

Note the change of the lower case in this equation from the original equation. This is due to the shifted Doppler frequency with the source frequency being the frequency of the receiver in this case. We now substitute for f_R from equation 4.2 into equation 4.12, giving us

$$f'_R = f_S + \frac{v_R}{c} f_S + \frac{v_S}{c}\left(f_S + \frac{v_R}{c}\right) \qquad 4.13$$

Since $|v_R| = |v_S|$ (=v, the target's velocity) and because v/c is very small, the term $(v/c)^2$ can be neglected. Equation 2.13 thus becomes

$$f'_R = f_S + \frac{2v}{c} f_S \qquad 4.14$$

and the Doppler difference frequency f_D, given again as $f_D = f_R - f_S$ thus becomes

$$f_D = \frac{2v}{c} f_S \qquad 4.15$$

This expression, known also as the **Doppler relationship** could equally well have been derived irrespective of whether the source moves towards the receiver or the receiver moves towards the source. It is thus the relative frequency between source and receiver that is used to compute the Doppler shift.

4.3 DESCRIPTION OF INSTRUMENT USED FOR THIS STUDY

The use of ultrasonic flowmeters for industrial applications began in the 1970s (Pipeline and Gas Journal, July 2000). The two companies that dominate the natural gas flow measurement scene today are **Instromet** (Dordrecht, The Netherlands) and **Daniel Industries** (Houston, Texas). Other commercially available instruments are available from **SonTek Inc**, including the *ADV-Acoustic Doppler Velocity flowmeter*, **Unidata's** *Starflow Doppler flowmeter* and the *DOP1000* ultrasonic velocity meter from **Signal Processing**. The Doppler meter that was used for this project is a local product of the company *Flotron* in Stellenbosch. A brief description of the apparatus follows.

The instrument used in this study is a portable dual channel processor designed to measure flows in small canals and pipes. It is marketed under the name: **DFM-P-067** (Doppler Flowmeter, Portable, Serial Number 067). It consists of a sensor or probe, which sends out continuous sound waves, connected to a microprocessor. This microprocessor converts the information received at the receiving end of the probe and the user has different display options available. It is equipped with a built-in single-line small alphanumerical LCD display used as a readout device and keypad. The user can read frequencies, velocities and even discharges. The microprocessor can also be set to read frequencies within a certain range. The microprocessor is also equipped with a connection to a datalogger. This datalogger stores all the readings that are taken at regular intervals when continuous readings are required. The interval at which readings are taken can be pre-set on the microprocessor. The datalogger can then be replaced at any time. The information on the datalogger can then be retrieved on a computer and becomes available as a normal spreadsheet.

The microprocessor can be seen in Fig.4.3. The apparatus used for this study makes use of the Doppler effect as described in the previous section. As mentioned previously, the instrument is programmed to give the user a choice of different readings. For the purpose of this study we will only be reading the Doppler shift frequency and convert that manually to velocities. The reason for this is that the microprocessor is programmed to convert frequencies to velocities with a Doppler constant of value *1100*, which is not applicable here. This constant was found by *Flotron* to be valid for pipe flow, which in most cases, operates under pressure.

The probe of this instrument consists of a transmitter, the source referred to in the previous section, and a receiver, which lie at an angle of *approximately* 10^0 to each other. See Fig.4.4. Both consist of crystals that transmit and receive sound waves. The angle between them is required to ensure that the transmitted wave gets reflected towards the receiver, once it has hit the target.

It is therefore required that there are suspended particles such as fine sediments in the water and that these particles follow the flow sufficiently closely. Tests carried out in clean water may therefore result in inaccurate readings. This requirement is usually met when measuring in a river, especially in South Africa, where there is no shortage of suspended sediments or colloidal particles. The signal received at the receiver will be passed on to the microprocessor where it can be read off as a frequency in Hz, which will be the required Doppler frequency.

Two students under guidance of Prof. A. Rooseboom, Stellenbosch University, (Skripsie Nr. W5/99, Kalibrasie van Meetwalle vir Hoogvloei Toestande met behulp van die Doppler Snelheidsmeter) used this instrument for their experiments carried out in 1999. The instrument was built in permanently at the Crump weir in the Jonkershoek River and all readings were continuously stored in the data logger. For the purpose of the experiments to be carried out for our study, the Doppler meter was moved around by attaching the probe to a vertical rod and placing it horizontally wherever readings were required inside the canal. The readings were taken manually at a constant time interval and not stored in the datalogger. The reason for not storing and extracting the data from the datalogger, was that for the purpose of the various experiments performed, better control over the measuring points and their respective data could be achieved.

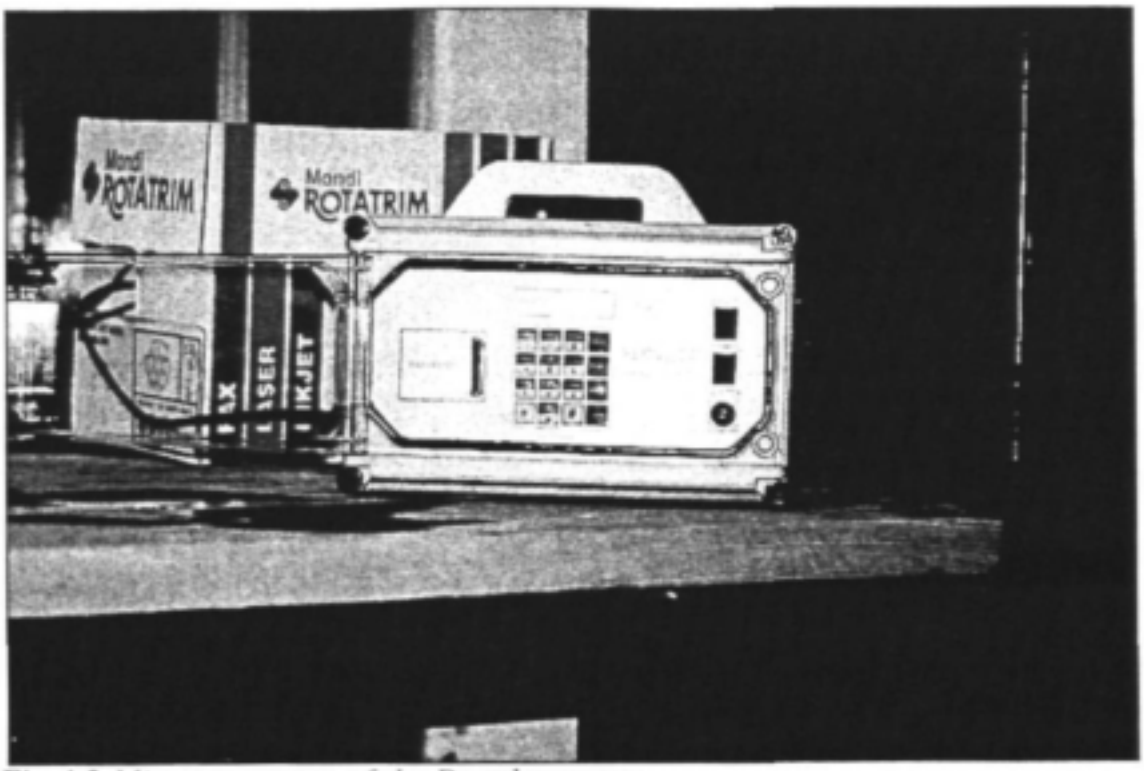


Fig.4.3 *Microprocessor of the Doppler meter.*

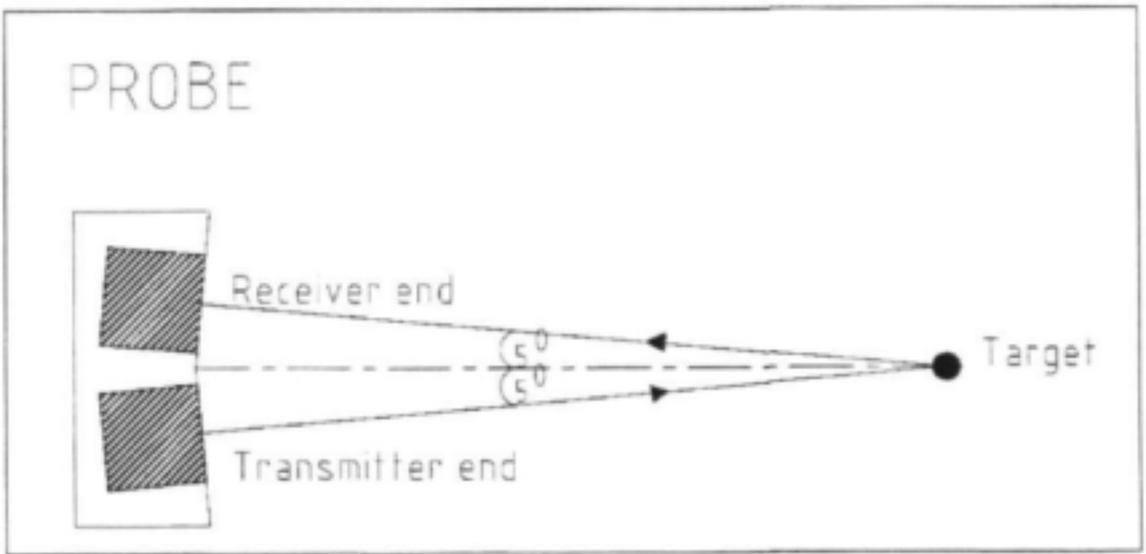
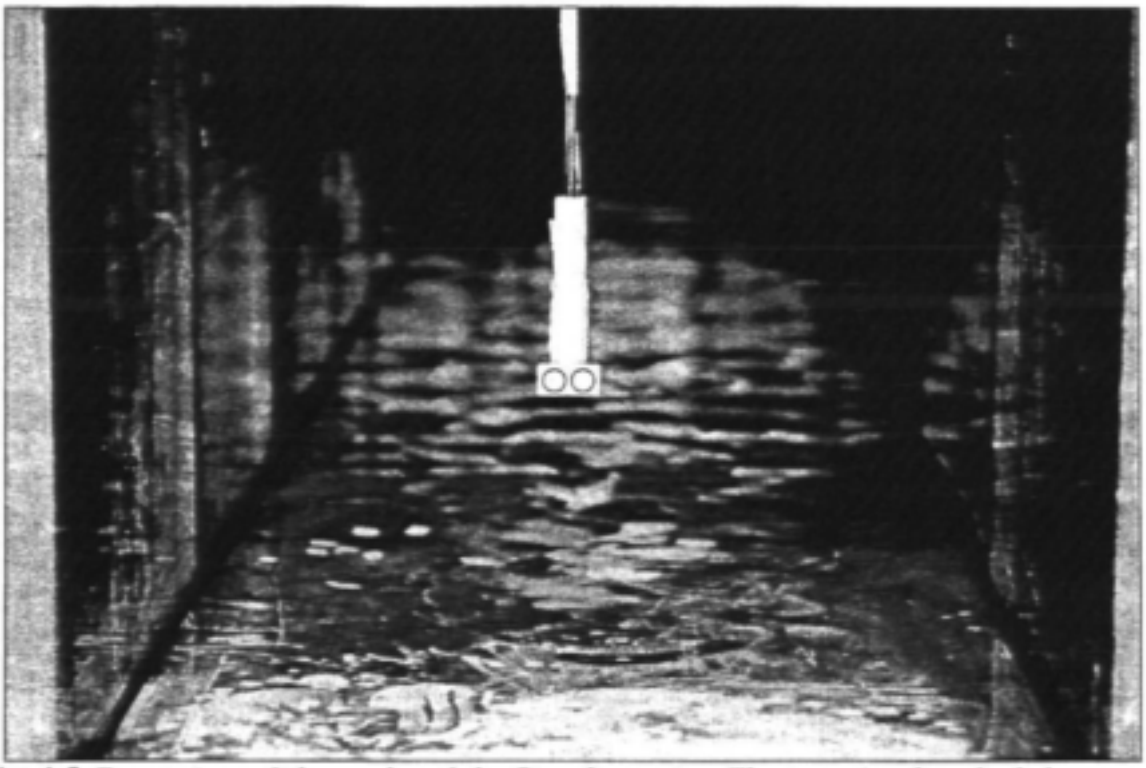


Fig.4.4 *Schematic representation of the crystals and their operation inside the probe of the Doppler meter.*



ig **4.5** *Front view of the probe of the Doppler meter. The two circular shaded areas on the front face of the probe are the respective areas where the transmitter and receiver crystals are situated.*

4.4 APPLICATION OF THE DOPPLER SHIFT TO THE DOPPLER METER IN THIS STUDY

As described earlier, the Doppler shift frequency is given by equation 4.15

$$f_D = \frac{2v}{c} f_S$$

The variable of interest in this equation is the approach velocity and this equation was thus rearranged to read:

$$v = \frac{f_D * c}{2 * f_S} \qquad \text{4.16}$$

The specific Doppler meter that was being used in this study sent out a sound wave with a frequency of 1 Mhz, i.e. f_S in equation 4.16. The speed of sound, c, through the medium water is given by

$$c = \sqrt{\frac{K}{\rho}} \text{..............................} 4.17$$

with

K = the Bulk Modulus of water

ρ = the density of water

The typical value of the Bulk Modulus for water at 20^0C is 2.1×10^9 N/m^2 [Massey, 1989] and that of the density at 20^0C, 998 kg/m$^{3.}$ If these values are substituted into equation 4.17, we calculate the speed of sound through water to be approximately 1450 m/s. Substituting this value and the value for f_S into equation 4.16, we obtain:

$$v = \frac{f_D}{1379} \text{..............................} 4.18$$

Now, since the receiver and the transmitter in the probe were at an angle of approximately 5 degrees to each other, see Fig.4.4, and we are interested in the component parallel to the flow, we obtain:

$$v = \frac{f_D}{1374} \text{..............................} 4.19$$

This formula was used in this study to convert the measured frequency, i.e. the Doppler frequency, into the required approach velocity. It must be mentioned here that the angle between the crystals is approximately 10 degrees (See

Fig.4.4). This angle can not be measured and it is thus very important to calibrate every instrument to obtain its own unique Doppler constant.

5 TESTS CARRIED OUT WITH THE DOPPLER METER

5.1 EXISTING DATA FROM A PREVIOUS STUDY

5.1.1 1999 STELLENBOSCH STUDY

In 1999, two fourth year students of the University of Stellenbosch (du Toit, Venter) carried out the first tests with a Doppler meter in the Jonkershoek River. The Doppler meter was installed permanently at the Crump weir in the Jonkershoek River and continuous readings were recorded. The instrument was installed by drilling holes into the upstream slopes of the Crump weir and inserting and cementing the probes flush with the surface, one on the lower crest and one on the higher crest, facing upstream. These probes thus measured the approach velocity component at an angle of 63.4^0 relative to the channel bed. They were put at a distance of 200 mm below the crest levels. It was intended to place them as far as possible below the crest level to avoid the area where strongest acceleration of water over the crest occurs and where the flow lines are not straight. On the other hand, because of the threat that sediments might block the probes, it was decided to place them not too far below the crest level of the weir and the arbitrary distance mentioned above was decided upon.

All the readings were taken automatically at regular intervals and stored on the datalogger. The datalogger was replaced weekly. The stored data on the datalogger were extracted on computer and transformed into a common spreadsheet.

5.1.2 SUMMARY OF THESE RESULTS

The method, to obtain a relationship between the measured and the calculated approach velocities, that was used during this investigation, relied on an assumed constant water level but different energy levels upstream of the two crest levels. The reason for this is that velocities were measured at both the low and the high crests. A far better correlation was however obtained for the lower crest due to factors such as lateral flow towards the lower crest affecting the approach velocity towards the higher crests with low flows over them. It was thus decided to only analyze the flows over the low crest.

The approach velocity of the water is a function of the cross sectional area, i.e. the pool depth and the depth of flow (since the channel width stays relatively constant). The pool depth during these experiments was found to be relatively constant at 0.4 metres for differing flows. The approach velocity thus became a function of the flow depth only and the readings of the Doppler meter were plotted against the corresponding water depths. Linear regression analysis of these points yielded the equation:

$v = 2.0625h$..............................5.1

The discharge over a Crump weir is given by equation 3.1 and the discharge coefficient is given by equation 3.3. The Department of Water Affairs and Forestry (DWAF) uses a discharge coefficient of 1.163 since it varies by less than 1% within the allowed limits of the applicability of the formula according to the BSI (1984). The discharge formula over a Crump weir thus becomes

$Q = 1.982bH^{\frac{3}{2}}$..............................5.2

The velocity calculated by the DWAF is thus given by:

$$v_w = \frac{1.982bH^{\frac{3}{2}}}{A} = \frac{1.982bH^{\frac{3}{2}}}{(0.4+h)b} \quad \text{.............................} 5.3$$

With these two velocities known the relationship between the two was expressed as a velocity factor of the form

$$f = \frac{v_w}{v} \quad \text{.............................} 5.4$$

A plot of this factor against the measured water depth (See Fig.5.1) indicated a clear trend that this factor approached an asymptotic value, indicating that it stabilized at higher water depths. This factor only applied to a pool depth of 0.4 metres below the crest level. The results reflected in Fig.5.1 strongly suggested that there exists a near linear relationship between the velocity measured at the crest of the Crump weir and that in the approach channel for greater depths of flow.

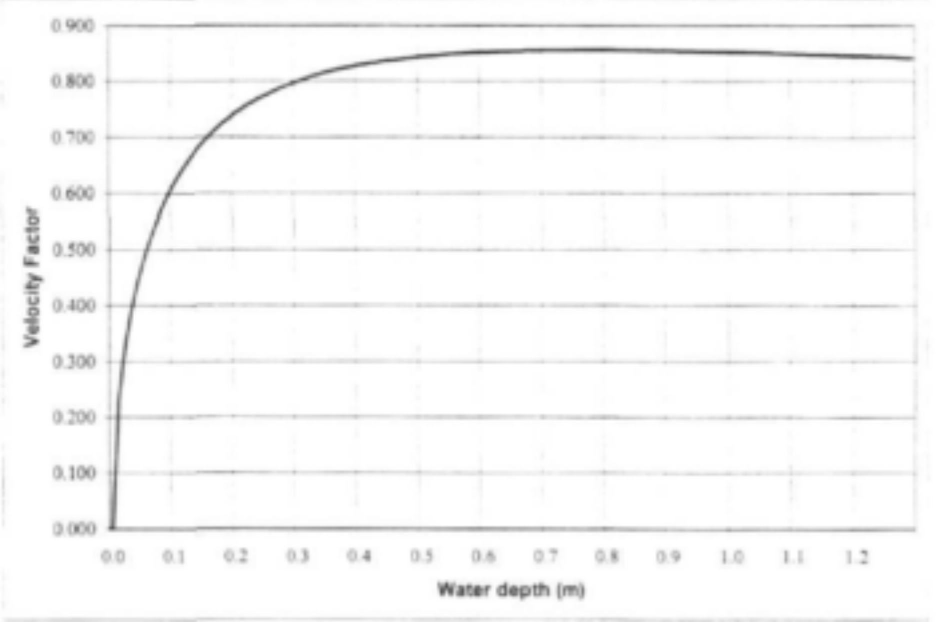


Fig.5.1 *Velocity factor established during previous study.*

In this study it was furthermore established that calibrations up to at least 40 % to 50 % of the maximum possible recorded water level are required to make extrapolations for high flows possible. This would result in measured flows to be accurate within 10 % (See Fig.5.2).

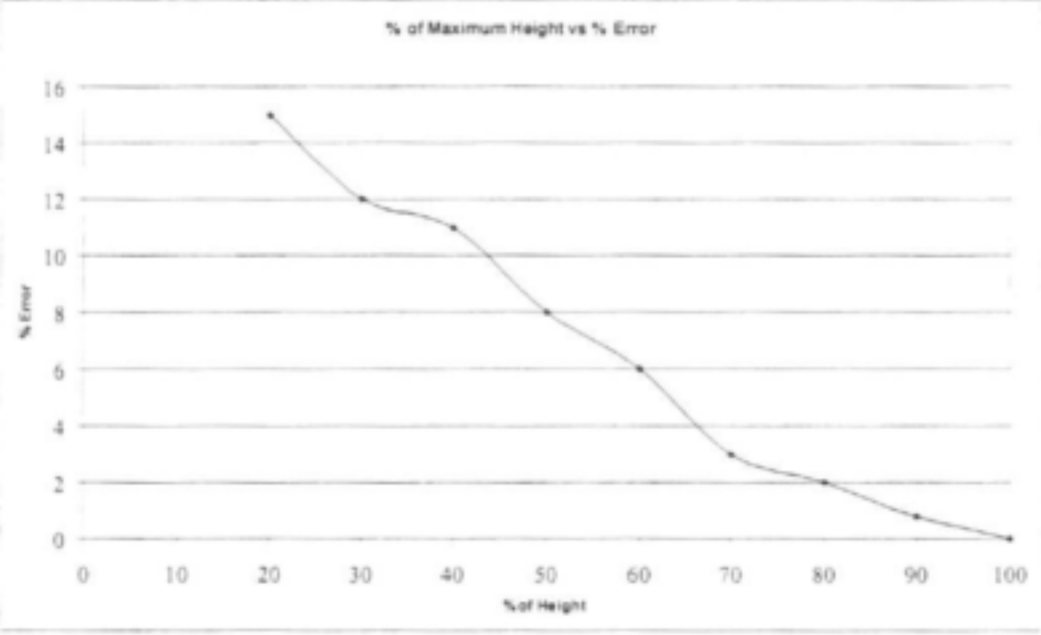


Fig.5.2 *Determination of minimum calibrated height required for accurate flow measurement.*

In general, the field study gave encouraging results which justified further tests on the use of the Doppler meter at Crump weirs.

5.1.3 RECOMMENDATIONS FOR FURTHER TESTING

The completed field research identified the following needs for further research:

- To test the accuracy of the Doppler meter in the laboratory.
- To find reasons for the wide scatter of the Doppler frequencies.

5.2 CALIBRATION OF INSTRUMENT IN THE LABORATORY

5.2.1 TEST PROCEDURE

Acoustic, or Doppler meters, should be calibrated before being put into service. With other Doppler meters it has been found that typical errors of up to 10 % can be expected for uncalibrated meters and depending on the application they could even be greater (Vermeyen, 1999).

The instrument that was used in this study was essentially the same as the one that was used for the study in the Jonkershoek River in 1999. The only difference between the two was that the probe of this instrument was not fixed and could be set at different angles and be used at different locations. No datalogger was used for the new tests and all readings were taken manually. A full description of the instrument was given in Section 4.1. The Doppler meter used in the Jonkershoek River in 1999 was not calibrated for open channel flow.

5.2.2 SET-UP OF INSTRUMENT

For the purposes of calibration, determining the effect of sediment concentrations in the water, as well as the effect of the time interval between readings on the output of the Doppler frequencies, the probe had to be held still and horizontally. Tests were carried out in a 600mm wide canal in the laboratory of the University of Stellenbosch. A rail was fixed to the top of the canal on which a trolley equipped with a measuring needle could run. This ensured that the probe could be adjusted in any horizontal or vertical position within the canal. The measuring needle had to be extended so that the probe could reach the water flowing within the canal. A long straight metal rod was fixed to the needle and the probe was fixed to this rod pointing horizontally in the upstream flow direction in the canal. The laboratory set-up can be seen in Figures 5.3 and 5.4.

The face of the probe was in line with a tapping point in the floor of the canal. This point was situated at half width and was connected to a stand pipe on the outside of the canal. The flow depth could thus be read off externally at the measuring position. A 90^0 V-notch weir was used to measure the discharge within the canal.

In the laboratory water is pumped into constant head tanks from where it is fed to the various models. Water for this model was supplied via a 300mm-diameter pipe from the constant head tanks. The pipe is equipped with a gate valve with which the flow can be regulated. Furthermore a 162.9mm orifice plate was installed in the pipe and mercury/water and water/air manometers were used to measure the flow passing through the pipe.

Both the manometers were calibrated by making use of the V-notch so that the flow was still measurable in the event of the V-notch being drowned. In order to raise the water depth in the canal a sluice gate was partially closed at the end of the canal and this drowned the V-notch at higher depths. Since the water/air manometer is more reliable for lower flows, the mercury/water manometer was not used for the measurement of the flow rates but merely to check whether the water/air manometer was correctly set up at the beginning of each day's work.

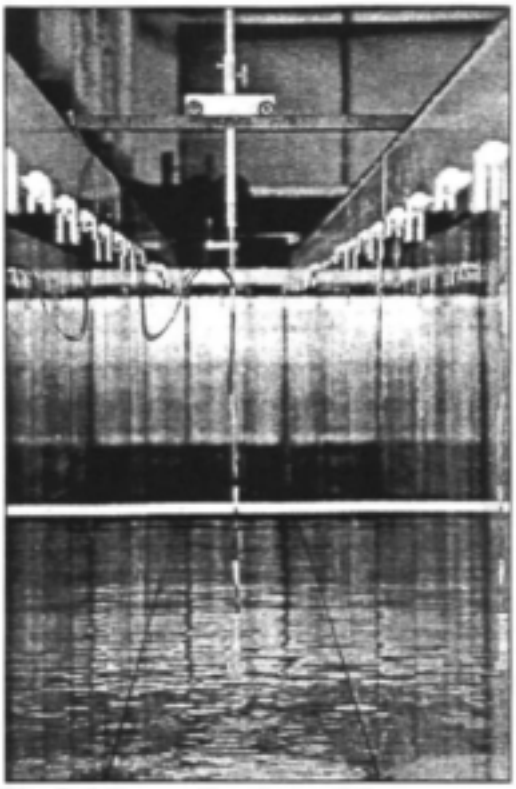


Fig 5.3 *Setup of probe in 600mm wide canal. The probe could be positioned in any horizontal or vertical position.*

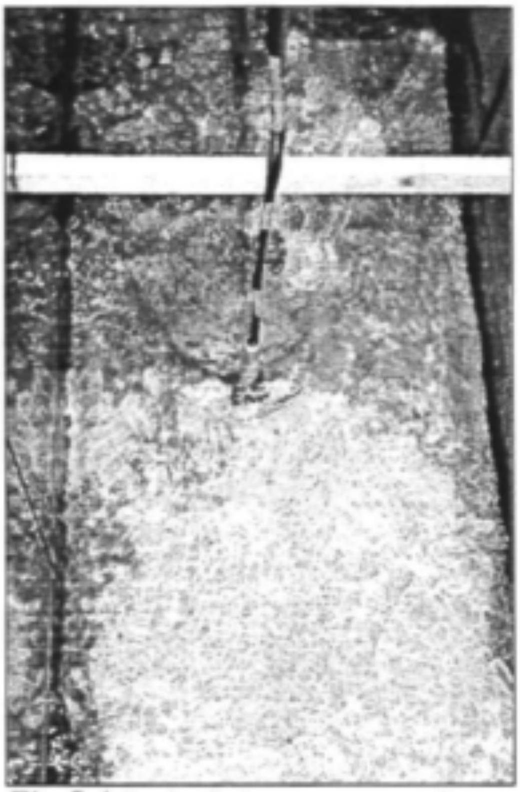


Fig 5.4 *Probe facing upstream and measuring Doppler frequencies.*

5.2.3 CALIBRATION OF DOPPLER METER

Because of the crucial nature of the measurements performed by flow meters, they are normally calibrated before being put into service. Flow meter calibration can be done using current meter measurements, other velocity-area methods, or using computations based on theoretical velocity profiles (USBR Water Measurement Manual, 1997). The calibration technique that was used here is essentially the velocity-area method and was recommended by the manufacturer of the instrument.

The theoretical derivation in Section 4 of this report yielded a constant that differed from the one used during 1999 in the Jonkershoek River. Hence it was decided to calibrate the Doppler meter in the laboratory to test whether the practical constant would be close to the theoretical one. The set-up for these experiments was as described above.

For the purpose of the calibration of the Doppler meter, the flow in the canal had to be known and the flow cross-section had to be sub-divided into segments. The Doppler frequency was then measured at the centre of each sub-division or segment. This is similar to the *velocity-area method* that is used to calculate discharge, but working backwards here with the flow already known. With the flow and water depth (measured at the front face of the probe) known, the depth and the width of the flow in the canal was divided into segments and the probe could be positioned at the centre of each segment.

The centre of the sub-divisions could be reached easily as the trolley could move on rails from the one side of the canal to the other side and the distance could then be measured. Likewise, the vertical shift could be adjusted with the needle to which the probe was attached. For most experiments the width of the canal was divided into 6 segments of 100mm width each, with as many as 10 of 60 mm width each. The trolley was then positioned on the rail so that the probe would take readings at the centre of the horizontal interval of each block, i.e. at 50mm, 150mm etc.

The flow depth was also divided into a number of intervals, depending on the water depth. The number of intervals ranged from one, up to ten for higher flow depths. The number of intervals was decided upon after the water depth had stabilized in the canal. Recall that the sluice gate at the end of the canal was closed partially for each experiment to create greater water depths. This was essential because very low water depths would result even at higher flow rates. The outlet of the canal was thus transformed into a submerged orifice and the water depth only stabilized once the head above the orifice became sufficiently high to balance the constant inflow rate. The vertical centre of each segment then had to be calculated and the needle could be adjusted so that the centre of the probe was at that exact vertical position. Readings were then taken at the centre of each individual segment.

Ten frequency readings, with a time interval of ten seconds between individual readings, were taken at the centre of each segment. The average of these readings was then taken to calculate the calibration constant.

5.3 VELOCITY READINGS AT A CRUMP WEIR IN THE LABORATORY

5.3.1 BACKGROUND AND SETUP OF EXISTING FLUME AND WEIR

The DWAF has supported extensive WRC sponsored research at the University of Stellenbosch, which has led to the development of a new type of gauging structure, the sluicing flume, (Rossouw et al, 1998). This structure can be used in conjunction with either sharp-crested or Crump weirs. The sluicing flume has been calibrated under free flow conditions in combination with both sharp-crested and Crump weirs. Recently these flumes, in combination with the weirs mentioned, have also been calibrated under non-modular flow conditions, (Bruce, 2000). A model of the flume in combination with Crump weirs was recently tested in the laboratory of the University of Stellenbosch. In order to save time and costs this same model was used for the tests on the Crump weir in combination with the Doppler meter. The water levels were recorded at various points in the canal and in the flume and then converted into a flow passing through the flume and over the Crump weir, (Bruce, 2000). For the position of the relevant points, refer to Fig.5.5. For the purpose of this study, the points numbered **2.2**, **5** and **8** were not used. Only points **2.1** and **2.3** were necessary to convert the recorded flow depth into a flow over the weir and through the flume under modular flow conditions. For non-modular flow conditions, water levels at points **7** and **8** were recorded in addition to the ones mentioned above to convert water levels into flows, (Bruce, 2000). Points **4** and **5** were also used for the purpose of establishing the pool depth upstream of the Crump weirs. All gauge points were connected to stand pipes and the water depth was then recorded inside the stand pipe.

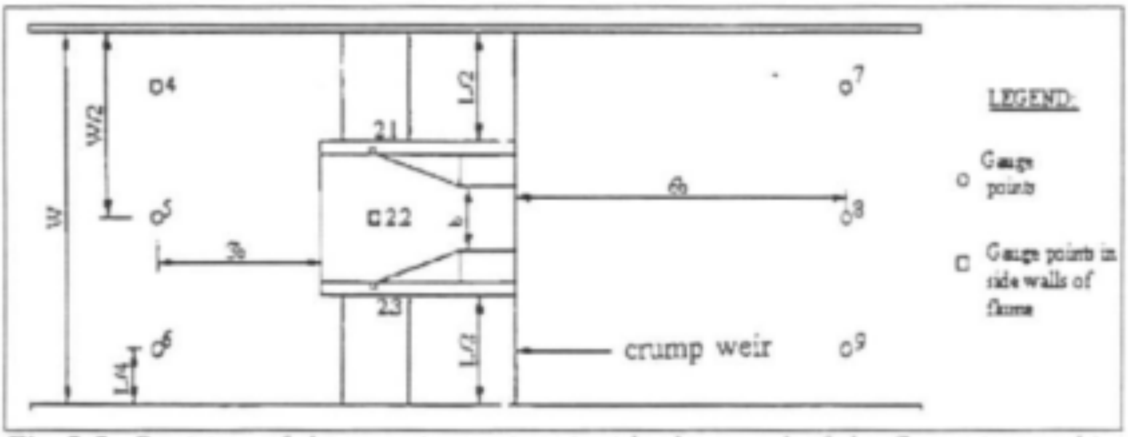


Fig 5.5: *Position of the gauging points inside the canal of the flume in combination with the Crump weir.*

5.3.2 SETUP OF DOPPLER METER

The probe of the Doppler meter was fixed to a needle, which in turn was fixed to a trolley running the full width of the canal. The probe was fixed so that it remained stationary and perfectly horizontal. The trolley was positioned on the rail so that the centre of the probe was at the same height as the crest level of the Crump weir and midway across the span of one of the Crump weirs. The width of one of the Crump weirs was 0.67 metres, denoted by L/2 in Fig. 5.5. Ten Doppler frequencies were recorded for each experiment.

A set of experiments, with different flow rates in the modular flow regime, was performed to establish a relationship between the recorded flow velocities at Crump crest level and the approach velocities upstream of the weir. To reach the modular limit, a sluice gate at the end of the canal was raised which caused the downstream water level to rise. A number of experiments were performed with different degrees of submergence. One set of experiments had a constant flow rate but different degrees of submergence due to the raising of the sluice

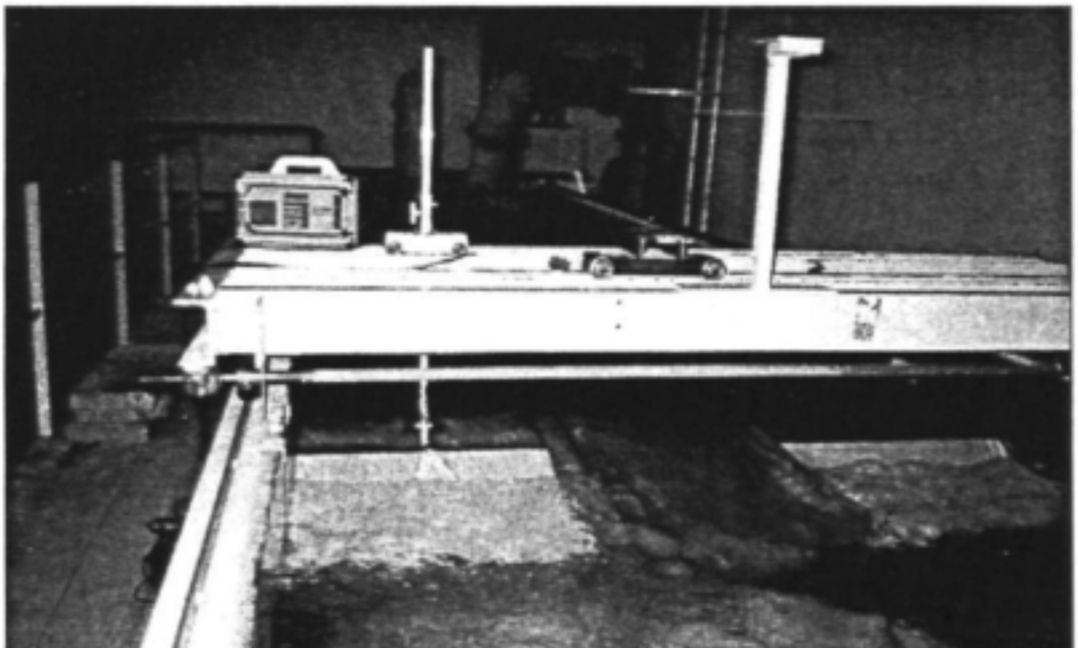


Fig 5.6: *Probe of Doppler meter visible at centre of Crump weir on the left hand side.*

gate at the end of the canal. It was impractical to lift the sluice gate higher and then to increase the discharge whilst keeping the sluice gate at constant height.

Submergence would then either not occur or only at the highest possible flow over the full range of flows attainable with the 300mm delivery pipe. Hence four sets of experiments were carried out that had a constant flow rate per set but different degrees of submergence. As mentioned previously, for each experiment a set of Doppler frequencies and relevant water depths were recorded.

5.4 TESTS TO ESTABLISH THE EFFECT OF CERTAIN FACTORS ON THE DOPPLER FREQUENCY

Apart from the calibration of the Doppler meter in the laboratory and the velocity readings at a Crump weir in combination with a flume, it was also decided to test various factors that are suspected of having an influence on the output of the Doppler frequency and in particular the scatter which was evident in the field test results. These factors were investigated individually in the laboratory to allow for conclusions to be drawn on each factor separately.

5.4.1 SEDIMENT CONCENTRATION IN WATER

The tests to investigate the influence of different sediment concentrations on the readings of the Doppler frequencies were carried out in a small glass canal 150mm wide. To add sediment to the water in the deep canal used for the calibration tests would be more difficult because one could not reach down into the water easily. It is furthermore important that the sediments disperse uniformly and that the probe would be in the flow path of the sediment particles. These conditions were obtained more readily in the smaller glass canal.

The probe of the Doppler meter was fixed to a needle and placed at 60 % of the flow depth at the far downstream end of the canal. This position remained the same for different experiments with different sediment concentrations but the same flow rate.

A funnel was used to introduce the sediments, fine sand in this case, into the water. The funnel could be fitted with 10 different lids, each with a different sized opening. The openings in the lids differed in size and in number. To generate different sediment concentrations, expressed in grams of sand added to the water per second, the funnel was filled with sand which was then poured out through the different openings. The quantity of sand, which passed through during 30-second intervals, was measured. For the bigger openings the time interval was reduced to 15 seconds as the bottle emptied in less than 30 seconds. Lids with more and bigger openings thus had a higher discharge of sand per time interval and thus introduced a higher sand or sediment concentration into the canal. It was not practically possible to obtain homogenous suspensions but it is believed that the results are valid based on the pattern which has been found.

Measurements were then taken at 10 second intervals once the funnel, with any one of the different lids screwed on, had been placed vertically into a round opening, located centrally 2.2 metres upstream of the probe. Refer to Figures 5.7 and 5.8. The sand was poured uniformly through the lid openings into the flowing water and was dispersed in the flow before reaching the probe.

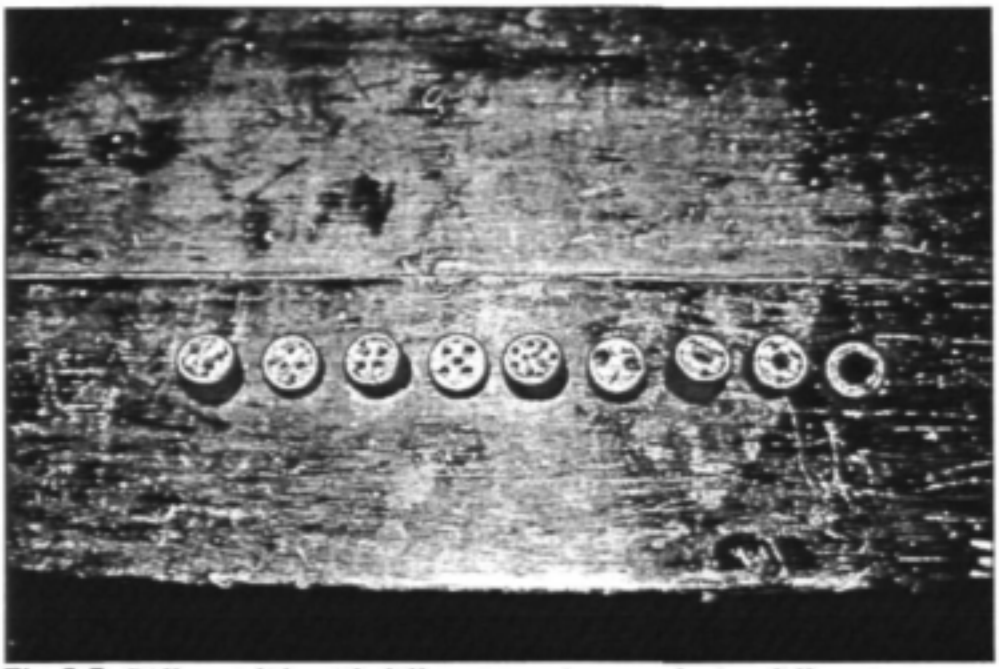


Fig 5.7: *Different lids with different openings producing different sediment concentrations, expressed as g/s added to the water.*

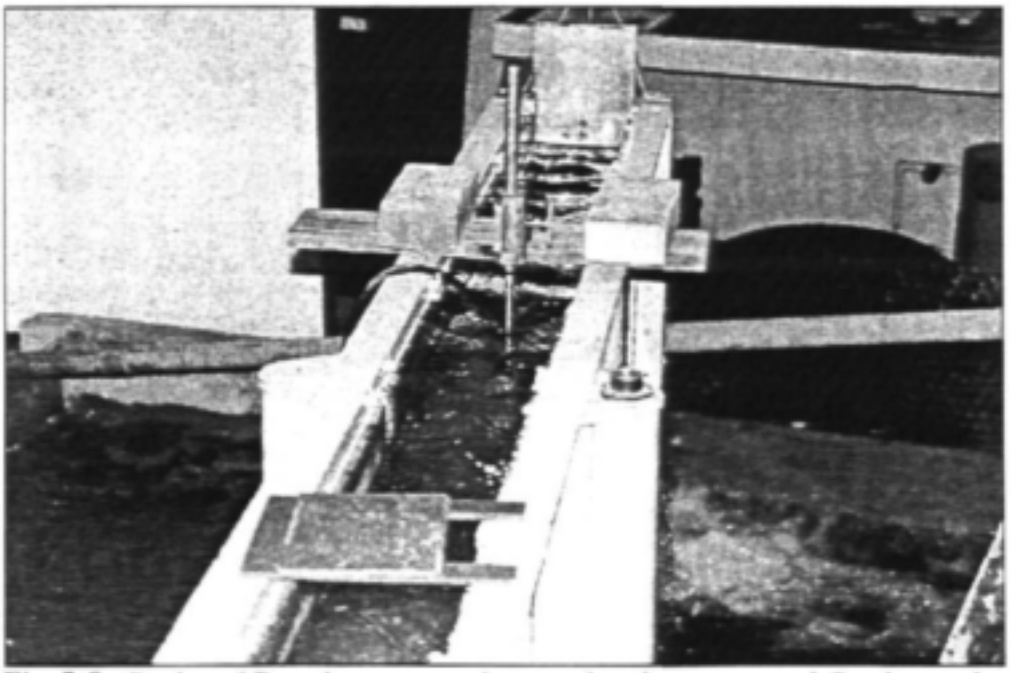


Fig 5.8: *Probe of Doppler meter submerged under water and fixed at end of canal. Sediment not visible but present.*

5.4.2 TIME INTERVAL BETWEEN READINGS

An experiment, regarding the effect of the time interval between individual readings on the overall average of the readings, was performed. For these tests it was very important that the probe was absolutely stationary in the canal and that the flow did not vary in time. The tests were performed during the calibration tests in the 600 mm wide canal. As described earlier on, the probe was fastened to the long metal rod and could not move. A series of tests was carried out where readings at various positions inside the flow cross-section were taken at 10 and 30 seconds respectively. The reason that the time interval was suspected of having an effect on the eventual average of the readings, was that the probe sent out a continuous signal and hypothetically received a continuous signal back. The signal on the display changed continuously and jumped from one value to the next. If a reading was taken, for example at 10-second intervals, only the reading that appeared on the display at that exact moment was indicated. The next split second often delivered a different reading again.

5.4.3 ANGLE OF PROBE RELATIVE TO THE CANAL BED

The probe that was installed in the Crump weir in the Jonkershoek River (du Toit, Venter, 1999) had an angle of 63^0 with the horizontal and a wide scatter of values was observed. During all the tests, regarding the calibration of the apparatus and the velocity measurements at a Crump weir in the laboratory, the probe of the Doppler meter was held perfectly horizontally. The effect that the angle of the probe relative to the channel bed has on the output of the Doppler frequencies was investigated.

The probe was fixed to a measuring staff, on which the angle of the probe could be changed. The vertical position at which the probe was positioned remained fixed and the flow rate for all the tests also remained constant. The angle of the probe was changed and read off with a protractor. The measuring staff with the probe fixed to it can be seen in Fig.5.9. Doppler frequencies were recorded for each respective angle of the probe.

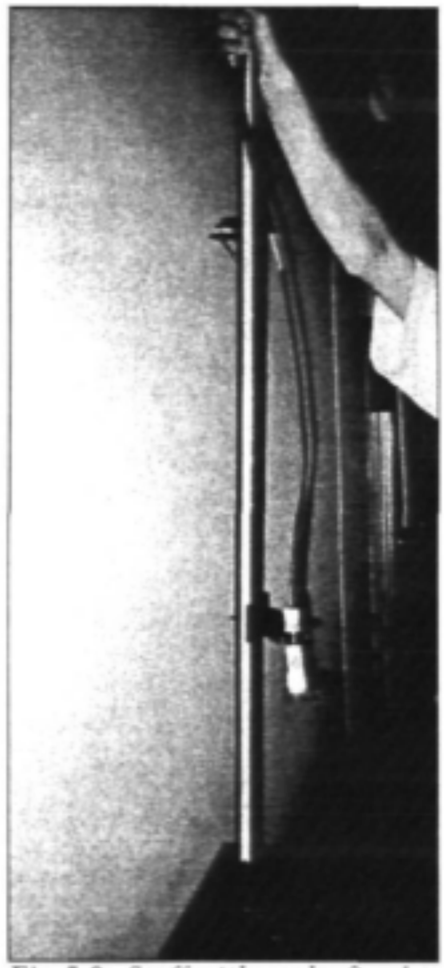


Fig 5.9: *Staff with probe fixed to it. The probe shown here is nearly parallel to the canal bed.*

5.5 OTHER TESTS TO INVESTIGATE THE ACCURACY OF THE INSTRUMENT

The following tests were also performed to investigate the accuracy of the instrument under circumstances where the instrument is suspected of giving faulty readings.

5.5.1 MINIMUM FLOW DEPTH FOR WHICH ACCURATE READINGS CAN BE EXPECTED

Reliable performance of other instruments such as the Starflow Doppler flowmeter, can only be expected approximately 50mm and further away from the channel bed (Vermeyen, 1999). To test this limitation for this instrument, three sets of experiments with different flow rates were performed in the canal used for the tests of the Doppler meter in combination with the Crump weir. The probe was positioned at position 6 (for location of positions refer to Section 5.3.1). The probe was put flush on the bed of the canal and then raised in steps of 20mm until the top face of the probe protruded out of the water. For each vertical position a set of ten Doppler frequencies at ten-second-intervals were observed.

5.5.2 MINIMUM VELOCITY THAT CAN BE MEASURED

These tests were carried out in the 2 metre wide canal which contained the Crump weir in combination with the sluicing flume. The flow rate varied over all experiments and the water level was then allowed to stabilize after each flow rate adjustment. Once the water level had stabilized the flow depth in the upstream channel was determined. The probe was then positioned directly above position 6 on Fig.5.5 and vertically at 60 percent of the flow depth (The theoretical point of the average velocity in a *wide* canal). For a typical set-up of a test refer to Fig.5.10.

The flow rate through the canal was determined from the manometer since these tests do not rely on how much flow is passing through the flume and over the Crump weir respectively. With the flow cross sectional area thus known, the average theoretical approach velocity could be calculated. The Doppler velocities were compared to this. The flume and the Crump weir were fully submerged by raising the sluice gate at the end of the canal high enough. This ensured a reasonably deep upstream pool and very low velocities for the flows that were passing through the canal. The effect of the flume of increasing the flow velocity in the centre section of the upstream pool was thus also reduced.

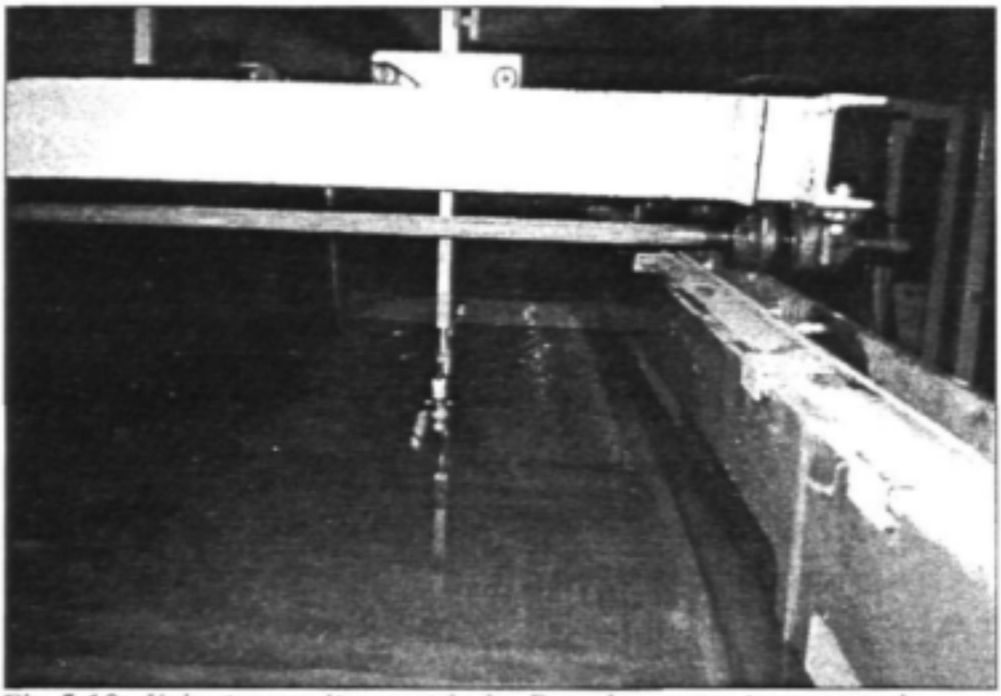


Fig 5.10: *Velocity readings with the Doppler meter in approach channel of the flume in combination with Crump weirs. The Probe is directly above position 6 on this photograph.*

The next chapter deals with the actual calibration of the Doppler meter, followed by the chapters discussing the results of all the other tests that were performed with this instrument.

6. INSTRUMENT CALIBRATION (RATING)

6.1 INTRODUCTION

In order to accurately determine the flow passing through the canal, the orifice flowmeter was first calibrated against the V-notch.

The discharge formula for an orifice plate in a pipe is derived from energy and continuity principles and is given by (Featherstone and Nalluri, 1995)

$$Q = C_d a_1 \sqrt{\frac{2gh}{k^2 - 1}} \quad \text{.............................6.1}$$

Where k $=a_1/a_2$

a_1 is the cross sectional area of the pipe

a_2 is the cross sectional area of the orifice

h is the head difference between sections 1 and 2

C_d is the discharge coefficient, equal to 0.61

Likewise, the discharge over a V-notch weir is given by (BSI, 1981)

$$Q = C_e \frac{8}{15} \sqrt{2g} h_e^{\frac{5}{2}} \quad \text{.............................6.2}$$

With C_e being the coefficient of discharge, taken as 0.59 (Figure 8, BSI, 1981)

h_e being the effective head = h + k_h

and h being the measured head and k_h is an experimentally determined value equal to 0.00085m for a 90^0 V-notch weir.

To calibrate the orifice flowmeter against the V-notch, the calculated discharge over the V-notch was taken to be 100% accurate and the discharge given by the orifice flowmeter was compared to this.
This is given by

$$\% \text{ of actual discharge} = \frac{Q_{manometer}}{Q_{V-notch}} \times 100\% \qquad \text{.............................6.3}$$

The average value for all the experiments, in terms of the *% of the actual value* was calculated and this was taken as the constant to correct the discharge as read from the manometer. The value was found to be 1.03, indicating that the orifice flowmeter underestimates the flow by 3%. The experimentally observed values and the calculations are found in Appendices A1 and A2

The flow for each experiment was now determined with the V-notch as it is more accurate than the orifice flowmeter. In cases where the water depth in the canal was too deep thus drowning the V-notch, the orifice flowmeter had to be used instead.

6.2 CALIBRATION RESULTS OF THE DOPPLER METER

6.2.1 METHOD USED FOR CALIBRATION

As mentioned in the previous chapter, the method employed to calibrate the Doppler meter was very similar to the *velocity-area method* that is used to calculate discharges in streams. This calibration method was recommended by the manufacturer of the product. The flow cross-section for each individual experiment was divided into a number of segments and the probe was then positioned so that it measured the Doppler frequency at the centre of each segment. Ten readings were taken at the centre of each segment and the average of these measured frequencies was then used to calculate the Doppler constant.

Recall that the velocity measured with a Doppler meter is given by equation 4.14 but instead of using the theoretical Doppler constant we now substitute

$$v_i = \frac{f_{Di}}{K} \text{..............................} 6.4$$

where K is the Doppler constant and f_{Di} being the Doppler frequency or the frequency we observed with the Doppler meter at block NR i and v_i the flow velocity through that segment.

With the flow velocity through each segment thus known, it can be stated that

$$Q_i = v_i A_i \text{..............................} 6.5$$

where Q_i is the flow rate,

v_i the flow velocity and

A_i the cross sectional flow area of each individual segment.

If we add all the Q_i's we must obtain the same Q-value as the discharge measured at the V-notch or the orifice flowmeter. The Doppler constant was assumed constant for all cross sectional areas. Therefore

$$Q_T = \sum_{1}^{N} Q_i = Q_{V-notch/manometer} \text{..............................} 6.6$$

where Q_T is the total flow

N the number of blocks per cross section and

$Q_{V\text{-}notch/manometer}$ is the flow as per the V-notch or the manometer

From this relationship the Doppler constant can easily be determined to be

$$K = \frac{\sum_{1}^{N} f_{Di} A_i}{Q_T} \quad \ldots\ldots\ldots\ldots\ldots 6.7$$

with all symbols as described above.

Seven experiments with different flow rates and flow depths were performed. For each experiment the Doppler constant was then determined as per equation 6.7. The constant varied for different flow rates and different flow depths, ranging from as low as 1403.8 to as high as 2514.9. The results are summarised in a graphical form in Fig.6.1. For all the readings and the calculation of the Doppler constant, refer to Appendix B.

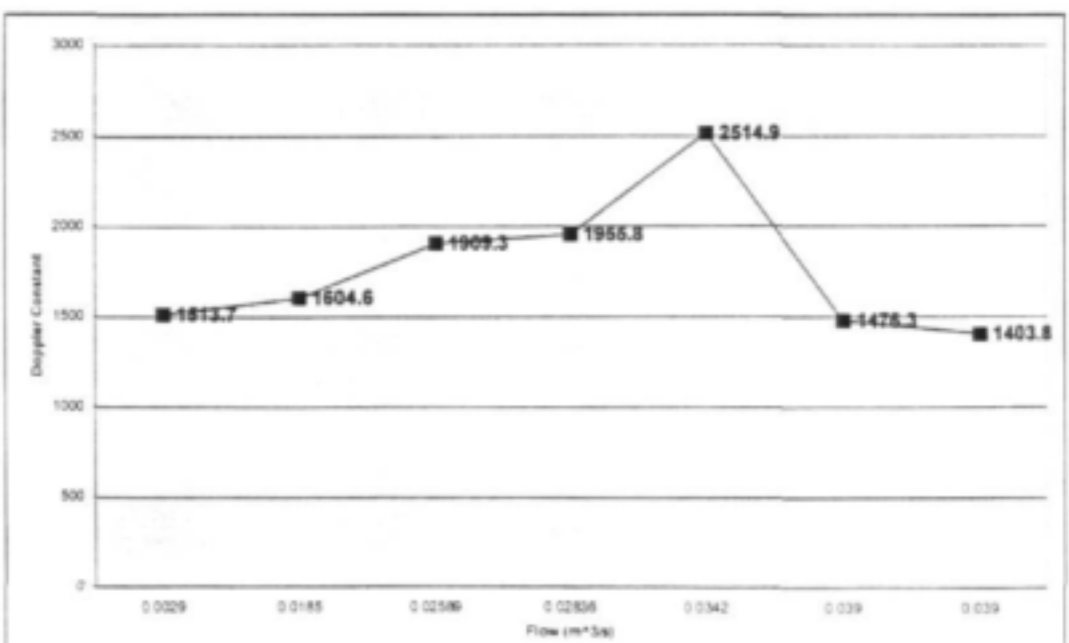


Fig.6.1 *Doppler constant with varying flow.*

6.2.2 DISCUSSION OF CALIBRATION RESULTS

As is evident from Fig.6.1, the constant showed variations through all the experiments and did not yield a constant value close to the theoretical value of **1375** derived in Section 4.4. The value of the constant had a range from **1403.8** to as high as **2514.9**.

A discussion of these results and possible effects some factors might have on the Doppler constant follows.

6.2.2.1 EFFECT OF DIFFERENT FLOW RATES

As mentioned above and considering Fig.6.1, the flow rate apparently had no well-defined relationship with the Doppler constant. No clear pattern, showing that the constant either increases or decreases with increasing flow or vice versa could be established. The flow rate however has a direct influence on the constant as the Doppler constant is calculated using the flow passing through the canal. Ideally, the constant should stay constant for different flows. This was not found in the experiments in the laboratory for reasons discussed later.

The effect of errors in the measurement of the flow rate was investigated and the summarised results can be seen in Appendix G. The table shows that an error in the measurement of the flow rate of 1 % roughly results in a change of about 1 % in the K value (Doppler constant). This approach assumes however that the measured Doppler frequencies are 100 % accurate, which is highly unlikely. The accuracy of discharge measurements made with a V-notch thin plate weir depends primarily on the accuracy of the head measurements and the applicability of the discharge formula and coefficients used. The accuracy in a single determination of discharge thus depends on the components of the uncertainty involved, but approximate ranges of uncertainty for a V-notch (at

95% confidence level) are from 1% to 2% (BSI, 1981). The uncertainty in the Doppler constant because of uncertainties in flow rates is thus likely to be in the same range, which is very small. The conclusion therefore was that the scatter of the Doppler constant was determined by other factors and not by the flow rate.

6.2.2.2 EFFECT OF FLOW DEPTH

All experiments, to determine the effect of the flow depth on the Doppler constant, were performed with different flow depths. Figure 6.2 shows how the Doppler constant changes with different flow depths. From this figure it appears that the calculated Doppler constant increases with increasing flow depths but this is however, in itself, not the case since the flow depth does not have a direct influence the Doppler constant. The flow depth was merely used as a basis to divide the flow cross sectional area into a number of segments or sub-divisions and with increasing flow depths more segments were applied at which readings were taken. The effect of these sub-divisions on the Doppler constant will be looked at further on in this chapter.

To prove this statement, a test with the **same flow rate** but with different flow depths was performed. These experiments were performed with flow depths of 14.2 cm and 26.6 cm respectively. This represents a difference of 47 % in flow depth. The Doppler constant however only differed by some 5 %, having a magnitude of 1403.8 for depth 14.2 cm and magnitude 1476.3 for depth 26.6 cm. If the flow depth had a direct influence on the Doppler constant, the difference in the two K values or the Doppler constants should have been more appreciable considering the percentage difference in the flow depth.

It thus becomes apparent again that the flow depth is directly dependent on some other factor, which in turn influences the Doppler constant. The statement that the Doppler constant increases with increasing flow depth from the trend depicted in Fig.6.2 is thus in itself not entirely correct. This other factor, which is inter alia dependent on the flow depth, thus appears to have a more direct effect on the varying Doppler constant.

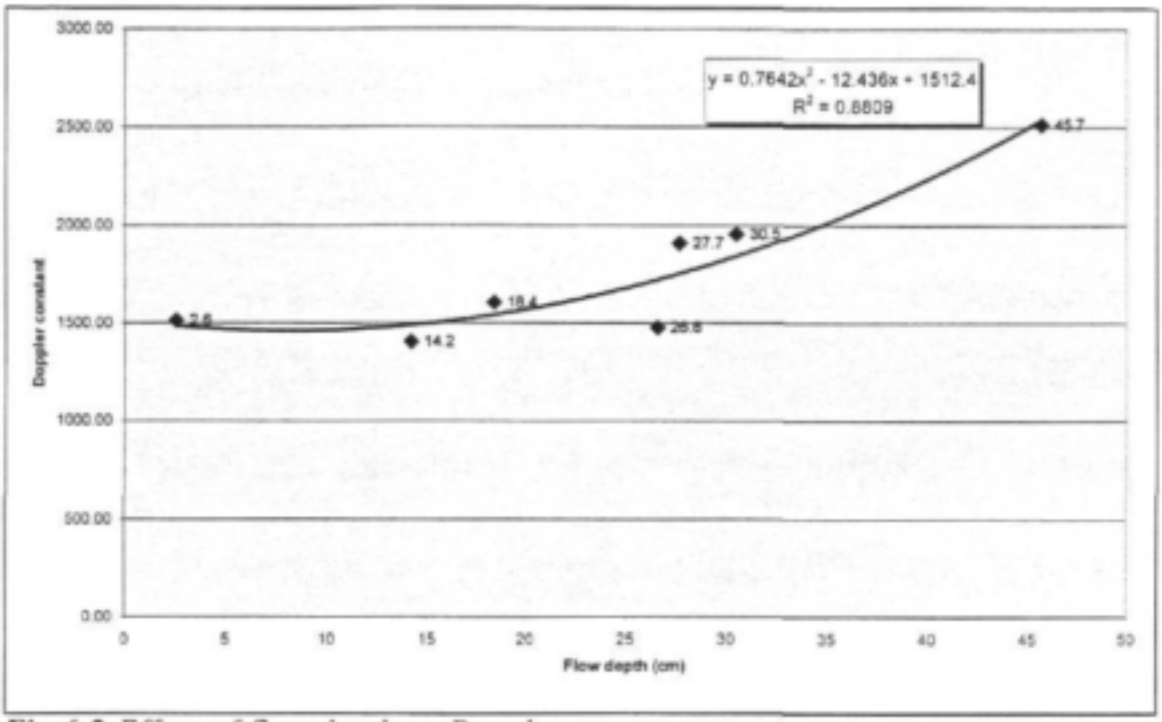


Fig.6.2 *Effect of flow depth on Doppler constant.*

6.2.2.3 EFFECT OF NUMBER AND SIZE OF CROSS-SECTIONAL SUB-DIVISIONS

As described previously, the cross-sectional flow area was divided up into segments, all of the same size. Each cross-sectional area element of the flow is to be linked with the *average* velocity measured through it. The total flow was then calculated by integrating over all segments. In general, the method is very similar to the *velocity-area method* and the same guidelines in terms of constraints have been applied here. Two important aspects are firstly that the measured velocity in each segment should represent the average velocity through that segment as closely as possible e.g. by measuring at 0.6 depth (one-point method) or at 0.2 and 0.8 depths (two-point method), and secondly that the flow through each segment should not exceed 10 % of the total flow (Shaw, 1983). Since the velocity-area method uses segments that stretch from the water surface to the bottom of the channel, both the one-point and two-point methods were applied. It is generally accepted that in wide channels, the average flow velocity occurs at 60 % of the depth measured from the water surface. In this study the velocities (frequencies) were measured at the centre of each small segment. The other constraint has however been met with the percentages of the flow through each segment being generally well below the 10 % limit. The only exception was experiment 7, where the highest percentage through a segment was 11.4 %, which is still very close to the limit. For the full table of the percentages through each segment, refer to Appendix C, Table 7.

Ideally a large number of segments should be used. Figure 6.3 depicts the relationship between the number of segments that have been used for each respective experiment and the Doppler constant. Theoretically the Doppler constant should be decreasing in value with increasing number of segments. It appears from Fig. 6.3 that this is not the case and that the Doppler constant remains fairly constant with the number of segments used. From Fig. 6.4 it appears however that the areas rather than the number of segments has a more pronounced effect on the Doppler constant. The area of each segment was plotted against the Doppler constant on this figure. It indicates that with smaller areas, the Doppler constant converges at around a value of 1500 and that the constant starts increasing with bigger areas.

For a given cross-section, the number of segments is clearly linked to the size of each segment. Figures 6.3 and 6.4 should therefore theoretically indicate the same trend. The reason that the trend on Fig.6.3 does not coincide with the trend on Fig. 6.4 may be that the minimum number of segments indicated in Figure 6.3 is already sufficient to provide a good estimate of the Doppler constant. The percentages of the flow that passed through each block were all well below ten percent with the exception of experiment 7 where the maximum percentage was 11.4 %. If higher percentages of the flow had passed through each segment, the trend as depicted by Fig.6.4 would also emerge. This means that in a bigger canal, even with more segments in the cross-section but with higher percentages of the total flow passing through each segment, the Doppler constant would in all likelihood start increasing to values higher than the ones obtained here.

The conclusion that can be drawn from this is that the number of segments that were used for these calibration experiments was sufficient so that less than ten percent of the flow passed through each of them. The Doppler constant thus appeared to be stable within this range. Within this limit of the flow being less than ten percent through each segment, the area of the individual segment however still showed some sensitivity to the calculated Doppler constant. Hypothetically, if the area of the segment would become infinitely small, the ideal condition would be obtained where the Doppler meter would measure the average flow velocity through that segment much more accurately. Due to time constraints and the calibration experiments being very time consuming and only six valid experiments remaining, the area of the segments was thus assumed to be the critical variable for deriving the correct Doppler constant.

Smaller areas give a more realistic representation of the average flow velocity through each segment than bigger areas. A bigger area might have the point where the average velocity occurs quite far away from the centre of the segment where the velocity is measured. This explains that with bigger areas, the Doppler constant increases slightly as is seen on Fig.6.4.

The experiment, which yielded a Doppler constant of value **2515** is clearly an outlier with the reason for this error given later on in the report. The constant obtained for this experiment is also plotted on both Figures 6.3 and 6.4.

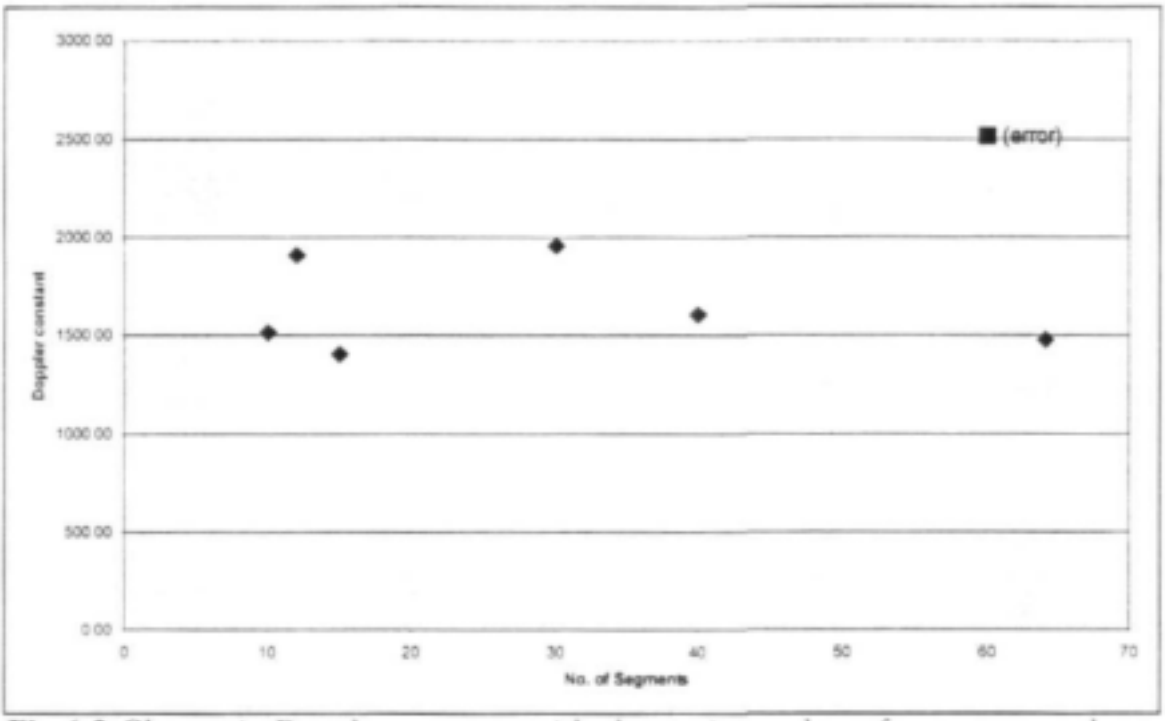


Fig.6.3 *Change in Doppler constant with change in number of segments used.*

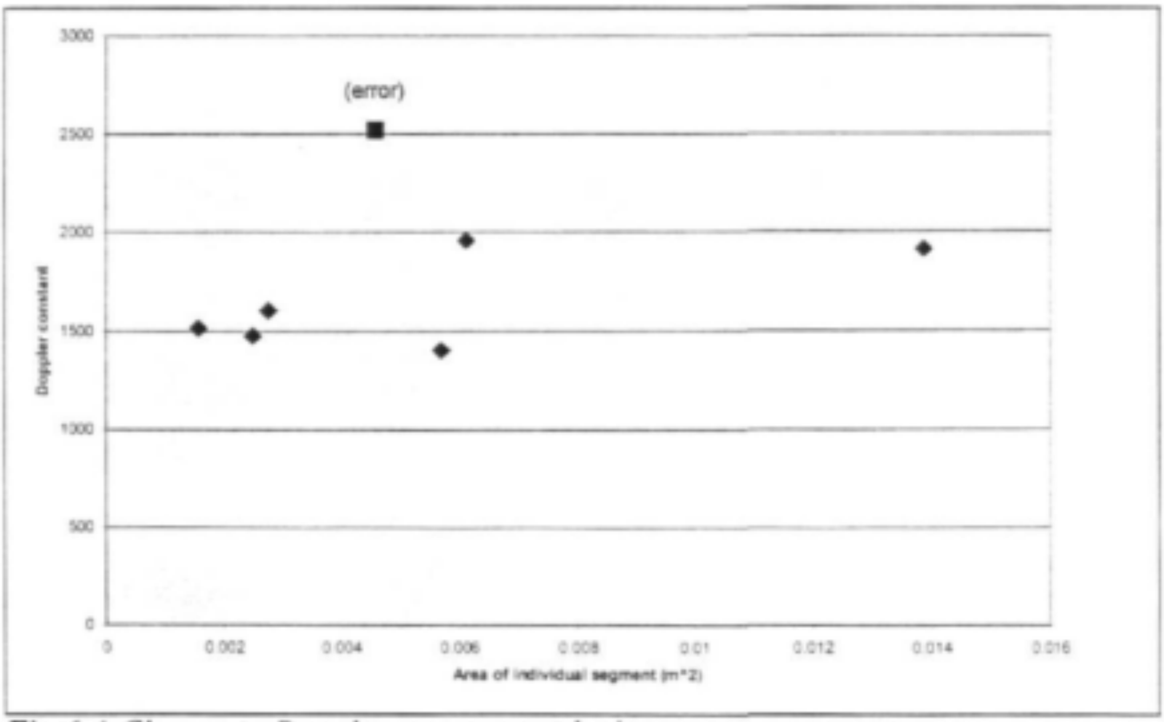


Fig.6.4 *Change in Doppler constant with change in segment area.*

6.2.2.4 EFFECT OF ANGLE BETWEEN TRANSMITTER AND RECEIVER IN THE PROBE

It has been mentioned earlier on in the report that the angle between the transmitting and the receiving crystals in the probe is unique to every probe and that this angle was roughly 10 degrees (Recall Fig.4.4). If an infinite number of tests are carried out in the laboratory, an average of all the Doppler constants can be found and working in reverse with this Doppler constant in equation 4.19, the angle between the crystals can be found. We will however follow a different approach and test what effect a slight change in the angle in equation 4.19 will have on the Doppler constant. The results are summarised in Table 6.1 below.

Angle between crystals	Theoretical Doppler constant	Parallel to flow component	% difference
5^0	1379	1378	-0.07
10^0	**1379**	**1374**	**-0.36**
15^0	1379	1367	-0.87
20^0	1379	1358	-1.52

Table 6.1 *Change in Doppler constant with change in "between-crystal" angle.*

The table clearly shows that the angle between the Doppler crystals has a very small influence on the Doppler constant, with the bold values representing the angle accepted in the theoretical derivation. If we assume the angle to lie in the range as per Table 6.1, the Doppler constant only differs from the nominal value by 0.07 % in the lower range and 1.5% in the upper range. This deviation is small and we can thus accept an angle of about ten degrees between the transmitting and the receiving crystals in the probe.

It can also be stated here that the USBR Water Research Manual, 1998, also cites that for every one degree of uncertainty in path angle, only about one percent uncertainty in velocity measurement was observed in their tests on acoustic flow measurements.

6.2.2.5 VELOCITY DISTRIBUTION INSIDE THE CANAL

The purpose of the Doppler meter is to measure the velocity at any given point inside a canal or a stream. The next step was to check whether the observed frequency and thus the respective point velocity agreed with the theoretical velocity at a point. The full calculations of the theoretical velocities and the velocity gradients are given in Appendix C, Tables 1 to 6. Table 2 indicates that the vertical velocity gradient in the lowest segment of each experiment is high, showing that the velocity increases rapidly with increasing height over this area. Towards the water surface the gradient decreases, showing some agreement with the theoretical vertical velocity distribution in a wide channel. A typical vertical velocity profile is depicted by Fig.6.5 (a).

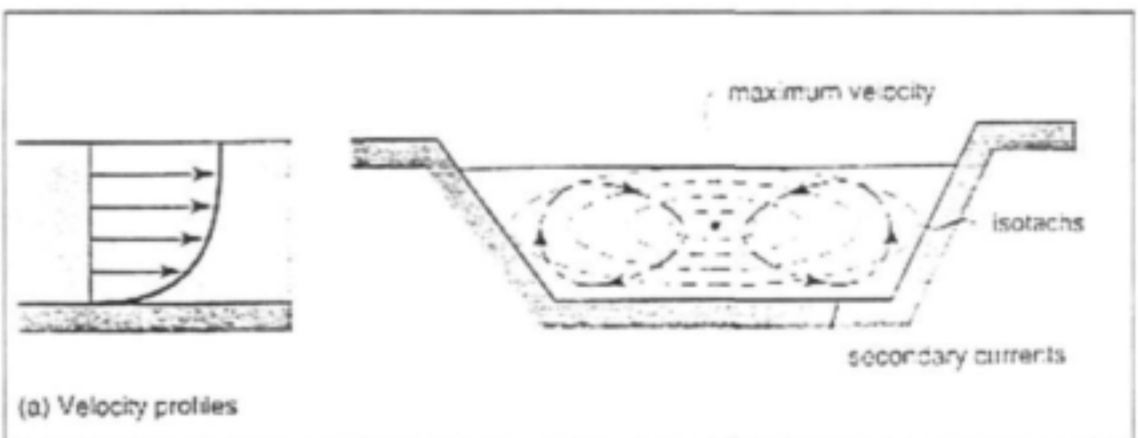


Fig.6.5 *Velocity distribution in a channel.*

The calculated theoretical velocities in the centre of the canal (See shaded segments in Appendix C, Table 4A) were also converted into a theoretical Doppler constant by using the theoretical velocity that should occur at each height in a wide channel. As mentioned in Section 6.2.4, the average of an infinite number of tests to calibrate a Doppler probe should yield a constant unique to that probe. The constant was averaged for each experiment and then averaged over the full range of experiments. A value of **1341** (Appendix C, Table 4B) was obtained, which is close to the theoretical value of **1374**. The difference from the theoretical Doppler constant value is only 2.4%. Note that only the centre segments were chosen, as they would approach two-dimensional flow more closely, which the theoretical calculation of velocities is based on.

All experiments were performed in a canal, 0.6 metres wide. This is far from being a wide channel. In a channel of limited width, the velocity is higher in the middle than at the sides and near the bed. Figure 6.5 shows the velocity profile in a typical channel and in cross-section, where isotachs (lines of equal velocity) are shown. The changes in velocity across the channel cause small changes in pressure and they in turn are responsible for setting up cross-currents which flow from the side of the channel towards the inside of the channel. They are called secondary currents. An explanation now for an increase of the Doppler constant for higher flow depths, is that at higher depths these currents became more pronounced in the narrow channel. A particle could thus be travelling from the canal side towards the centre and the Doppler meter would register the component toward the probe of that particle. At lower flow depths, the flow became more two-dimensional or uniform, as indicated by Table 6 (Appendix C), where the actual flow approaches the theoretical flow more closely. This also explains the trend that with increasing flow depths a higher Doppler constant was observed in Fig.6.2. To prove again that the flow depth had no actual effect on the Doppler constant, the percentage of the segment area to the flow area (dependent on the flow depth) was plotted against the Doppler constant and can be seen in Fig. 6.6. If the flow depth had an influence on the constant, then the Doppler constant should be increasing with decreasing percentages, i.e. flow depth increases with segment areas remaining constant thus lowering the percentage. This is not evident from the graph, where the points have a random distribution around a horizontal line. The cross-currents mentioned here are thus the reason the Doppler constant increases with increasing flow depths and not the flow depth in itself.

These cross-currents also reduce the actual translatory velocity at higher depths in a narrow channel from what would occur in pure two-dimensional flow. Closer to the surface the actual velocity in a narrow channel is thus expected to be lower than the velocity at the same depth in a wide channel where two-dimensional flow prevails.

This observation was also made when the ratio between the measured Doppler velocity and the theoretical velocity was plotted against the velocity gradient (See Figure 6.7). All plots show the same trend, that with increasing velocity gradient, the percentage difference between them seems to stabilise and that at lower gradients the percentage seems to decrease. This means that at lower velocity gradients, the measured Doppler velocity underestimates the theoretical velocity that should occur in a wide channel at that depth, even more.

The implication of this plot was that the Doppler meter actually measured correct velocities at each respective depth and that it consistently underestimated the theoretical velocity. This would however be expected for a narrow channel. To explain this further, a plot of the velocity profile for a typical experiment, experiment 4 in this case, was drawn. The theoretical velocity profile is shown, as well as the measured Doppler velocity profile (See Figure 6.7). The measured Doppler velocity profile is typical for conditions in a narrow channel such as the one being used here. Both figures show that closer to the channel floor the two velocities are in better agreement than closer to the water surface. The reasons for this were once again the cross-currents, becoming stronger at higher depths.

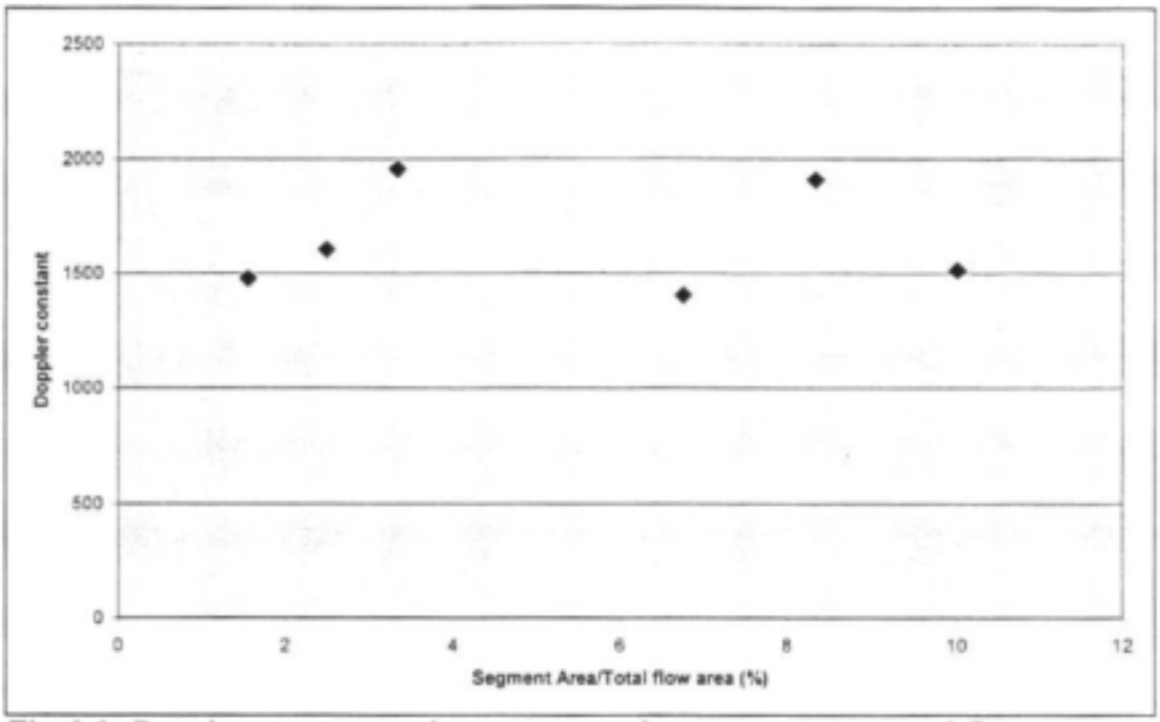


Fig 6.6: *Doppler constant with percentage of segment area to total flow area.*

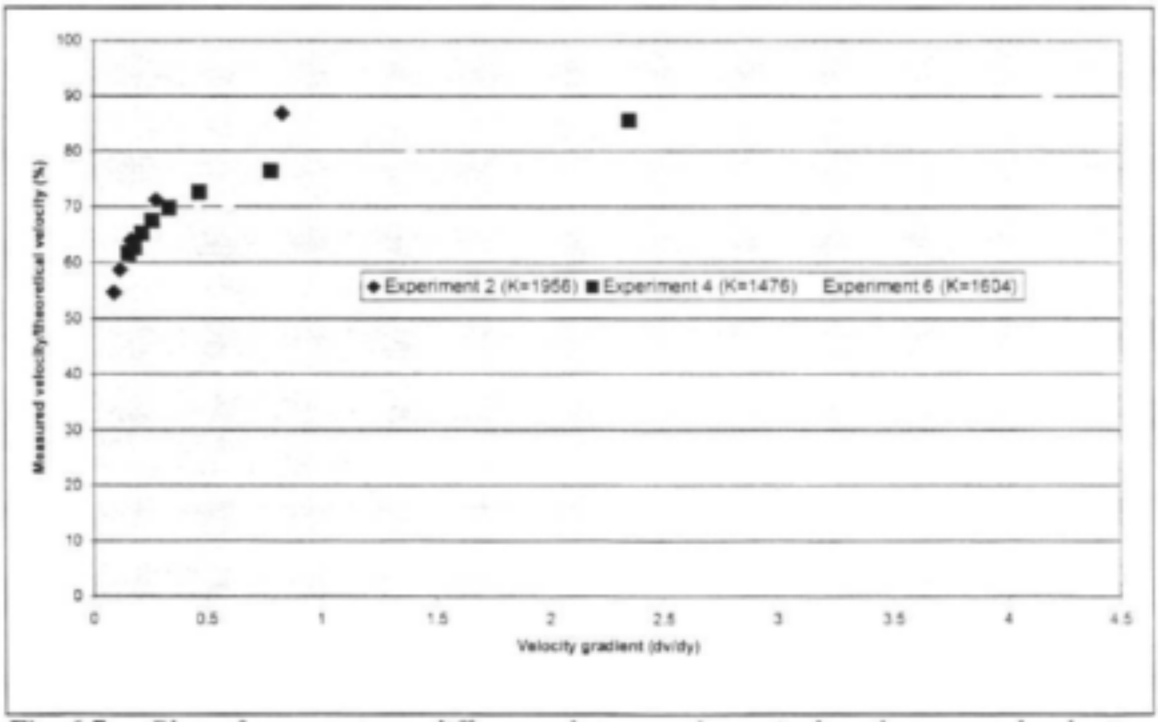


Fig 6.7: *Plot of percentage difference between theoretical and measured velocity against the vertical velocity gradient.*

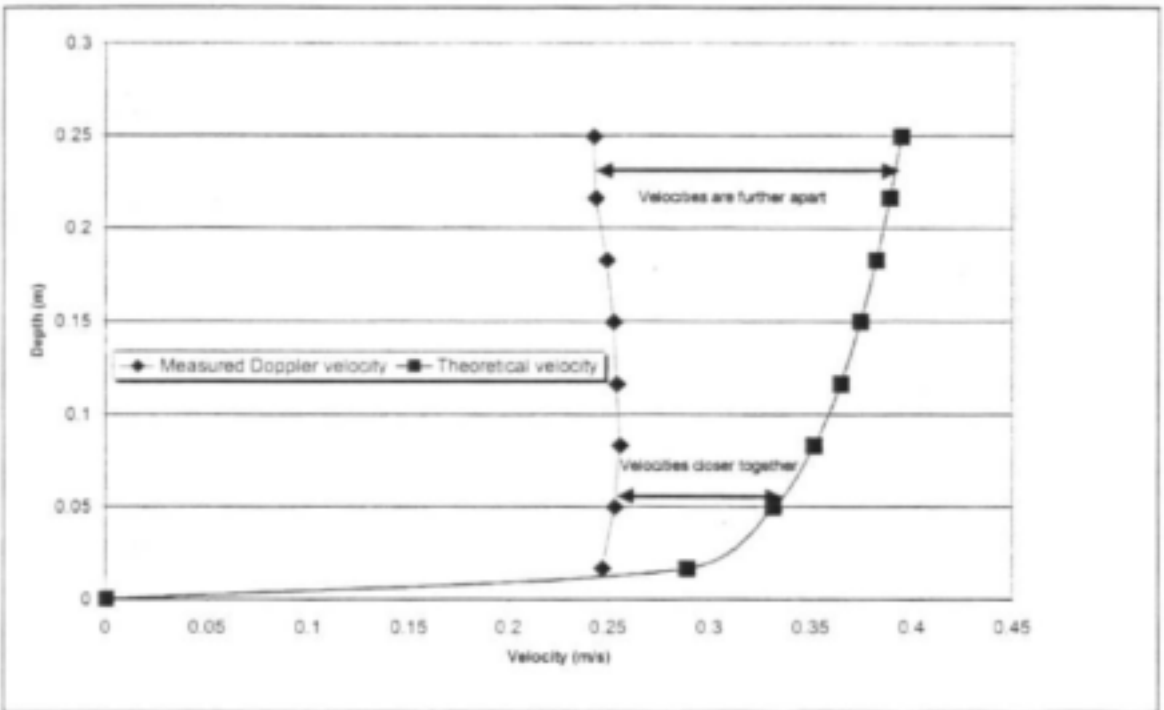


Fig 6.8: *Velocity profiles for the theoretical velocity and the measured Doppler velocity for experiment 4.*

The Doppler constant could not be linked directly to the velocity gradient as the gradient differed over each depth but the Doppler constant was assumed to remain constant for the whole experiment, i.e. for all depths. The Doppler meter is expected to give accurate readings over all velocity gradients (from the velocity profile in Fig.6.8) and it should be linked to the sub-divisions used in the calibration. From observing the trend on Figure 6.4 again, it is apparent that decreasing areas of the segments leads to a reduced value of the Doppler constant. Smaller areas make provision for more velocity measurements and the integration over the total flow thus becomes more accurate. The velocity gradient has a limited effect on the readings of the Doppler meter.

6.2.2.6 VARIATIONS OF FREQUENCIES OVER TIME

The probe of the Doppler meter continuously sends out sound waves and will show a reading every time a wave gets reflected by a moving particle. At times one reading will thus be stationary on the display of the microprocessor for a few seconds and at other times the readings change about every second. In order to take only one reading at a time, especially at times when the readings changed rapidly from one value to the next, only the readings displayed at *exactly* 10-second intervals were taken. In order to check the validity of 10 readings taken at only one position once, a test was performed to see how much a next set of readings would differ from the first. Different positions, in terms of the horizontal position (x) and the vertical position (y) in the canal were chosen and tested at random and then compared to each other. The results are summarised in Table 6.2 and the readings in Appendix D.

	x/y	x/y	x/y
	49.84/150	17.85/350	36.12/550
Overall Mean	**306.5**	**363.2**	**320.1**
	% Individual Tests Mean is off from Overall Mean		
Run 1	1.5	-1.9	-0.3
Run 2	-1.8	2.6	-1.2
Run 3	-0.2	-0.4	0.6
Run 4	0.6	-0.3	0.8

Table 6.2 *Difference in readings at same position.*

As can be seen in Table 6.2, the variations from one set of readings to the next is very small, with the mean value of one set of readings not deviating from the overall mean by more than 2,6 %. It can thus be concluded that the single sets of readings at all the various positions provide a good indication of the average frequencies observed there.

6.2.2.7 EFECT OF TIME INTERVAL USED

Calibration tests were performed by taking readings every 10 and 30 seconds respectively. The readings, together with the calculations of the variations are summarised in Appendix E. Readings were taken at different vertical and horizontal positions. The vertical and horizontal positions correspond with the calibration test, Experiment 2, in Appendix B. For each vertical *level* the difference between the average of the two sets of readings was expressed as a percentage difference. The summary of these differences is given below in Table 6.3.

As is evident from the table, the time interval between readings does not have a significant influence on the average of a set of readings. In most cases the difference in the average of the whole set of readings is less than 1 %. The time interval of 10 seconds between individual readings thus provides a realistic representation of the Doppler frequency.

Vertical Position	Average % Difference
y_1	1.5
y_2	-0.6
y_3	-0.3
y_4	-0.8
y_5	0.7
Average	***-0.25***

Table 6.3: *Summary of differences in readings for 10 and 30 s time intervals between readings.*

7 CONCLUSIONS ON THE CALIBRATION OF THE DOPPLER METER

7.1 CALIBRATION OF THE DOPPLER METER

7.1.1 CALIBRATION RESULTS

In order to carry on with this project, i.e. to test the Doppler meter at a Crump weir for both low and high flows, the Doppler meter had to be calibrated and conclusions had to be drawn on the Doppler constant to be used for further tests. Even though the calibration facilities in the laboratory were not ideal for the Doppler meter, i.e. narrow canals, an estimation of the constant for further tests was carried through.

From the discussion in the previous chapter, it is clear that the only variables having a significant enough influence on the Doppler constant, are the number and size of the sub-divisions that were used for each experiment.

The Doppler constant of 2514.9, obtained in Experiment 3, Appendix B, is an outlier. According to Fig. 6.4 in Chapter 6, the value of the constant for that experiment should be close to 1500. Even the effect of the cross-flow cited in the previous chapter, could not have pushed the constant to such a high value. The only real reason for this outlier value can be the inaccurate measurement of the discharge for that experiment. The water/air manometer, which was used after it had been replaced with another, gave problems during the experiments. It was found that every morning, air was present in the pipes of the manometer and even after the instrument had been bled, sometimes, for no apparent reason, air showed up in the pipes again. In this specific experiment the flow depth drowned the V-notch and the flow measurements were thus performed with the orifice flowmeter. In all other experiments flow was measured with the V-notch. The manometer was checked that day and also compared to the V-notch prior to the experiment but by the time the experiment got underway, air must have entered the manometer's pipes again and thus an incorrect head was recorded. According to Fig. 6.4 an experiment with segment areas of the size that were used here should yield a Doppler value of about 1500. All other experiments show that trend and if Experiment 3 was not an outlier because of an error in the measurements taken during that test, other experiments should have shown a more random distribution of the constant as well. If Fig 6.4 is plotted again, ignoring the value obtained in Experiment 3, the trend, that with smaller segment areas the constant converges at around 1500, is much clearer. In fact the value would approach about 1460 when the area of the segments would become infinitely small. These points were plotted and linear regression analysis applied to them. Fig. 7.1 depicts the trend and also the trend line of the points.

It was mentioned in the previous Chapter that in order to obtain the angle between the transmitting and the receiving crystals in the probe, a number of tests must be performed to calibrate the Doppler meter. The angle of the probe can then be found by working backwards in equation 4.19 and by using the average of all the Doppler constants obtained. To calibrate a Doppler meter thus, a number of tests must be performed and the average of all the tests is an indication of the Doppler constant unique to that particular Doppler meter. Excluding Experiment 3 here, the average of the other 6 experiments yields a Doppler constant of *1643,9*. Only six valid sets of results remain and ideally a larger number of experiments are required to obtain an average value accurately representing the Doppler constant. These experiments should include tests over different flow depths, widths, flow rates and individual block cross-sectional areas that are sufficiently small. Our experiments were all performed in a 600 mm wide canal. In order to derive a calibration value with this limited data available, the point where the trend line in Fig. 7.1 cuts the Y-axis, i.e. the Doppler value, will be taken as the correct constant to be used for this instrument. This represents the hypothetical value if an infinite number of sub-divisions would be used and their areas would be infinitely small. A conservative estimate of the average over a large range of flow conditions and sub-divisions would thus be achieved. This point corresponds to a value 1459,5 and rounded off to a value of **1460**. The use of this value will also be justified in the next section.

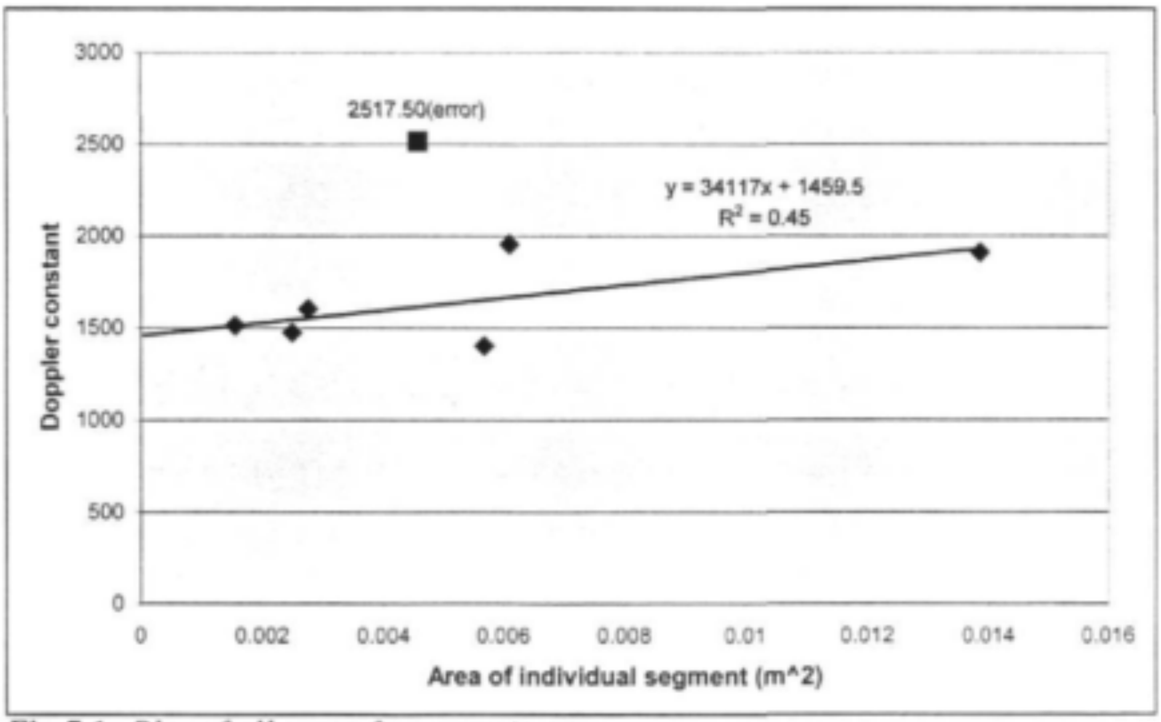


Fig 7.1: *Plot of all error free experiments.*

7.2 ELECTROMAGNETIC FLOWMETER: A COMPARISON

The opportunity arose to test and compare a portable flowmeter, the Marsh-McBirney Model 2000 Flo-Mate, with the Doppler meter. It was tested in the same canal where the calibration experiments for the Doppler meter were carried out. The unit uses an electromagnetic sensor to measure the velocity in any conductive liquid such as water. The velocity is measured in one direction and displayed in either feet per second (ft/s) or metres per second (m/s). It operates according to the Faraday law of electromagnetic induction. This law states that as a conductor moves through a magnetic field, a voltage is produced. The magnitude of this voltage is directly proportional to the velocity at which the conductor moves through the magnetic field. When the flow approaches the sensor from directly in front, then the direction of the flow, the magnetic field and the sensed voltage are mutually perpendicular to each other. Hence, the voltage output will represent the velocity of the flow at the electrodes. The sensor is equipped with an electromagnetic coil that produces the magnetic field. A pair of carbon electrodes measures the voltage produced by the velocity of the conductor, in this case water. The measured voltage is processed by the electronics and the output is a linear measurement of velocity.

The instrument uses a wading rod that is held in the water manually, with a support at the bottom. A scale is engraved onto the staff and a simple procedure makes it possible to measure at 60 % of the flow depth, the point where the average velocity theoretically exists. For a given flow depth, this point can be determined quickly and the sensor is positioned there. The Doppler meter was tested in the same position.

7.2.1 COMPARISON OF READINGS

After Experiments 4 and 5, the electromagnetic flowmeter was tested inside the canal at 60 % of the flow depth. The probe of the Doppler meter was then positioned in the same position horizontally and vertically. For the full set of readings refer to Appendix F. A summary of the readings and a comparison can be seen in Table 7.1. The Doppler frequency was first converted into a velocity by using the Doppler constant that was derived for that particular experiment, **1476.3** for Experiment 4 and **1403.8** for Experiment 5. The values are given under column "(a)" in Table 7.1. The averaged Doppler constant or calibration constant derived for this instrument of magnitude **1460** was then used to convert the frequencies into velocities. The values are shown under column "(b)" in Table 7.1.

	VELOCITY (m/s)				
TEST	**FLOW-MATE**	$K_{EXPERIMENT}$ (a)	$K_{CALIBRATE}$ (b)	% Difference (a)	% Difference (b)
1	**0.473**	0.482	**0.463**	1.9	**2.1**
2	**0.264**	0.255	**0.258**	3.4	**2.3**
			Average	**2.7**	**2.2**

Table 7.1: *Difference in flow velocities between Electromagnetic flowmeter and Doppler meter. (a) – Value as per constant for Experiments 4 and 5 and (b) - as per calibrated constant.*

The difference in the measured flow velocity between the two instruments was then calculated for both cases. The calibrated constant shows better agreement with the electromagnetic flowmeter with the values only differing on average by 2.3 %. In other words, using the calibrated value of **1460** as the Doppler constant would result in velocities very close to the velocities that were measured with the electromagnetic flowmeter. This additional experiment supports the theory of deriving the Doppler constant for this apparatus as per Section 7.1 and also the applicability of the calibrated value because it would be highly unlikely that both flowmeters measure incorrect velocities of the same magnitude. By looking at the difference in the velocities derived by using the Doppler constant for each individual experiment, one can deduce that both devices measure virtually the same velocities in magnitude.

Equation 4.19, to convert the measured Doppler shift frequency into a velocity, thus becomes:

$$v = \frac{f_D}{1459.5} \approx \frac{f_D}{1460} \qquad 7.1$$

This equation will from now on be used to convert the measured Doppler shift frequencies of this specific instrument into flow velocities.

7.3 NUMBER OF SUB-DIVISIONS NEEDED FOR CALIBRATION

The exact number of segments that are needed for the correct calibration of the Doppler meter can not be given. A plot of the experimental results, excluding Experiment 3, as shown in Figure 6.6, shows the Doppler constant calculated for each respective experiment against the percentage of the segment area to the total flow area. There is no trend that with an increase in the percentage, i.e. each segment representing a bigger portion of the total cross-section, the Doppler constant decreases or increases. The only conclusion that can be drawn is that when the panel area to the total flow area is below approximately **3 %** (To avoid higher variations becoming dominant), the Doppler constant which is obtained would be a reliable estimate of the value to be used. The Figure shows that variations in the constant were only introduced above a value of approximately 3 %. If, as a first assumption, the segments are taken to be square, then each side will have dimension:

$$x = \sqrt{0.03 \times W \times d} \qquad 7.2$$

Where W is the flow width and d the flow depth.

The approximate number of segments thus needed is obtained by dividing the canal width and the flow depth by the dimension of the square block.

$$\textit{No of segments in the vertical} = \frac{d}{x} = c_{11} \ldots\ldots 7.3$$

$$\textit{No of segments in the horizontal} = \frac{W}{x} = c_{21} \ldots\ldots 7.4$$

These values, i.e. c_{11} and c_{21} need to be rounded off to the nearest integer, i.e.

$$c_{11} \Rightarrow c_{12}$$
$$c_{21} \Rightarrow c_{22}$$

The number of segments to be used, that are within approximately 3 percent of the total flow cross-sectional area, are thus:

$$\textit{Total no of segments} = c_{12} * c_{22} \ldots\ldots 7.5$$

The estimate of the number of segments to be used is very conservative and would apply to canals that are fairly small in dimension. From observing Fig. 6.6, it seems that the constant remains fairly constant throughout the range of percentages up to approximately ten percent. Percentages higher than three percent introduce slight variations in the constant but in general it appears to be stable. If the calibration is to be performed in canals of bigger dimensions the 3 percent in equation 7.2 can be increased to values as high as 10 percent so that the number of segments to be used is reduced. The calibration procedure is time consuming and when working with bigger flow cross-sectional areas, i.e. in a bigger canal, this would result in a very large number of segments being applied. In order to save time the number of segments can be reduced by substituting values up to 10 percent instead of 3 percent. It appears that this would still result in a reasonable estimate of the Doppler constant, especially so if the flow is fairly uniform. If the flow is non-uniform, the conservative estimate of 3 percent should still be applied.

The key in calibration is that a sufficient number of tests must be performed and that the areas of the sub-divisions should be sufficiently small so that a similar trend to that depicted on Figure 7.1 is obtained. This calibration is to be used when the Doppler meter is to be used for field tests for point velocities in fully developed turbulent flow. If the Doppler meter is to be built in permanently at a weir and laboratory facilities are not available, it can also be calibrated in-situ before installation. This can be done, e.g. by positioning the probe at 60 % of the flow depth in the upstream pool of the weir and by comparing the readings of the Doppler meter with the calculated average velocity. The Doppler readings should give the same velocity at this point. The constant can thus be obtained accordingly.

It can be mentioned here, that the Doppler constant obtained in this study, only differs from the theoretical value of 1375 by approximately 6 %. Every instrument is expected to have its own calibration constant due to variations in the acoustic field that is dependent on the internal dimensions of the probe.

7.4 FREQUENCY OF READINGS

A discussion of these tests follows here as they might have had a direct influence on the calibration results.

A set of ten readings taken at 10-second intervals provides a good representation of the average Doppler frequency or ultimately the average flow velocity at a particular point. Such a set of readings does not change much from another set taken at the same location at a different time for steady flow. Refer to Table 6.2. As mentioned in Chapter 6, averaging of readings is essential for

Doppler meters as the backscattered frequencies originate not from a single point but from a small acoustic field close to the probe. By averaging the readings, an estimation of the average flow velocity in front of the probe (i.e. in the acoustic field) is achieved. Because of the small size of the transducer and the emitted frequency having a fairly low frequency (other Doppler meters have frequencies of 10 MHz) the acoustic field of this instrument is small. More about this in the next chapter.

For the purpose of the remaining study, the Doppler constant obtained in this chapter will be used.

8 DISCUSSION AND RESULTS OF THE FACTORS THOUGHT TO HAVE AN INFLUENCE ON THE OBSERVED DOPPLER FREQUENCY

8.1 EFFECT OF THE ANGLE OF THE PROBE

In perfectly uniform flow any angle (θ) that the probe makes with the horizontal, facing upstream, should theoretically result in Doppler frequencies observed that are lower than had the probe been held perfectly horizontally. The reason for this is that the probe would only detect the horizontal flow component of any particle toward the probe. The horizontal flow component is the value we are interested in and the observed frequency, if the probe is held at an angle, thus has to be converted to the horizontal component by dividing the observed reading by cosθ. In other words:

$$observed\ \ frequency = horizontal\ \ component \times \cos\theta$$

Since cos(0) is equal to one, i.e. if the probe is horizontal, any other angle will result in a multiplier smaller than unity and hence lowering the observed value. Theoretically the observed value with an inclined probe should thus always be smaller than the observed values with a horizontal probe.

The results of the tests with different angles of the probe relative to the channel bottom were plotted and the results agree with the above hypothesis. Refer to Fig. 8.1. From the discussion above, the Doppler readings at different angles should theoretically follow a cosine function. A best fit of form y = parameter×cos(angle) was established and that function is also plotted. A fairly good fit was achieved, with an R^2–value of 0.94. The small differences between the observed values and the regression line can be attributed to the fact that the regression analysis is based on the angles of the probe read off with a protractor. Any error in the reading of the angle with the protractor will thus introduce an error in the actual regression line joining all the points. From Fig. 8.1 it does however become clear that the angle of the probe, when accurately measured, should not affect the Doppler frequency and that the measured Doppler frequency, when the probe is held perfectly horizontally, is at a maximum.

It can thus be concluded that the probe, when held at an angle, can also be used to measure the horizontal flow component by simply multiplying the observed frequency by the cosine of the angle of the probe relative to the horizontal.

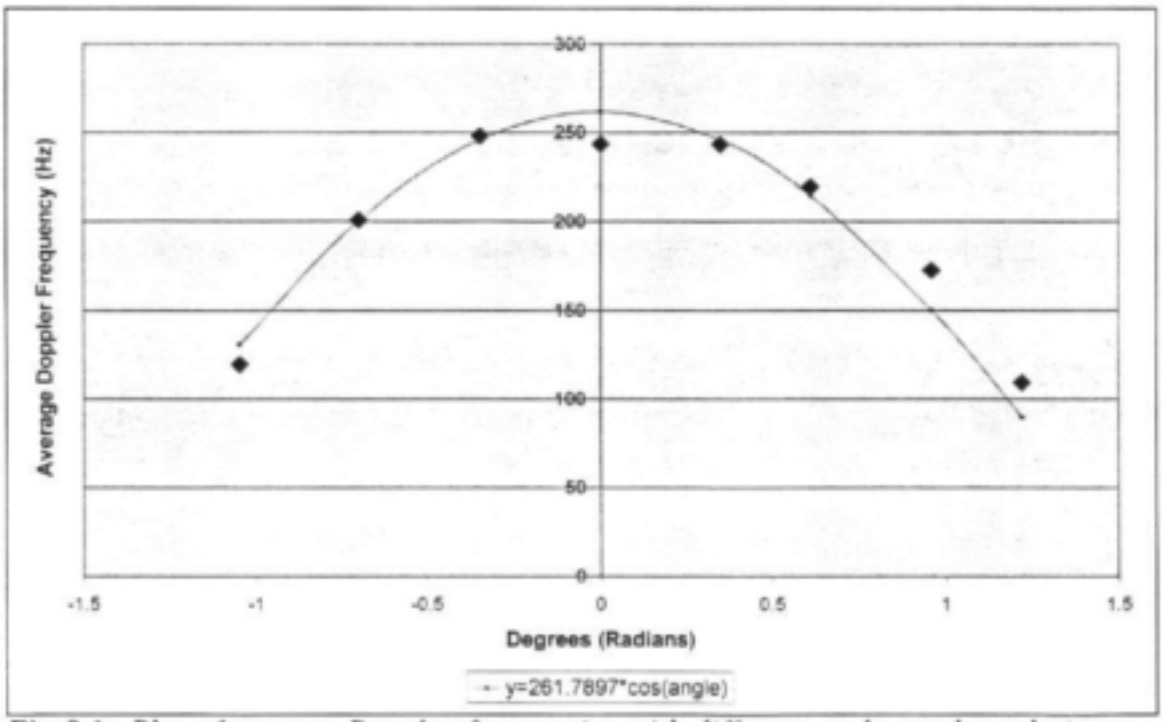


Fig 8.1: *Plot of average Doppler frequencies with different probe angles relative to the horizontal.*

8.2 EFFECT OF SEDIMENT CONCENTRATION

The sediment feed rates were plotted against the recorded average Doppler frequencies and can be seen in Fig.8.2. It seems that the Doppler frequencies jump to higher values when sediments are introduced to the canal and that they stay fairly constant throughout the range of sediment concentrations added. At very high sediment additions the frequency tends to be lower again.

The plots for the "clean" water and that for the high sediment addition rate were treated as outlying values and linear regression analysis was applied to the remaining points. The plot for the "clean" water differed by **–3.62%** from the linear regression line and that for the high sediment addition rate by **–1.57%**. Both values are thus still close to the expected Doppler frequency. The regression line also depicts the trend that the Doppler meter is not sensitive to different sediment concentrations. Ideally, the line should be perfectly horizontal, i.e. with no gradient. With only limited data available, the trend is however confirmed by the very small gradient. The sediment that was used for these experiments consisted of very fine sand and the canal used was only 150mm wide.

It seems that the Doppler meter observes lower frequency readings in the "clean" water than in water to which sediment has been added. It can however be mentioned here that the Doppler meter did not show any change in the readings in the 2 metre wide canal (tests with the Crump weir). Sand with clay was released into the water by hand upstream of the probe and when the cloud of suspended sediments reached the probe, no change in the frequencies could be observed.

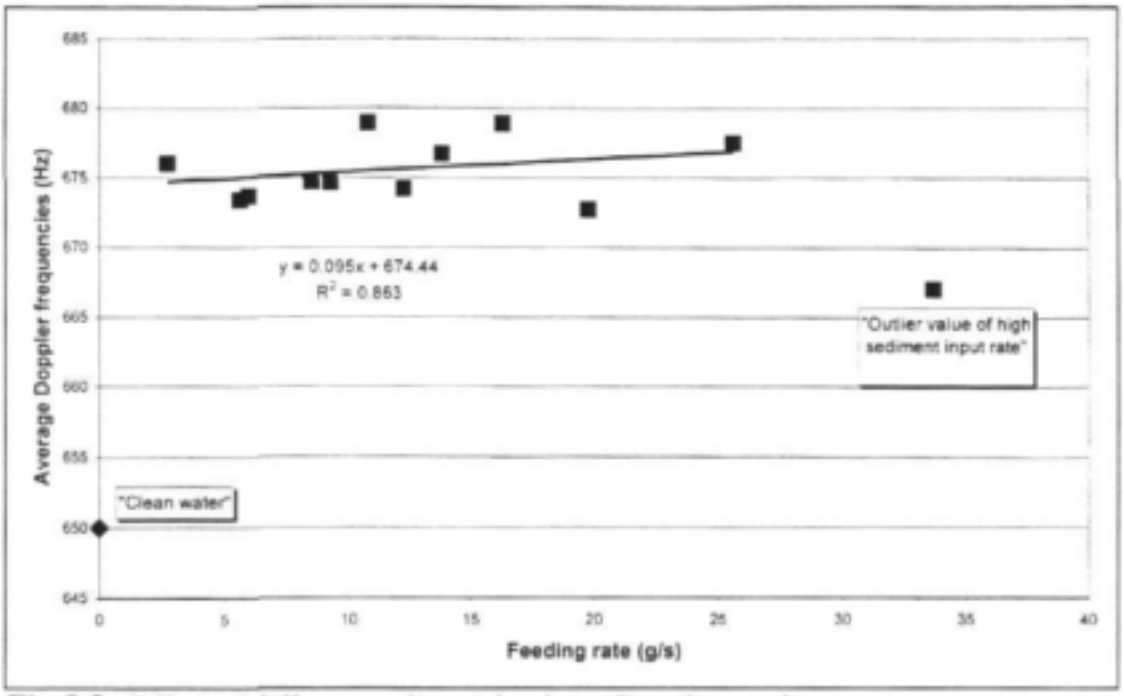


Fig 8.2: *Effect of different sediment loads on Doppler readings.*

In general, by just observing the small difference in the "outlying" values from the remaining sediment values mentioned above, it can be said that the Doppler meter is not sensitive to different sediment concentrations as long as the water is not perfectly clean. The Doppler shift makes use of the echo of the sound wave which it emits and that gets reflected by any moving particle in the water. The small sediment particles that are suspended in the water follow the path of the eddies in the water sufficiently closely to also represent the translatory velocity of the body of water (Rooseboom, 1992). Any one particle that reflects the acoustic wave of the Doppler meter at the level at which the Doppler probe emits the wave thus represents the translatory velocity of that particle, having its centre of rotation at the same vertical level at which the probe is positioned. In really clean water, there are no particles that can reflect the acoustic wave and the Doppler meter will give false readings. The water that gets circulated in the laboratory is not perfectly clean and it will thus be treated here as giving accurate readings since the error, when compared to the remaining sediment tests, is small (3.6 %).

8.3 MINIMUM AND MAXIMUM VERTICAL LEVELS AT WHICH THE DOPPLER METER CAN BE EXPECTED TO READ ACCURATELY

The Doppler frequencies were converted into velocities by dividing the readings by the Doppler constant obtained from the calibration of the instrument. These velocities were plotted against the depth at which they were measured. A typical vertical velocity distribution for a wide channel is depicted by Fig.6.5(a). The average velocity usually occurs at about 60% of the flow depth. The Doppler velocities measured through the full depth of the respective flows show good agreement with this and the results are summarised in Table 8.1. The errors are very small even though the Doppler probe was never positioned at the exact theoretical vertical position where the average velocity should occur. The theoretical average velocity and the depth at which it occurs were calculated and were merely used to check the results. The probe was positioned in the channel and then lowered in increments so that it took measurements throughout the vertical profile. This was not a test to establish the theoretical velocity and its location within the vertical flow profile, but a test to check measurements at different flow depths and to observe any possible deviations at any vertical depth.

The Doppler velocities that were measured very close to the water surface deviate from the theoretical velocity profile (Fig.6.5(a)). The top of the Doppler probe protruded out of the water and it is possible that the crystals of the probe also momentarily were out of the water due to waves on the water surface. When this occurs, the Doppler meter will read the velocity of the water running down the front face of the crystals. Faulty readings can thus be expected very close to the surface of the water. As long as the probe remains entirely submerged accurate results should be expected, as is also evident in Fig. 8.3. It can be noted here, that the probe reads a zero frequency when taken out of the water.

Close to the bed the velocity should approach zero. Since the crystals of the probe are situated a few millimetres above the bottom edge of the probe it will read a velocity at that height above bed level. This explains why the velocity obtained with the Doppler meter at the lowest possible level, i.e. when the Doppler probe is placed on the bed of the channel, is not close to zero. The velocities for the 3 experiments were plotted together with their respective water surface levels (Fig.8.3).

From Fig.8.3 and from the discussion above it can thus be concluded that the Doppler meter can be used at any level as long as the probe is completely submerged under water. Only at the highest levels when the probe momentarily came out of the water, did the recorded velocity deviate from the typical velocity profile.

Another check for any deviation of the measured Doppler velocity from the actual velocity is to plot the velocities against the log of the depth. The values should plot on a straight line and any deviation should clearly be visible. The 3 profiles were plotted and are seen in Fig. 8.4. All 3 profiles plot on a line, with slight deviations being clearly visible for tests M2 and M3. These are the points were the probe momentarily came out of the water. For all other depths, down to the channel floor, the points plot on the straight line. The probe can thus be reliably used on the channel floor and very close to the water surface as long as the probe's face does not come out of the water.

Experiment	M1	M2	M3
Theoretical average velocity depth (m)	0.0832	0.0900	0.0984
Closest value to this height (m)	0.0817	0.8170	0.1017
Calculated average velocity (m/s)	0.1290	0.1720	0.2260
Measured velocity measured at theoretical height (m/s)	0.1350	0.1770	0.2260
%error	**4.65**	**2.91**	**0.00**
Average error (%)	**2.5**		
Standard deviation (%)	**2.3**		

Table 8.1: *Summary of comparison of theoretical average velocity and measured "average" velocity.*

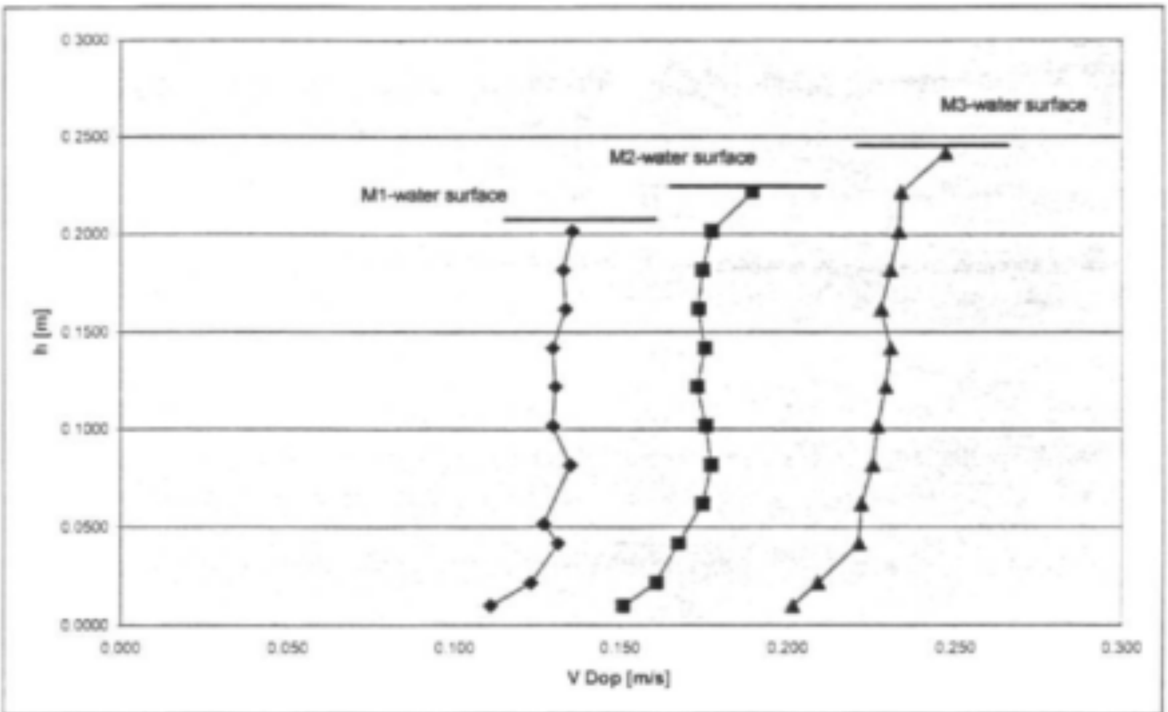


Fig 8.3: *Plot of measured Doppler velocities recorded at different flow depths.*

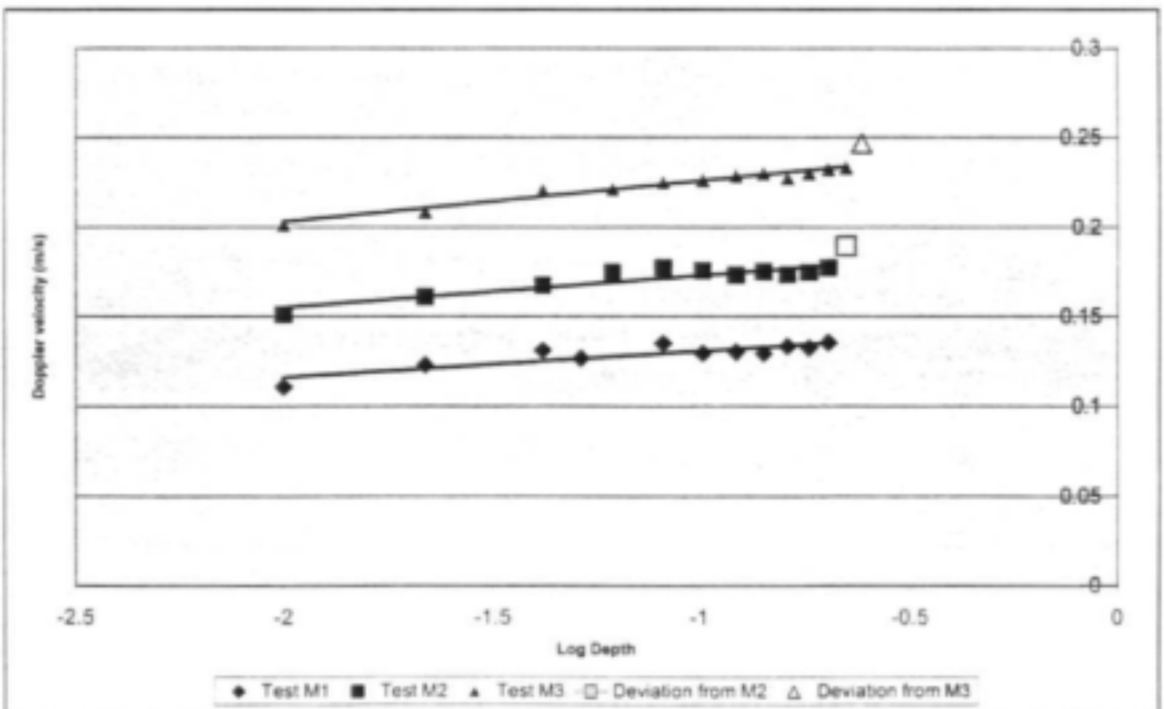


Fig 8.4: *Plot of the velocities against the log depth for all 3 experiments.*

8.4 MINIMUM VELOCITY THAT CAN BE MEASURED ACCURATELY

An experiment was performed to obtain an estimate of the minimum flow velocity this Doppler meter could detect accurately.

The average velocity of the canal was calculated by dividing the flow rate read off at the manometer by the measured flow cross sectional area. Six experiments were performed, starting with very low flow velocities and then increasing the velocities. The lower flow velocities achieved here were the lowest practically achievable in the 2 metre wide canal. The aim of this experiment was to find a relationship between the average flow velocity in the canal and the measured Doppler velocity and to investigate if there was any deviation in the measured Doppler velocity at some point. The Doppler velocities were also measured at 60% of the flow depth, not in the centre of the canal but 300mm from the side. The velocities at 300mm from the edge, read with the Doppler meter, were compared with the calculated average velocity.

The relationship obtained for these two velocities can be seen in Fig. 8.5. This figure shows that there seems to be a linear relationship for the 3 experiments for the higher velocities. Linear regression was applied to these points with the line intersection at $y = 0$. Theoretically, when the flow rate in the canal is zero, both the average flow velocity and the Doppler velocity should be zero. These 3 experiments agree well with an R^2-value of 0.96 (Note that the sample size consists of only 3 points, but with the origin taken as another point it is increased to 4). At some point, the Doppler velocity starts to deviate from this line as can be seen on Figure 8.5, with the results of the 3 experiments with the lower flow velocities starting to deviate from the straight line. Another way of obtaining the minimum velocity that the Doppler meter can detect accurately is to plot the measured Doppler velocities against the log of the calculated average velocity. The point where the measured velocities start to deviate from the linear relationship obtained here for the 3 experiments with the higher flow velocities (See Figure 8.6), should indicate the minimum velocity that the Doppler meter can detect accurately. Linear regression was only applied to the three experiments with the higher flow velocities as it was proven by Fig. 8.5 that it is reasonable to assume that they follow a linear trend with the origin included in that analysis. If the origin had been included in this analysis, the log of zero would yield an infinitely high negative value and thus the linear trend on the log plot would not hold anymore. On Fig. 8.6 it can now be seen that the three experiments with the lower flow velocities start to deviate randomly from the straight line. They represent inaccurate readings of the Doppler meter at flow velocities lower than approximately 0.046 m/s. For the purpose of this study this will be accepted as the minimum velocity that the Doppler meter can detect and read accurately, i.e. the minimum velocity that falls within the linear trend on Fig. 8.6.

This velocity is higher than that given for other commercially available Doppler meters such as the Argonaut-Acoustic Doppler Velocity (ADV) meter that can detect velocities accurately down to as low as 0.0001 m/s (Argonaut-ADV Principles of Operation, online: http://www.sontek.com/princop/aadv/). This means that the DFM-P-067 measures a minimum velocity 460 times swifter than the minimum velocity of the Argonaut Doppler meter.

It must be mentioned here that the water in the laboratory is fairly clean and that the working of the Doppler meter relies on suspended matter. Any suspended matter has certain settling velocity, that is proportional to the particle diameter. It has been shown (Rooseboom, 1992) that whenever alternate modes of flow exist, i.e. particles settling or remaining on the channel floor, or particles starting to be suspended or to remain in suspension, that require the least amount of unit power, will be followed. In the clean water of the laboratory, with very low suspended fine sediment concentrations, only few particles will be in suspension at very low velocities. Very low velocities will result in the few sediment particles settling to the channel floor. The Doppler meter relies on sediments following the flow in a translatory direction to give an accurate reading of the flow velocity. In water with higher sediment loads, as is the case in most or all streams occurring naturally, the Doppler meter could thus possibly measure velocities that are even smaller than the minimum velocity cited here as the sediment concentration and also the spectrum of sediment particle diameters will be bigger. There could thus be some sediments in suspension which follow the fluid sufficiently closely. This could be the reason for the comparatively high minimum flow velocity that this Doppler meter was able to detect accurately in the laboratory.

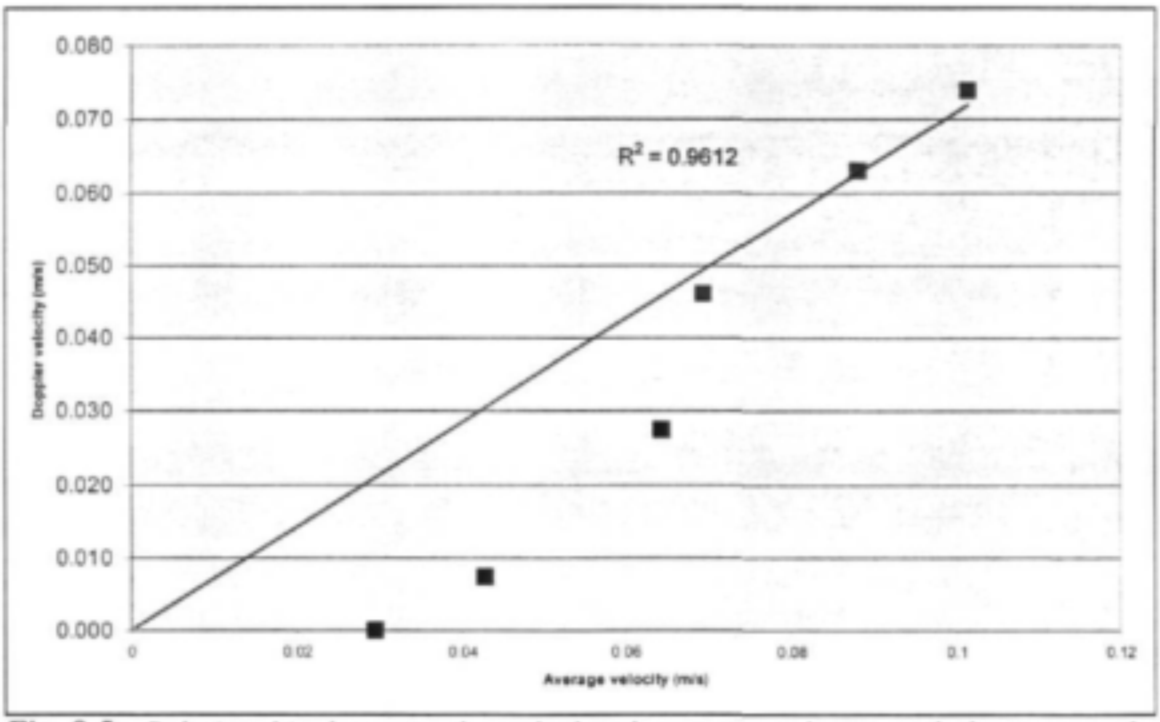


Fig 8.5: *Relationship between the calculated average velocity and the measured Doppler velocity at low flow rates and hence low flow velocities.*

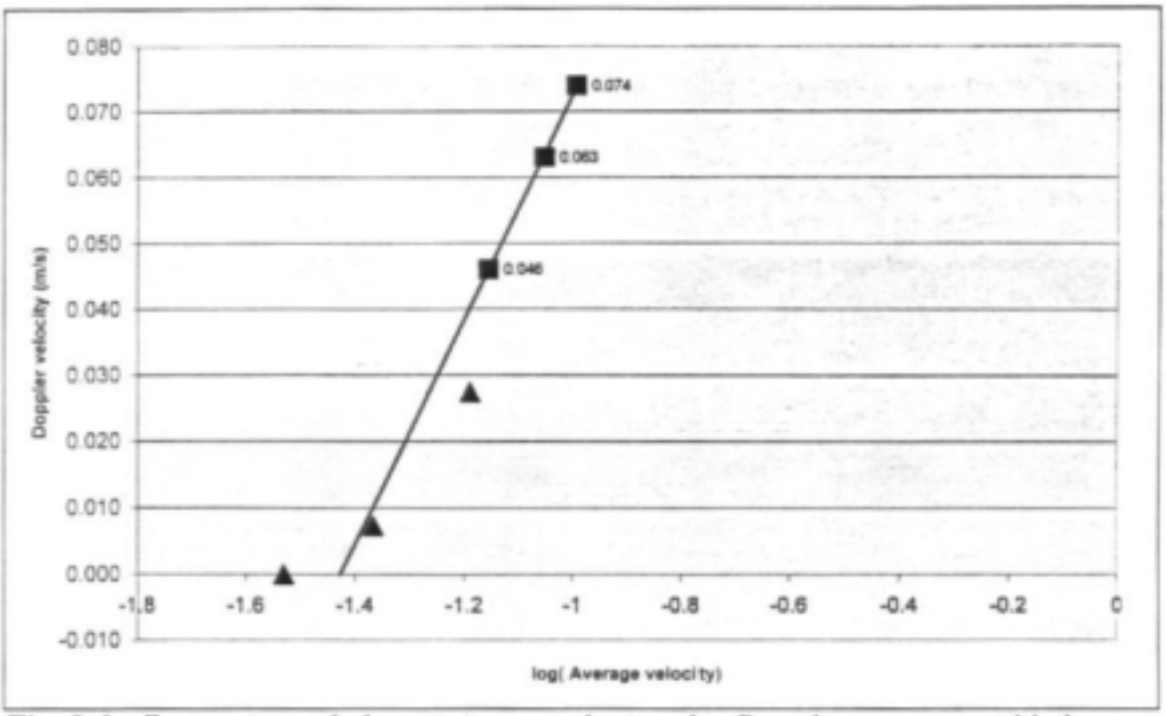


Fig 8.6: *Estimation of the minimum velocity the Doppler meter could detect accurately.*

8.5 DISCUSSION OF THE ULTRASONIC FIELD WHERE THE DOPPLER METER IS EXPECTED TO PICK UP READINGS

The characteristics of the acoustic field depend on the size and shape of the piezoelectric element (probe). A typical acoustic field possesses two characteristic regions. The zone between the transducer and Z (See Fig.8.7) is called the near field. In the near field the acoustic field is basically cylindrical with the same diameter as the transducer or the transmitter in the probe. The equation below gives the value of this field, which depends on the wavelength L and the radius A of the transducer. The equation is (Technical information on ultrasonic technics, *Signal Processing,* 1998):

$$Z = \frac{A^2}{\lambda} \qquad \text{.............................. 8.1}$$

with Z being the near field
A being the radius of the transmitter
and λ being the wavelength of the transmitted acoustic wave.

The zone lying beyond Z is called the far field. In the near field, the intensity of the acoustic field varies as the inverse of the square of the distance from the transducer. In the far field, the acoustic field may possess intensity lobes as one moves away from the axis of the transducer. The acoustic energy contained in the secondary lobes is always much less than that contained in the main lobe and does not influence the measurement in most cases. The angle of divergence of the main lobe can be approximated by the following equation:

$$\delta = 2 \bullet \sin^{-1}\left(\frac{0.61 \bullet \lambda}{A}\right) \ldots\ldots\ldots\ldots\ldots 8.2$$

For an estimation of the acoustic field of the Doppler meter used in this project, we substitute the frequency of the acoustic signal emitted (1 MHz) and the speed of sound through water (1450 m/s) into the equation

$$\lambda = \frac{c}{f} \ldots\ldots\ldots\ldots\ldots 8.3$$

This gives a value of *0.00145 m* for the wavelength of the acoustic signal. Substituting this value into equations 8.1 and 8.2 and also substituting the radius of the transducer of 0.005 m, we obtain a value of *0.0172 m* (*17,2 mm*) for the near field and an angle of divergence of *20.38* degrees. This is thus the approximate size of the acoustic field from where we can expect backscattered frequencies.

The manufacturer of the Signal Processing Doppler meters also states that it is quite difficult to give an accurate value for the accuracy of information extracted from the backscattered echoes due to the fact that the measuring volume is not a single point but that it contains a lot of particles. These particles are not all moving in absolutely the same direction. This is especially the case with turbulent flow. As all these particles contribute to the measurement of the mean Doppler frequency shift of a gate (one point in the velocity profile), their movements will induce fluctuation in the measured velocity. Backscattered echoes from a large sampling volume will be more affected by this phenomenon. This explains the fluctuations in the observed frequencies in this study and also the observed frequencies in the Jonkershoek River in 1999.

Variations in observed frequencies are also induced by single particles passing through the ultrasonic beam. The angle between the direction of the particle velocity and the ultrasonic wave changes as it moves. *Signal Processing,*1998, states that in applications, the accuracy of the velocity measurements is around 5 to 10% without any averaging of the observed frequencies. This could be increased to 2 to 3% by averaging the observed frequencies.

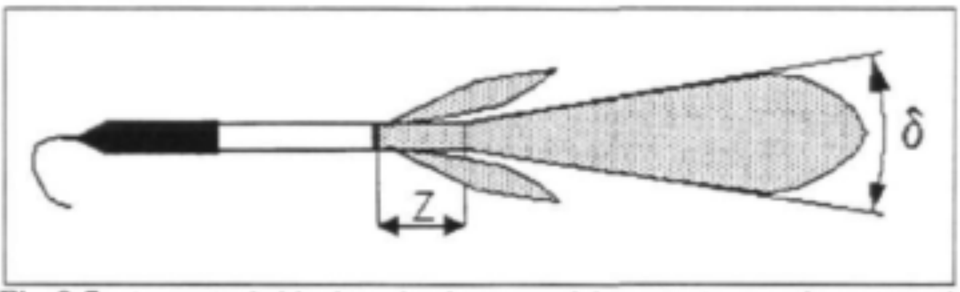


Fig 8.7: *Acoustic field where backscattered frequencies can be expected to originate from.*

9 CALIBRATION RESULTS OF CRUMP WEIR WITH DOPPLER METER

This chapter deals with the possible use of a Doppler meter at a Crump weir for the measurement of discharges under modular and non-modular flow regimes. The Doppler meter was first used at a Crump weir operating under modular flow conditions to compare the results obtained in the laboratory with the readings obtained at a prototype. Finally, the tests conducted in the non-modular flow regime in the laboratory will also be analysed.

9.1 MODULAR FLOW RANGE

The Doppler constant of **1460** obtained from the calibration of the Doppler meter in the laboratory has been used for all further calculations.

Fifteen experiments with different flow rates were performed in the modular flow range. The heads were measured and then converted into flows passing through the flume and over the Crump weir. An iteration process with the help of a spreadsheet (Bruce, 2000) was used to convert the water levels into discharges. An example of this spreadsheet for the modular flow range can be seen in Appendix I(i). With the flow passing over the weir thus known, the approach velocity upstream of the weir can be determined through the relationship:

$$Q = v * A \quad or \quad v = \frac{Q}{A}$$

The upstream flow cross-sectional area was determined by measuring the water depth at a distance $4H_{max}$ upstream of the weir. Initially, the whole flow cross section in the canal was used to calculate the approach velocity but this yielded approach velocities higher than the velocities passing over the crest of the

Crump weir. It was therefore decided to use only that part of the flow passing over the weir, Q_{wf}, and also to treat the canal width as being the sum of the spans of the two Crump weirs, i.e. ignoring the flume. The approach velocities calculated in this way were all lower than the Crump crest velocities. For the readings from these experiments and the calculation results refer to Appendix J.

The upstream energy head of the Crump weir was also calculated according to the methods developed for the flume in combination with weirs (Bruce,2000). This was done to check that the water level recorded upstream of the weir is lower than the energy head. For low flows it is imperative to measure the flow very accurately as an error in the reading with the needle of 0.5mm could result in an observed water level higher than the calculated energy level. Good accuracy was however achieved. (Refer to Appendix I for the calculated energy levels and the observed water levels. A sketch of the different terms used in the calculation on the spreadsheet has been included.)

Once the flows were calculated accurately the upstream approach velocity in the canal could be determined and compared with the average Doppler velocity at Crump crest level.

9.1.1 RELATIONSHIP BETWEEN DOPPLER VELOCITY AND APPROACH VELOCITY

Each Doppler Crump crest velocity was plotted against its calculated approach velocity. The approach velocity was plotted on the x-axis as this is the independent variable in these calculations, i.e. the calculated approach velocity is considered to be the accurate or real value to which the Doppler velocity should be compared to. A polynomial fit was plotted through all the points (Figure 9.1), showing very good agreement (R^2 = 0.989), with the y-intersect (i.e. Doppler velocity) being zero for a zero approach velocity as would be expected. For the purpose of this investigation however, i.e. within the ranges worked in, it is reasonable to accept that there exists a linear relationship between the approach velocity and the measured Doppler velocity. The aim was not to compare actual velocities here (i.e. measured Doppler velocities at 60 % of the flow depth), but to investigate the possibility of establishing a relationship.

In addition to the polynomial, a linear fit was also plotted through the points. The linear fit does only apply to the range of experiments performed. This line is also shown in Figure 9.1 with an R^2 – value of 0.9902, indicating a better fit through the points within this range. We will thus, for the purpose of this investigation, assume a linear relationship between the Doppler velocity measured at Crump crest level and the measured approach velocity, even though the line does not go through the origin. It must however be noted, that as the discharge becomes smaller, the ratio between the Doppler velocity and the approach velocity becomes greater and greater and it is thus to be expected that the curve in Fig. 9.1 will curve downwards as the origin is approached. This is however expected to occur outside of the region within which these experiments were performed in, and the linear fit will thus be assumed for the purpose of this investigation. Furthermore, all measured Doppler velocities were higher than the minimum velocity which the instrument can measure accurately (0.06m/s) and they will thus be regarded as being accurate.

The average error for all the points is –0.32% and the standard deviation 4.27% (Refer to Figure 9.2), indicating that the assumption that the relationship between the Doppler velocity and the approach velocity is linear, is valid.

The linear relationship obtained in the ranges of these experiments proves that the Doppler meter is not sensitive to the curved flow lines that prevail in the region of the crest of the Crump weir.

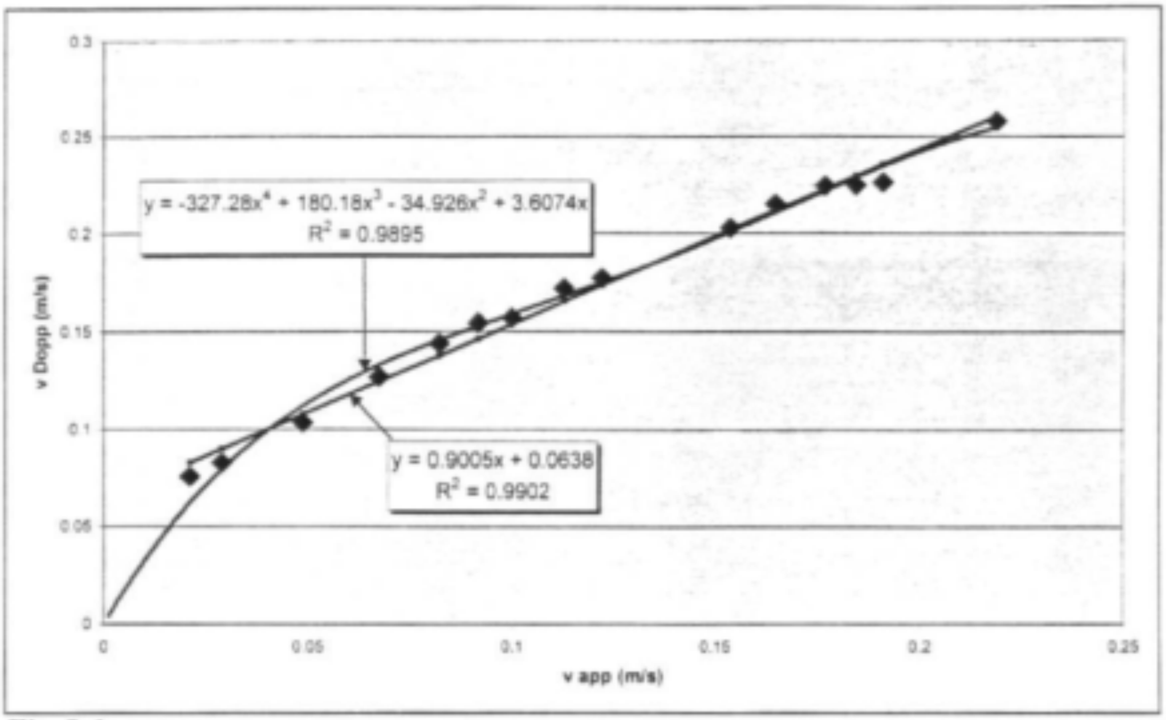


Fig 9.1: *Relationship between Doppler velocity and approach velocity for model tests in the modular flow range.*

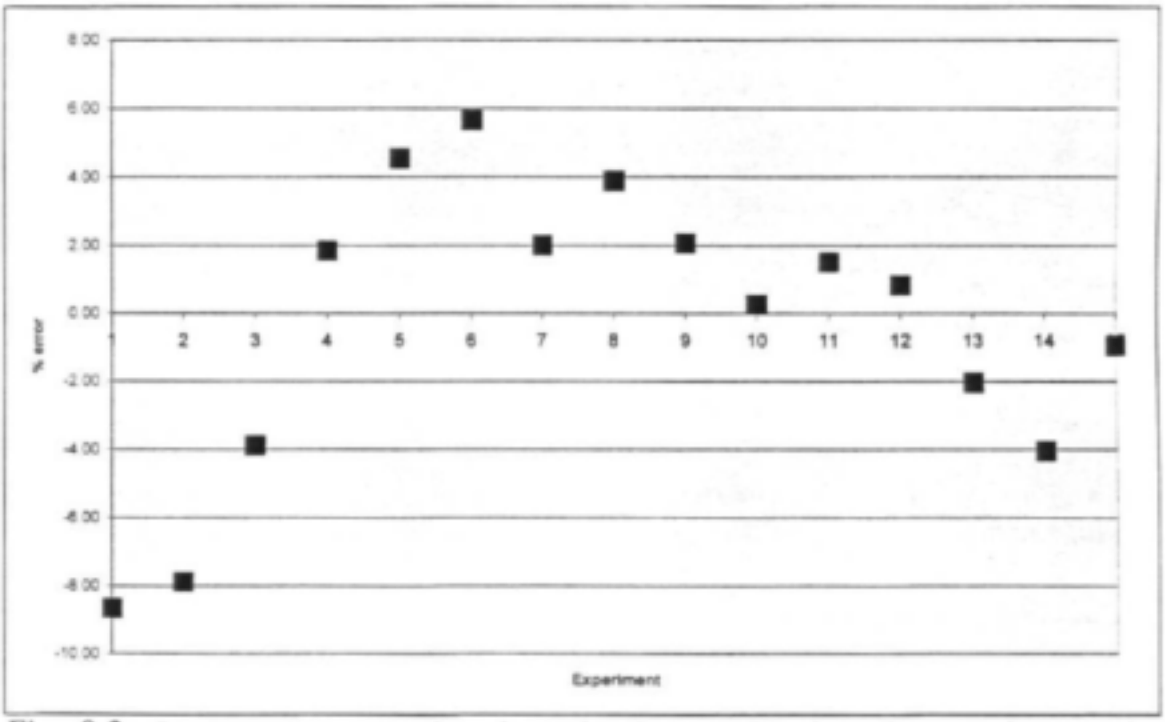


Fig. 9.2: *Percentage error in the relationship between Doppler velocity and approach velocity.*

9.2 RELATIONSHIP BETWEEN DOPPLER VELOCITY AND APPROACH VELOCITY FOR PROTOTYPE

The readings taken in the Jonkershoek River during 1999 (du Toit, Venter, 1999) were also analysed. Due to a very high number of readings available (the readings were continuously stored on a datalogger) only 13 different water level heads above the lower Crump crest were chosen. For head levels higher than approximately 0.65m, very few readings are available as the water level had rarely reached these levels and only after a heavy rainstorm. These heads were thus discarded because a few readings do not represent the overall mean for that height and therefore results will be unreliable. The average of all readings for each particular head of the stored Doppler velocities was calculated.

The Doppler velocities for each respective head were plotted against the approach velocities. The approach velocity was calculated with the relationship of $Q = vA$, (du Toit, Venter, 1999). As for the modular experiments in the laboratory, a linear relationship was obtained. See Fig.9.3. The average error of all points around the regression line is only 0.03% and the standard deviation 9.71%. The assumption that the relationship is linear is therefore justified. One value deviates from the regression line by 25.44 %. All the other points are within 10 % of the regression line and this point can hence be regarded as an outlier for reasons unknown. It should be noted that this error occurred at a relatively low flow, a head of 0.1m and people may have been swimming or playing in the pool upstream of the weir, thus creating additional currents – all of these are possible reasons for the error.

Once again a linear fit within the ranges of these experiments was assumed even though a polynomial should be fitted through these points with the origin at zero. It must be mentioned here, that the minimum velocity the Doppler meter can measure is around 0.046 m/s, and that lower readings would in all likelihood be faulty. This means that for lower approach velocities, the Doppler velocity would also decrease and for readings within this cut-off range the relationship would not be valid due to errors in the reading of the Doppler meter.

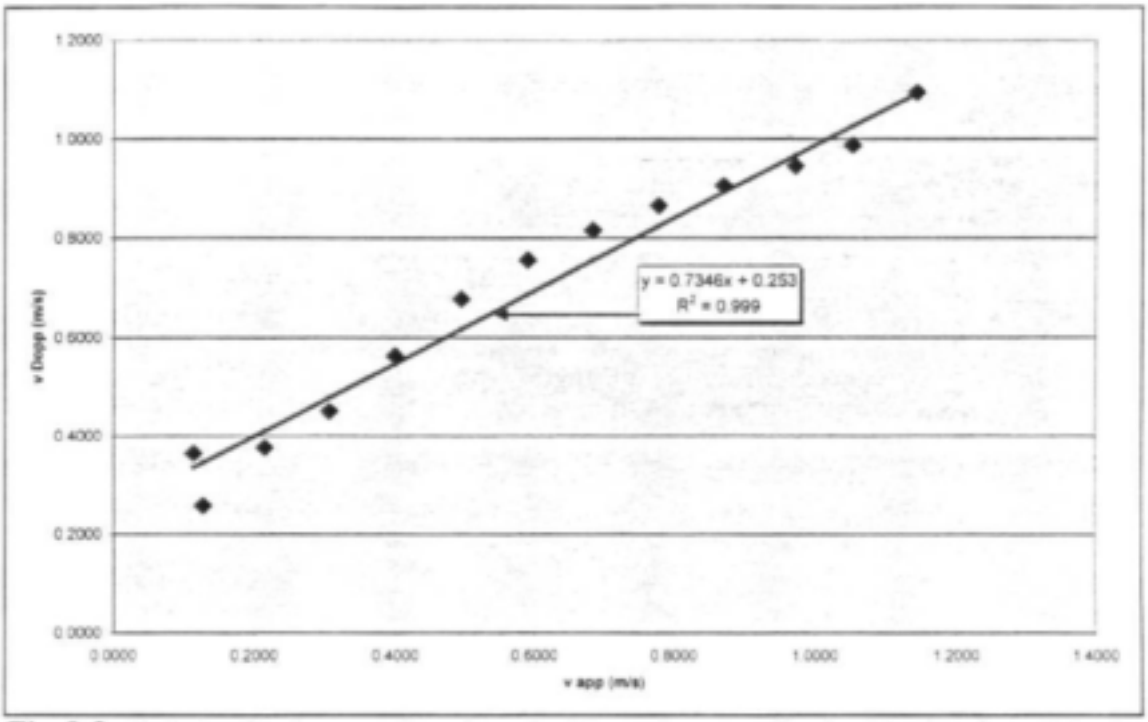


Fig 9.3: *Relationship between Doppler velocities and approach velocities for the weir in the Jonkershoek River.*

9.3 NON-MODULAR FLOW TESTED IN LABORATORY

The calibration method developed for the flume in combination with weirs (Bruce, 2000), was used to calculate the flow passing over the weir under non-modular flow conditions. Again an iterative process is needed to calculate the flows over the weir and through the flume. A spreadsheet was developed (Bruce, 2000) that speeds up calculations and this was also used for this study. It is shown in Appendix I together with the observed water levels for the non-modular tests.

Experiment D4 was discarded altogether as the calculated discharge differs from the actual discharge by a constant, high value. The average error for this experiment underestimates the flow by about 22 % (Refer to Appendix I, Spreadsheet on non-modular flow). The remaining experiments yielded calculated discharges within acceptable limits. It was decided to include only experiments where the discharge did not differ from the actual discharge by more than 10 %. Ideally, the limit should be set lower at values of about 5% because any error in the calculated discharge will inevitably introduce an error into the calculated approach velocity.

All tests that were carried out aimed to have a submergence ratio between 0.75 and 1.0 for the Crump weir. Recall that the modular limit for a Crump weir is defined at a degree of submergence of 0.75 (Ackers et al,1978). While working in the laboratory some tests seemed to be within this range, but when the calculations on the spreadsheet were performed it was found that they were still in the modular flow range. The Crump weir becomes submerged much later than the flume. These experiments were thus also discarded. For the remaining valid experiments please refer to bold values under column "total error" in the spreadsheet for non-modular flow calculation (Appendix I).

Again the approach velocity in the channel was calculated as described in Section 9.1. For each of the non-modular experiments, i.e. D1 through to D3, one experiment was performed with the flow being modular. These points should establish the linear relationship between the Doppler velocity and the approach velocity. The non-modular points could then be compared with this relationship. A plot of these points is seen in Fig.9.4. This Figure also shows all the non-modular results that were considered for analysis. Note that the sample size of the experiments within the modular limit is small and consists of only 3 points and thus a good fit with an R^2-value close to unity could be achieved. The experiments in the modular flow regime described in the previous section did prove however that the points do in fact follow a straight line and that the conclusion based on this small sample size of a linear trend is thus justified.

The three values that deviate furthest from the regression line of the modular points, belonging to Experiments **D2.7**, **D2.8** and **D3.5**, have the highest degree of submergence for each respective set of experiments and fall within the tolerance level of being within 10 % of the actual discharge . For a Crump weir the degree of submergence is measured in terms of the downstream energy head relative to the upstream energy head and not the downstream water level relative to the upstream water level as for sharp-crested weirs. The downstream water level relative to the upstream water level is however a valid indication of the degree of submergence for the Crump weir being used here. For these three experiments the degree of submergence measured in this way averaged out to be approximately 96% or 0.96. This can be expected since degrees of submergence greater than 0.95 introduce more significant errors into the discharge calculation and this in turn affects the calculation of the approach velocity in the upstream channel. These 3 experiments were further eliminated and the remaining points were once more plotted against the free flow experiments. For both plots refer to Figures 9.4 and 9.5. Figure 9.5 shows a much better correlation in terms of these points following a linear relationship.

It was found that the flume in combination with weirs required different corrections for different ranges of submergence (Bruce, 2000). This was also mentioned in Chapter 3, where the BSI specify different corrections for degrees of submergence between 0.75 and 0.93 and those greater than 0.93. Due to limited available data, i.e. not many points falling within either of these ranges, the degrees of submergence here were also divided into two ranges, those falling between 0.75 and 0.95 and those falling above 0.95. Again linear regression was applied to each set of points respectively to check whether a better linear fit can be established. Refer to Fig.9.6.

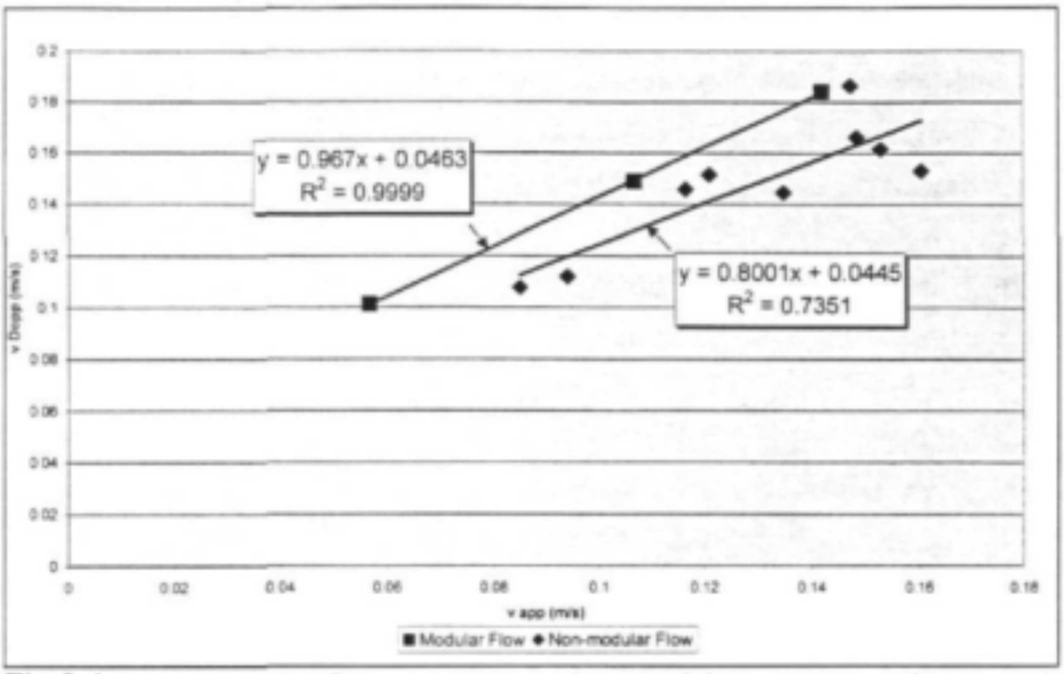


Fig 9.4: *Plot of modular flow experiments and non-modular experiments that are within 10 % of the calculated theoretical flow. Linear regression is applied to both modular and non-modular experiments.*

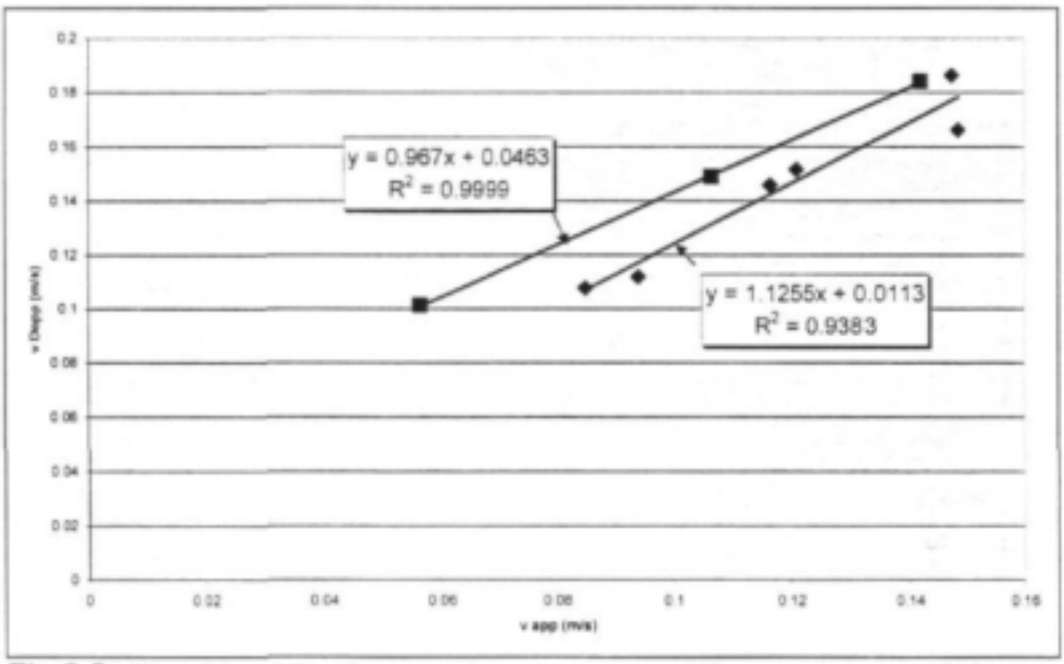


Fig 9.5: *Plot of 3modular flow experiments vs. non-modular experiments with the 3 non-modular experiments* ***D2.7***, ***D2.8*** *and* ***D3.5*** *omitted. Linear regression analysis was applied to both series and the non-modular experiments show a much better correlation to both the modular flow experiments regression line and a linear assumption.*

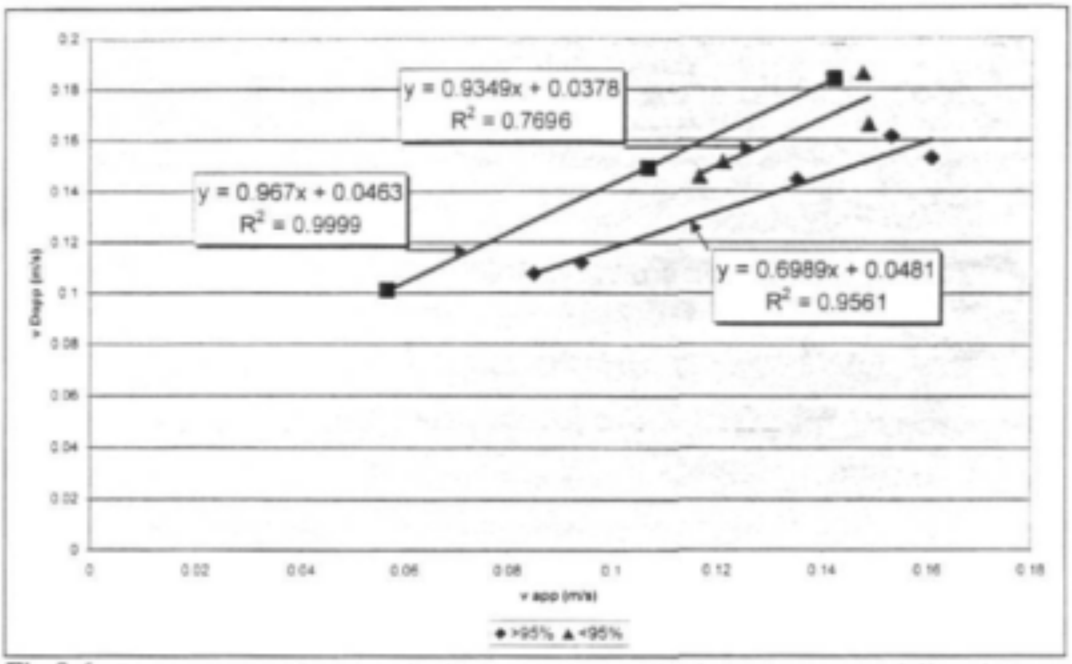


Fig 9.6: *Regression analysis applied to two regions of submergence, one falling below 95 % and the other one falling above 95 %.*

9.3.1 DISCUSSION OF RESULTS FOR NON-MODULAR FLOW

As is evident from Figures 8.4 to 8.6, the assumption that the relationship between the approach velocity and the Doppler velocity, as measured at Crump crest level is linear, is valid. To support this assumption, the errors of the plots to the regression line have been plotted and calculated. For the experiments in Fig.9.5, i.e., the plot of the experiments without the 3 "outlying" values, the average error is only –0.06%, with a standard deviation of 4.62%. The maximum error is –6.89 % and the minimum error 0.68%. Linear regression applied to the two different ranges of submergence as depicted by Fig.9.6, show a slightly better fit, with the average error being only –0.01%, a standard deviation of 3.83% and a maximum and minimum error of 6.11% and 0.18% respectively. The average error for both scenarios is very small and the maximum errors do not deviate further than 7% from the regression line.

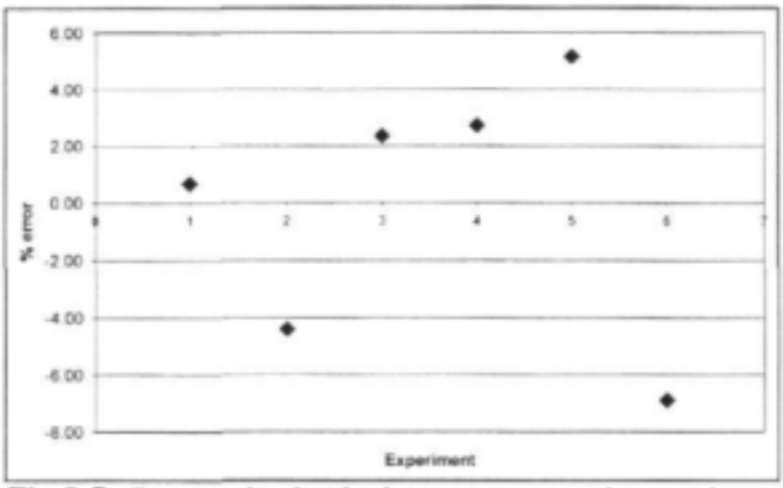


Fig 9.7: *Errors of individual experiments with regard to regression line of non-modular flow from Fig.9.5.*

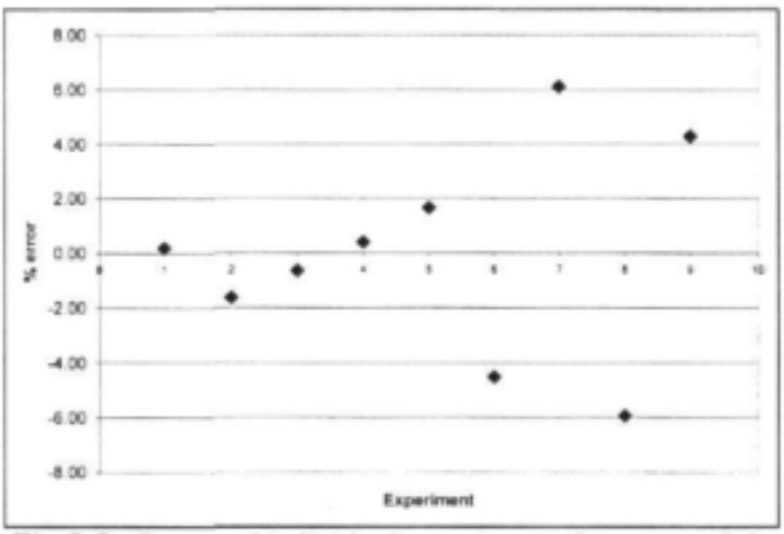


Fig 9.8: *Errors of individual experiments for non-modular flow with respect to piecewise regression analysis.*

A summary of the errors depicted by Figures 9.7 and 9.8 is summarised in Table 9.1.

Drowned	Single regression	Piecewise regression
Average error (%)	-0.06	-0.01
Standard Deviation (%)	4.62	3.83
Maximum error (%)	-6.89	6.11
Minimum error (%)	0.68	0.18
No. of points	6	9

Table 9.1 *Summary of errors of linear regression analysis applied to the non-modular flow experiments.*

9.4 COMPARISON OF NON-MODULAR FLOW AND MODULAR FLOW

The relationship between the approach velocity and the Doppler velocity for the non-modular experiments was plotted against the relationship obtained for free flow. The experiments conducted in the modular flow range again showed a good linear fit albeit the sample size only consisted of 3 points (A rounded R^2-value of 1). This is in agreement with the results obtained earlier for the free flow experiments in the prototype and the laboratory. The non-modular experiments plot below the free flow experiments throughout. Refer to Fig.9.4 to 9.6. The difference between the regression line obtained for the modular flow and the regression line obtained for the non-modular flow, as depicted by Fig.9.5, was calculated for each respective point. The results are summarised in Table 9.2.

Average error (%)	-10.16
Standard Deviation (%)	4.38
Maximum error (%)	-16.03
Minimum error (%)	-6.03
No. of points	6

Table 9.2 *Summary of the difference, expressed as a percentage, between the regression lines obtained for the modular and non-modular experiments.*

The average error is fairly high (-10.16%) and the range of the differences (between –6.03% and –16.03%) indicates that the plot for the drowned experiments is indeed linear and on average approximately 10 % lower than the linear relationship obtained for the modular experiments. If very accurate and reliable flow measurements were available for the Crump weir, it is likely that the difference between the two lines obtained, i.e. between the modular and the non-modular flow, will become smaller. It can be noted here, that the non-modular plots that are closest to the linear regression line of the modular experiments, represent the drowned flows with the smallest level of submergence. For increasing degrees of submergence, the relationship between the drowned approach velocity and the drowned Doppler velocity deviates further from the relationship obtained for free flow. The degree of submergence was plotted against the percentage by which the non-modular experiments differ from the modular relationship. The plot clearly shows that with increasing levels of submergence, the difference between the two also increases.

The Doppler meter does however establish a linear relationship between the approach velocity and the velocity at Crump crest level for both modular and non-modular flows. It is thus not very sensitive to curved flow lines that prevail at Crump crest level. Better results should also be achieved in the prototype if the probe is installed horizontally and readings for each head are taken at 10-second intervals. In the laboratory, the probe itself, due to its size relative to the model (Figure 5.6), created curved flow lines over the weir and notwithstanding that, a very good linear relationship was still achieved for both the free flow experiments and the drowned experiments.

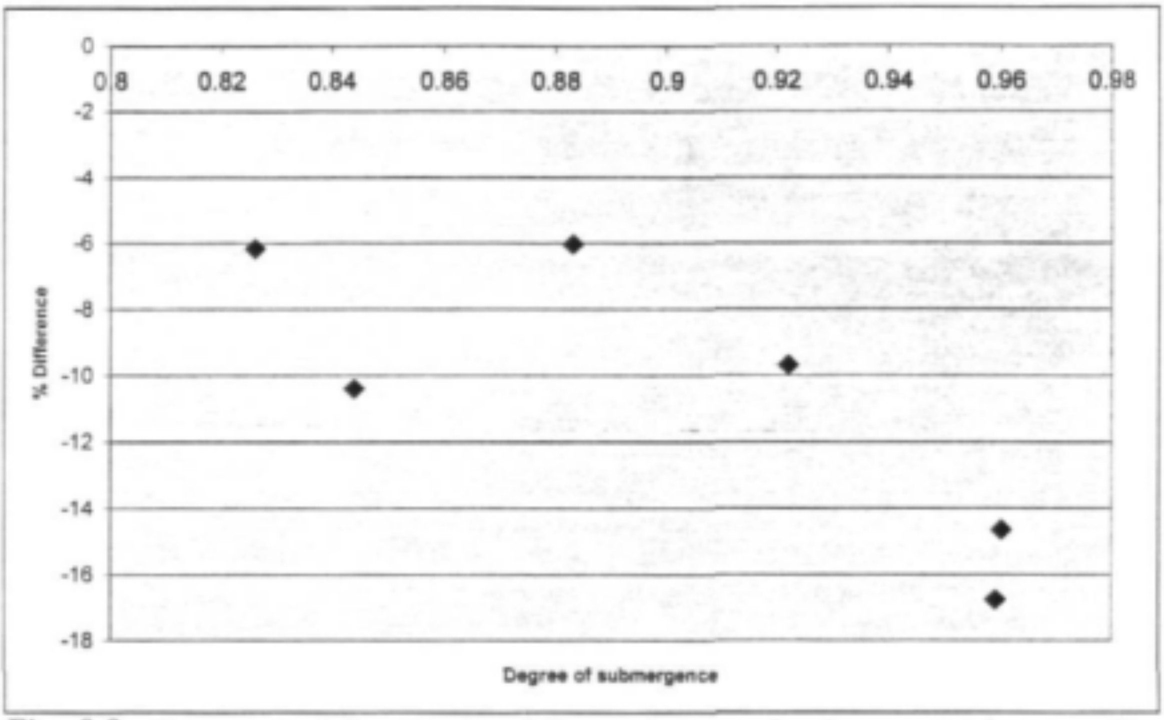


Fig 9.9: *Percentage difference for different degrees of submergence, between the relationship of the approach velocity to the Doppler velocity, for non-modular flow to that of modular flow.*

Table 9.1 shows the differences in the errors obtained for single linear regression for all drowned flows and piecewise linear regression analysis. For the single regression line, all experiments with the highest degree of submergence were however ignored and are thus not included in the calculation of the average error and the standard deviation. This is not the case for the piecewise regression. Had these points been included in the linear regression for the single line, the errors and standard deviation for that assumption are very likely to increase. Refer to Fig.9.4, where this information is plotted. The errors for the piecewise linear regression are small enough to accept that the drowned flow's relationship between the approach velocity and the Doppler velocity follows a linear trend within the boundaries of different levels of submergence. This is strongly supported by Fig.9.9, with a clear indication that the relationship deviates further away from the free flow plot for increasing levels of submergence. Another observation from Fig.9.9 is that the error remains at or below 10% for submergence ratios of less than 0.94. This is in agreement with the ranges of submergence levels presently being used to calculate the correction factor for the discharge over a Crump weir. Recall from Chapter 3, that the regions of submergence are submergence ratios of (a) between 0.75 and 0.93 and (b) submergence ratios of greater than 0.93. The difference between the regression lines of the submerged tests and the free flow tests in the region of submergence between 0.75 and 0.93 will possibly reduce further with better control in the discharge calculation in larger models. It was very difficult to control the degree of submergence in the model in the laboratory due to the presence of the flume and it submerging prior to the weir. Submergence ratios greater than 0.95 fall into a region of very unstable flow and errors can be expected there. Most of the tests conducted here fall within this range.

9.5 POSSIBLE DIRECT APPLICATION OF DOPPLER METERS IN MEASURING FLOWS AT CRUMP WEIRS

9.5.1 MODULAR FLOW

The linear relationship that exists between the Doppler velocity at Crump crest level and the approach velocity can be used directly to calculate the discharge over a weir. Since this method will be used in the field, i.e. in the prototype, it was tested for that case. The study in the Jonkershoek River (du Toit, Venter, 1999) made use of a probe on both the high and low crests (compound structure) of the weir. The readings taken on the high crest were however ignored due to lateral flow towards the lower crest.

From the linear relationship between the approach velocity and the Doppler velocity it follows that the approach velocity is given by:

$$v_{app} = \frac{v_{Dopp} - 0.253}{0.7346} \qquad \text{.............................9.1}$$

where v_{app} is the approach velocity in m / s
and v_{Dopp} the Doppler velocity at Crump crest

This expression can now be substituted into the discharge equation of a Crump weir (Recall equation 3.2 with C_D and C_v being acounted for) to give

$$Q = 1.982 * L * H^{\frac{3}{2}}$$
$$= 1.982 * L * (\frac{v_{app}^{2}}{2g} + h)^{\frac{3}{2}} \qquad \text{..............................9.2}$$

Only the flow over the lower crest was considered and the results are summarised in Table 9.3. The flow over the higher crest was ignored because theoretically the flows should be separated by dividing walls and then added together. The Doppler frequency as read on the lower crest is thus not representative of the higher crest, which should have its own unique linear relationship with the approach velocity. Flow commenced over the high crest when the measured head $4H_{max}$ upstream of the crest reached a level of higher than 0.3m. All readings below that level were thus considered.

The results are very encouraging with an average error of only 0.11% and a very small standard deviation. The errors shown here merely represent another way of looking at the regression line obtained for the relationship between the Doppler velocity and the approach velocity and the associated errors between the observed values to that line (Section 9.2). The iterative loop for calculating the energy head presently being used in the formula for a Crump weir, to convert the measured head relative to the crest level into flow, can thus be omitted if this relationship has been obtained, i.e. if the structure has been calibrated. It is worthwhile noting that the average error, once flow commences over the high crest, averages at 20.9%. This is due to the fact, that as mentioned, the flows should be treated separately, i.e. one flowing over the low crest and one flowing over the high crest and then added together. Each crest gives a unique relationship between the Doppler velocity measured there and the approach velocity.

h	Q_{Actual}	v_{Dopp}	V_{app}(calc)	Q_{calc}	error
(m)	(m^3/s)	(m/s)	(m/s)	(m^3/s)	(%)
0.092	0.33541	0.36510	0.15260	0.33829	**0.86**
0.100	0.38070	0.25830	0.00721	0.37607	**-1.21**
0.150	0.70709	0.37710	0.16894	0.70094	**-0.87**
0.200	1.10198	0.45120	0.26981	1.09339	**-0.78**
0.250	1.55980	0.56240	0.42118	1.56787	**0.52**
0.300	2.07708	0.67630	0.57623	2.12171	**2.15**
				Average	**0.11**
				Std. Dev.	**1.30**
				Max.	**2.15**
				Min.	**0.52**

Table 9.3 *Errors in the calculations of the flow for the prototype. Flow only occurs over the lower crest.*

9.5.2 NON-MODULAR FLOW

The degree of submergence of a Crump weir is expressed in terms of the downstream energy level relative to the upstream energy level. Refer to Section 3.5.2. To calculate the degree of submergence, a first indication of the degree of submergence is the downstream water level relative to the upstream water level. This value is used to calculate the correction factor to be applied to the discharge equation for free flow. Refer to Section 3.5.2. The process to calculate the discharge in the non-modular flow range thus involves a double loop in the iteration process to solve for the discharge. This may become very tedious and it was decided to test the discharge equation of a Crump weir by applying the relationship established between the measured Doppler velocity at crest and the approach velocity and then to use that value to calculate the flow from equation 9.2.

The linear relationship for the drowned experiments in the range of submergence ratios (measured in terms of the water levels and not the energy levels) less than 0.95 and greater than 0.95 were applied to calculate the approach velocities in the approach channel. Recall that these relationships are:

$$v_{app} = \frac{(v_{Dopp} - 0.0378)}{0.934} \quad \textit{for submergence} \leq 0.95 \ldots\ldots\ldots\ldots\ldots 9.3$$

$$v_{app} = \frac{(v_{Dopp} - 0.0481)}{0.6989} \quad \textit{for submergence} > 0.95 \ldots\ldots\ldots\ldots\ldots 9.4$$

The approach velocity calculated in this way was then used to obtain the discharge. The results are summarized in Table 9.4.

y	H	t/h_v	Q_{Actual}	V_{Dopp}	V_{app}(calc)	Q_{calc}	error
(m)	(m)		(m^3/s)	(m/s)	(m/s)	(m^3/s)	(%)
0.210	0.039	**0.959**	0.0239	0.1077	0.0853	0.0204	**-14.84**
0.211	0.040	**0.960**	0.0266	0.1120	0.0914	0.0215	**-19.15**
0.218	0.047	**0.944**	0.0340	0.1458	0.1156	0.0272	**-19.95**
0.222	0.051	**0.922**	0.0360	0.1516	0.1218	0.0310	**-13.89**
0.228	0.057	**0.958**	0.0412	0.1447	0.1382	0.0368	**-10.71**
0.242	0.070	**0.971**	0.0520	0.1531	0.1502	0.0508	**-2.25**
0.229	0.058	**0.826**	0.0453	0.1864	0.1591	0.0383	**-15.36**
0.230	0.059	**0.883**	0.0458	0.1662	0.1375	0.0388	**-15.28**
0.238	0.067	**0.954**	0.0487	0.1616	0.1623	0.0469	**-3.63**
						Average	**-12.78**
						Std. Dev.	**6.22**
						Max.	**19.95**
						Min.	**-2.25**

Table 9.4 *Errors in the discharge calculation for drowned flow by using the relationship between the Doppler velocity and the approach velocity.*

The results are encouraging, with an average error of –12.78% and a standard deviation of 6.22%. It is very likely that the drowned experiments should also rather be divided into ranges of submergence smaller than 0.93 and those bigger than 0.93 (Recall equations 3.4 and 3.5) or even into more ranges. With only limited data available the ranges that were chosen here required the results to be divided into two to have sufficient points for regression analysis. With more points available over the full range of submergence ratios the regression lines would surely move somewhat and this in turn could reduce the error in the calculated discharge. It must also be noted here that the calculated discharge for the drowned experiments introduced errors of magnitude up to 8.5% and that these values were used as the actual or real discharge. With very accurate results of drowned discharge over a Crump weir in combination with flumes, the errors obtained in Table 9.4 might further change. In general it seems likely however, that the linear relationship between the Doppler velocity and the approach velocity obtained for the non-modular experiments, can reliably be used to calculate the discharge over a Crump weir. It is believed that the Doppler meter could be calibrated in situ under modular flow conditions and that the relationship between approach velocities and Doppler velocities could then be used for non-modular flow measurements.

10 CONCLUSIONS AND RECOMMENDATIONS

10.1 CONCLUSIONS

- Within the ranges of the flow rates tested in the laboratory, it can be concluded that the Doppler meter can be used to obtain a relationship between the approach velocity and the measured Doppler velocity at a Crump weir for both modular and non-modular flow conditions. Linear relationships were obtained for both modular and non-modular flow conditions.

- The linear relationship obtained here between the two velocities, proves that the Doppler meter is not very sensitive to curved flow lines over the Crump's crest at different flow depths. The relative size of the probe in the prototype situation should lead to much less obstruction whilst the radius of curvature of the flow lines should also be less. Better correlation is thus expected in the prototype than in the model between the different velocities. The results in the non-modular flow range are also encouraging and different linear relationships are obtained for different degrees of submergence. There is a strong indication that for submergence ratios lower than approximately 0.93, the error between the plots for the drowned experiments and the free experiments becomes sufficiently small to regard these drowned plots to follow the linear relationship that exists for modular flow. In general it can be concluded that the Doppler meter can be developed to directly read the approach velocity upstream of a Crump weir and hence simplify the calculation of discharge.

- The wide scatter of the readings in the Jonkershoek River can be attributed to not averaging the readings. A constant time interval between readings of 10 seconds and taking ten readings is sufficient to obtain an average Doppler frequency. This should eliminate the wide scatter of the readings. Working with average frequency readings taken over a certain time span and not every single reading is a more representative measure of the average discharge. The Doppler meter reads continuously and picks up readings from within the acoustic field in front of the probe. These readings must be averaged to obtain a representative velocity from within this small acoustic field

- Within the constraint of limited channel width for the calibration of the Doppler meter in the laboratory, the opportunity to compare the electromagnetic flowmeter to the Doppler flowmeter, showed that the two instruments gave velocity readings within 2.3% of each other. The likelihood that both instruments are incorrect and furthermore to the same magnitude, support the derivation and calculation of the Doppler constant to be accurate within these constraints. The Doppler meter also performed well under limiting conditions, giving reliable readings very close to the channel floor as well as to the water surface.

- The constant obtained from the calibration of the Doppler meter with the "clean" water of the laboratory had frequency readings, on average, only 3.6% lower than for water with higher sediment concentrations. This will only marginally influence the calibration of the Doppler meter in water with higher sediment concentrations.

- One drawback of the apparatus is its inability to measure flow velocities below 0.046 m/s. Other commercially available Doppler meters are supposed to read velocities smaller in magnitude than this.

10.2 RECOMMENDATIONS

- The relationship between the Doppler velocity and the approach velocity in the non-modular flow regime range should further be investigated, especially for submergence ratios of between 0.75 and 0.93 where more accurate calibration should be possible in a larger model or prototype. The relationship established for this submergence range should then be compared to the relationship that exists for free flow conditions. It is believed that the relationship for free flow conditions could be extrapolated for use under non-modular flow conditions.

- The Doppler meter should again be calibrated at a Crump weir. The relationship obtained between the approach velocity and the measured Doppler velocity should then be compared to the relationship obtained here, to establish whether any differences in (a) the magnitude of the calibration constant and (b) the relationship between the approach velocity and the Doppler velocity at the weir are evident. The calibration at the Crump weir should also allow for better control of submergence ratios for high flows.

- It has been mentioned in the report that it is imperative that there are suspended particles in the water that follow the path of the flow lines sufficiently closely so that the Doppler meter can function correctly. It is recommended that the sensitivity of the Doppler meter to **very low** sediment concentrations be investigated further. This minimum concentration, beyond which the instrument shows no sensitivity to changes in the sediment concentrations, should be established. In areas where fishes can be expected to occur, the influence their relative movements might have on the measured frequencies should also be looked into.

- The use of the Doppler meter in combination with other weirs, such as sharp-crested weirs, should also be investigated further.

11 GUIDELINES FOR THE USE OF THE DFM-P-062 DOPPLER METER

This chapter has been added at the end of this report, after the conclusions and recommendations, to provide guidelines for the use of the Doppler meter. It represents the integrated outcome of the research.

11.1 CALIBRATION OF DOPPLER METER

- The laboratory calibration procedure which has been used, is applicable to all Doppler meters, but it seems possible that the Doppler meter can also be calibrated in the upstream pool of a weir when laboratory facilities are not available. In this case the Doppler sensor must be positioned at 60 % of the flow depth in the approach channel where the average approach velocity should be present.

- For point measurements in fully developed turbulent flow the Doppler meter must be calibrated in the laboratory where the discharge can be measured accurately by other means such as an orifice plate. The number of segments required in a cross-section must be sufficient to limit the discharge through any segment to less than 10 % of the total discharge.

- Every Doppler meter must be calibrated for its own Doppler constant. The Doppler constant obtained here must not be misleading as it only differs by 6 % from the theoretical value. Other meters might have constants in excess of this value or less than this.

- The manufacturer claims that periodic calibration is not required provided that the sonic properties of the liquid do not change.

11.2 WHERE AND WHEN TO USE THE INSTRUMENT

- The Doppler meter is suitable for measuring high velocities and from the tests of this study it can be concluded that the sensor can be positioned anywhere in a flowing stream, i.e. close to the water surface, the channel floor and close to the channel walls.

- The Doppler meter is not suitable to measure flow velocities in regions where very low flow velocities are expected. This would mean that the sensor should not be used in the upstream pool of a weir under low flow conditions. Under these conditions the flow velocities in the upstream pool will be very low and faulty readings can be expected. At the weir crest however, the flow is accelerated and the higher velocities should be measurable here.

- The minimum velocity this instrument can measure is 0.046 m/s. In streams where very low flow velocities occur that are below this critical value, faulty readings must be expected.

- The sensor can be set at any angle in the stream but the measured frequency must then be converted into the horizontal velocity component by multiplying by the cosine of the angle at which the sensor is held.

- The time span between readings does not influence the average of the observed Doppler frequencies. The readings must however be read at constant time intervals and the datalogger, with which the microprocessor is equipped, can be used to set this interval. Continuous readings can thus also be taken, meaning that the time interval between readings is very small. For the same flow conditions, i.e. same upstream water depth at a weir for example, the readings should then be averaged.

- The Doppler meter should not be used in very clean water as it relies on suspended particles or air bubbles in the flowing stream. The manufacturer gives this minimum required sediment concentration as 125 ppm. The manufacturer also states that the minimum particle diameter should be 50 micron.

11.3 MEASUREMENTS AT WEIRS

- The Doppler meter can be used to relate the velocity at a Crump crest to the approach velocity. This is especially true for free flow conditions with provisional tests showing that there is a strong likelihood that this is also the case for drowned flow. Tests on facilities where the submergence ratios can be controlled better should bear this out.

- The probe can be positioned anywhere close to the crest but it should be in a position where it will not be silted up. The ideal position will also be the centre of the span of the crest.

- The probe can be positioned at an angle at crest level or close to crest level and the measurements must then be converted into the horizontal velocity components.

12 REFERENCES

ACKERS, P., WHITE, W.R., PERKINS, J.A. and HARRISON, A.J.M. *Weirs and flumes for flow measurement.* Chichester: John Wiley & Sons, 1978

HAYWARD, A. T. J. *Flowmeters.* London: The Macmillan Press Ltd., 1979

ARGONAUT-ADV PRINCIPLES OF OPERATION: *Argonaut-ADV Principles of Operation.* [Online]. Available: http://www.sontek.com/princop/aadv/

BHAGWAN ET AL., 1999.*Some recent developments in water demand management in South Africa.* Report delivered at the Ninth South African National Hydrology Symposium: RSA. Western Cape

BRUCE,H.2000. *The rating of sluicing flumes in combination with sharp-crested and Crump weirs under modular and non-modular flow conditions.* WRC Report No./2000. Water Research Commission: Pretoria

BSI. 1981. *Methods of measurement of liquid flow in open channels. Part 4A. Thin-plate weirs.* British Standards Institution

BSI. 1984. *Methods of measurement of liquid flow in open channels. Part 4B. Triangular profile weirs.* British Standards Institution

MASSEY, B. S. *Mechanics of fluids.* 6th. Ed. Chapman & Hall, 1989

CLAYTON, C. G. *Modern developments in flow measurement.* Peter Peregrinns Ltd., 1972

DELPORT AND LE ROUX (1990): *Handleiding vir kalibrasieprogramme.* Manual for Calibration Programs. Pretoria: Department of Water Affairs.

DRAIN, L. E. *The laser Doppler technique.* John Wiley & Sons Ltd., 1980

DU TOIT AND VENTER. 1999. *Kalibrasie van Meetwalle vir Hoogvloei Toestande met behulp van die Doppler Snelheidsmeter.* Stellenbosch: Universiy of Stellenbosch. Skripsie Nr. W5/99

HARR, M. E. *Groundwater and seepage.* London: McGraw-Hill, 1962

HENDERSON, F. M. *Open channel flow.* New York: Macmillan Publishing Co. Inc., 1966

GRIBBIN, J. *Q is for quantum. Particle physics from A to Z.* London: Phoenix Giant, 1999

LOWELL, F.C., ET AL., *Open Channel Flowrate Measurement Using Multipath Acoustic Flowmeters.* New York: ASCE, 1985 [online]. Available: http://www.webpatent.com/examples/proposal/

Manual on Stream Gauging. Volume I: *Fieldwork.* Geneva: World Metereological Organization, 1980

Manual on Stream Gauging. Volume II: *Computation of Discharge.* Geneva: World Metereological Organization, 1980

MATTHAI, H. F. 1967 *Measurements of peak discharge at width contractions by indirect methods.* In: Techniques of Water Resources Investigation of the United States Geological Survey. Washington: U.S. Department of the Interior

MATTHEE, G. G. 1993. *Die aanwending van Crump-meetstrukture op verskillende hoogtes in riviervloeimeetstasies.* Stellenbosch: University of Stellenbosch. MSc Thesis

KAY, M. *Practical Hydraulics.* New York: E & FN SPON, 1998

ATKINSON, P and WOODCOCK, J. P. *Doppler ultrasound and its use in clinical measurement.* Academic Press, 1982

PIPELINE AND GAS JOURNAL, 2000. *Ultrasonic Meters: A natural choice to measure gas flow.* [Online]. Available: http://www.undergroundinfo.com/pg%20archive/

FEATHERSTONE, R. E. and NALLURI, C. *Civil Engineering Hydraulics.* 3rd ed. Blackwell Science, 1995

ROOSEBOOM, A. 1992. *Sediment transport in rivers and a reservoirs – a Southern African perspective.* WRC Report No. 297/1/92. Pretoria: Water Research Commission

ROOSEBOOM, A. and LOTRIET, H. H. 1995. *River discharge measurement in South African rivers. The development of improved measuring techniques.* WRC Report No. 442/2/95. Pretoria: water research Commission

ROSSOUW, J. ROOSEBOOM, A. and WESSELS P. 1995. *Laboratory calibration of compound sharp-crested and Crump weirs.* WRC Report No. 442/1/95. Pretoria: Water Research Commission.

ROSSOUW, J. et al. 1998. *Sluicing flumes: New structures for discharge measurement in sediment laden rivers.* WRC Report No. 442/3/98. Water Research Commission: Pretoria

CANTO, R. R. 2000. *Compound sharp-crested weirs under modular and non-modualr flow conditions.* Stellenbosch: University of Stellenbosch. MSc. Thesis

MILLER, R. W. *Flow measurement engineering handbook.* New York: McGraw-Hill Book Company,1983

SHAW, E. M. *Hydrology in practice.* Berkshire: Van Nostrund Reinhold (UK) Co. Ltd., 1983

SIGNAL PROCESSING. 1998: *Technical Information.* [Online]. Available: http://www.signal-processing.com/

TECHNICAL INFORMATION ON ULTRASONIC TECHNIQUES. *Introducing DOP Ultrasonic Velocimeter.* [Online]. Available: http://www.signal-processing.com/tech/

U.S. DEPARTMENT OF THE INTERIOR/BUREAU OF RECLAMATION. 1997. *USBR Water Research Manual*. [Online]. Available: http://www.usbr.gov/wrrl/fmt/wmm

VERMEYEN, T.B., ET AL., *A Laboratory Evaluation of Unidata's Starflow Doppler Flowmeter and MGD Technologies Acoustic Doppler FlowMeter.* 1999: [Online] Available: http://www.usbr.gov/wrrl/tvermeyen/starflow/

WEBBER, N. B. *Fluid mechanics for civil engineers.* London: Chapman and Hall Ltd., 1971

WESSELS, P. *The calibration of compound Crump and sharp-crested gauging weirs in South Africa.* Stellenbosch: University of Stellenbosch. MSc Thesis.

WOLFAARDT, E. W. 1992. *Invloed van poeldiepte, traphoogte en oorloopwydte op kalibrasie van skerpkruinriviervloeimeetstsies.* Stellenbosch: University of Stellenbosch. MSc Thesis

WORLD METEOROLOGICAL ORGANIZATION. *Manual on Stream Gauging, Volume 1, Fieldwork.* World Meteorological Organization, 1980

YEVJEVICH, V. and STAROSOLSKY, Ö. *Controversies between water resources development and protection of the environment.* Journal of Hydraulic Research, Volume 36, 1998, pp. 135-143

APPENDIX A

Laboratory calibration of manometer

A.1.

Tests performed to calibrate the manometer:

Test 1:

Zero datum reading (V-notch): 15.04 cm

V-notch

Reading	h	h_e	Q
(cm)	(cm)	(m)	(m^3/s)
23.54	23.54	0.23625	0.03698
28.00	28.00	0.28085	0.05698
21.42	21.42	0.21505	0.02923
32.09	32.09	0.32175	0.08004
29.95	29.95	0.30035	0.06739
26.49	26.49	0.26575	0.04963
29.61	29.61	0.29695	0.0655
27.53	27.53	0.27615	0.05462
32.99	32.99	0.33075	0.08576
29.00	29.00	0.29085	0.06219

Water manometer

h	Q
(mm)	(m^3/s)
4.0	0.00373
48.0	0.01291
32.0	0.01054
77.0	0.01635
72.0	0.01581
44.0	0.01236
57.0	0.01407
42.0	0.01208
90.0	0.01768
61.0	0.01455

Mercury manometer

Reading	h	Q
(mm)	(mm)	(m^3/s)
0.3	4.083	0.00377
3.5	47.635	0.01286
2.5	34.025	0.01087
6.0	81.66	0.01684
5.6	76.216	0.01627
3.5	47.635	0.01286
4.2	57.162	0.01409
3.3	44.913	0.01249
7.0	95.27	0.01819
4.7	63.967	0.01490

Q for the V-notch calculated as per the BS 3680:Part 4A: 1981

C_e from Figure 8 = 0.577

Test 2:

The data of the previous day showed no correlation and it was found that air was present in the pipe and thus both manometers

New Needle:

bottom channel: 1.39 cm

zero-datum: 31.25 cm

p 0.2986 m

B 0.6 m

p/B 0.49767

V-notch

Reading	h	h_e	Q
(cm)	(cm)	(m)	(m^3/s)
44.12	12.87	0.12955	0.00823
53.39	22.14	0.22225	0.03174
51.35	20.10	0.20185	0.02495
48.89	17.64	0.17725	0.01803
46.47	15.22	0.15305	0.01249
48.72	17.47	0.17555	0.01760
46.73	15.48	0.15565	0.01303
48.39	17.14	0.17225	0.01679
45.93	14.68	0.14765	0.01142
48.37	17.12	0.17205	0.01674

Water/air manometer

h	av h	Q	Remarks
(cm)	(cm)	(m^3/s)	
1.91	1.91	0.00814	
27.0-27.4	27.20	0.03073	Oscillated
16.8-17.1	16.95	0.02426	Oscillated
8.91	8.91	0.01759	
4.3	4.30	0.01222	
8.3-8.5	8.40	0.01708	Oscillated
4.6	4.60	0.01264	
7.5-7.6	7.55	0.01619	Oscillated
3.5	3.50	0.01102	
7.4-7.5	7.45	0.01608	Oscillated

Mercury/water manometer

Reading	h	Q
(mm)	(mm)	(m^3/s)
1.2	0.01633	0.00753
21.1	0.28717	0.03158
13.0	0.17693	0.02479
7.0	0.09527	0.01819
3.9	0.05308	0.01358
6.4	0.08710	0.01739
4.0	0.05444	0.01375
5.9	0.08030	0.01670
3.4	0.04627	0.01268
5.6	0.07622	0.01627

Q for the V-notch calculated as per the BS 3680:Part 4A: 1981

C_e from Figure 8 = 0.577

A.2.
Calculation to calibrate the manometer

Calibration was based on second experiment only.

To calibrate the manometer, the V-notch was assumed to be 100% accurate.

V-notch		Manometer (water)			Manometer (mercury)	
Q		Q	% accurate		Q	% accurate
(m^3/s)		(m^3/s)			(m^3/s)	
0.00823		0.00814	98.9		0.00753	91.5
0.03174		0.03073	96.8		0.03158	99.5
0.02495		0.02426	97.2		0.02479	99.3
0.01803		0.01759	97.6		0.01819	100.9
0.01249		0.01222	97.8		0.01358	108.7
0.01760		0.01708	97.0		0.01739	98.8
0.01303		0.01264	97.0		0.01375	105.5
0.01679		0.01619	96.5		0.01670	99.5
0.01142		0.01102	96.6		0.01268	111.0
0.01674		0.01608	96.1		0.01627	97.2
Average			**97.2**			**101.2**

The mercury/water manometer was not as consistent as the water/air manometer. It was thus only worked with the water/air manometer The water/air manometer underestimated the flow on average by 2.8%. The calibration multiplier was thus:

1.03

APPENDIX B

Laboratory calibration of Doppler meter

B.1.

Experiment 1

Readings of flow and water depth

Flow: Zero-datum: 31.25 cm

V-notch	Manometer	Mercury
(cm)	(cm)	(mm)
51.65*	17.9-18.2**	14

** V-notch not drowned*

*** Water column oscillated between these 2 values*

Channel width: 600 mm

Doppler Meter:

flow depth (d)	Channel bottom*
(cm)	(cm)
27.7	16.05

** Reading when the probe is flush with the bottom of the channel.*

Divide *d* into two blocks, each 13.85 cm deep.
Take readings in the centre of these blocks, i.e. at y_1 = 6.925 cm and at y_2 = 20.775 cm above the bottom of the channel.

y_1 reading on needle	y_2 reading on needle
(cm)	(cm)
22.6	36.4

Also divide width of channel into blocks each 100 mm wide and take readings at centre of each block, I.e. at

x_1 = 50

x_2 = 150

x_3 = 250

x_4 = 350

x_5 = 450

x_6 = 550

Readings of Doppler Frequencies

All readings were taken at 10 second intervals

FREQUENCIES AT y_1 (Hz)

x	50	150	250	350	450	550
1	312	322	316	310	310	320
2	322	320	340	304	320	298
3	322	312	322	328	308	348
4	326	318	322	336	320	326
5	316	306	314	306	316	316
6	316	304	332	328	328	336
7	306	342	316	320	314	312
8	332	302	322	316	290	328
9	304	308	336	328	306	316
10	300	310	322	336	338	310
Average	**315.6**	**314.4**	**324.2**	**321.2**	**315**	**321**

FREQUENCIES AT y_2 (Hz)

x	50	150	250	350	450	550
1	260	276	286	270	270	276
2	274	284	268	286	270	270
3	256	268	280	282	286	288
4	272	290	272	276	276	278
5	270	270	268	284	256	290
6	268	280	290	274	282	300
7	276	276	266	278	278	288
8	252	264	260	288	292	282
9	248	274	272	286	286	282
10	268	270	276	284	284	300
Average	**264.4**	**275.2**	**273.8**	**280.8**	**278**	**285.4**

Calculation of Flow and Doppler constant

Calculation of Flow

	V-notch	Manomete	Manometer'
Q (m^3/s)	0.025889	0.02504	0.02579

' *denotes calibrated value*

Calculation of Doppler constant

	delta A	f	delta Q/K
	(m^2)	(Hz)	(m^3/s)
1	0.01385	315.6	4.3711
2	0.01385	314.4	4.3544
3	0.01385	324.2	4.4902
4	0.01385	321.2	4.4486
5	0.01385	315.0	4.3628
6	0.01385	321.0	4.4459
7	0.01385	264.4	3.6619
8	0.01385	275.2	3.8115
9	0.01385	273.8	3.7921
10	0.01385	280.8	3.8891
11	0.01385	278.0	3.8503
12	0.01385	285.4	3.9528
Sum			**49.4307**

Now the sum of the delta Q's must equal the Q as calculated by the V-notch.

i.e. 49.4307/K = 0.02589

K= 1909.3

B.2.

Experiment 2

Readings of flow and water depth

Zero-datum:

Flow: Zero-datum: 31.69 cm

V-notch	Manometer	Mercury
(cm)	(cm)	(mm)
52.85*	23.6-24.1**	N/A

V-notch not drowned

** *Water column oscillated between these 2 values*

Channel width: 600 mm

Doppler Meter:

flow depth (d)	Channel bottom*
(cm)	(cm)
30.5	16.05

* *Reading when the probe is flush with the bottom of the channel.*

Divide *d* into 5 blocks, each 6.1 cm deep.

Take readings in the centre of these blocks, i.e. at y_1 = 3.05 cm, y_2 = 9.15 cm, y_3 = 15.25 cm, y_4 = 21.35 cm and y_5 = 27.45 cm above the bottom of the channel.

y_1 reading on needle	y_2 reading on needle	y_3 reading on needle	y_4 reading on needle
(cm)	(cm)	(cm)	(cm)
18.7	24.8	30.9	37.0

Also divide the width of channel into blocks each 100 mm wide and take readings at centre of each block, I.e. at

x_1 = 50

x_2 = 150

x_3 = 250

x_4 = 350

x_5 = 450

x_6 = 550

Readings of Doppler Frequencies

(i) Readings at 10 second intervals

FREQUENCIES AT y_1 (Hz)

x	50	150	250	350	450	550
1	344	338	342	338	346	324
2	340	332	346	344	326	334
3	320	334	370	356	310	342
4	306	336	326	344	344	338
5	342	352	350	338	322	316
6	318	324	324	358	330	328
7	326	326	358	346	346	320
8	332	330	332	358	318	344
9	332	330	330	336	328	324
10	328	334	360	350	342	306
Average	**328.8**	**333.6**	**343.8**	**346.8**	**331.2**	**327.6**

FREQUENCIES AT y_2 (Hz)

x	50	150	250	350	450	550
1	312	310	318	324	342	330
2	308	314	318	310	320	320
3	294	308	322	312	300	324
4	302	314	342	318	314	282
5	312	322	322	318	308	316
6	324	340	332	306	332	324
7	288	318	324	318	328	348
8	304	308	322	316	326	310
9	324	326	336	340	328	300
10	308	332	312	324	326	312
Average	**307.6**	**319.2**	**324.8**	**318.6**	**322.4**	**316.6**

FREQUENCIES AT y_3 (Hz)

x	50	150	250	350	450	550
1	294	296	308	318	296	300
2	304	300	296	286	300	300
3	298	302	304	316	308	298
4	278	300	298	300	310	292
5	298	286	314	308	326	302
6	286	296	304	288	288	294
7	304	306	298	326	302	290
8	308	308	304	312	304	298
9	306	292	324	302	298	312
10	304	332	314	286	302	288
Average	**298**	**301.8**	**306.4**	**304.2**	**303.4**	**297.4**

Readings of Doppler Frequencies

(i) Readings at 10 second intervals

FREQUENCIES AT y_4 (Hz)

x	50	150	250	350	450	550
1	300	276	296	282	282	274
2	312	286	298	290	302	290
3	290	284	288	288	300	292
4	300	284	290	276	298	298
5	294	292	286	292	282	294
6	286	292	284	296	286	290
7	282	294	296	282	288	282
8	290	284	282	298	288	288
9	300	276	294	300	296	274
10	282	296	292	290	288	284
Average	**293.6**	**286.4**	**290.6**	**289.4**	**291**	**286.6**

FREQUENCIES AT y_5 (Hz)

x	50	150	250	350	450	550
1	238	272	276	274	286	272
2	258	284	268	272	280	256
3	260	268	302	282	268	276
4	254	274	276	274	280	268
5	256	272	266	266	264	260
6	260	284	276	274	270	270
7	258	284	280	278	282	260
8	258	288	282	270	266	248
9	260	270	270	292	272	252
10	254	270	284	272	284	252
Average	**255.6**	**276.6**	**278**	**275.4**	**275.2**	**261.4**

Readings of Doppler Frequencies

(ii) Readings at 30 s intervals

FREQUENCIES AT y_1 (Hz)

x	50	150	250	350	450	550
1	328	334	326	330	342	340
2	330	340	348	346	324	338
3	320	314	332	310	332	310
4	334	326	316	332	364	342
5	306	332	310	342	330	316
6	316	318	334	322	320	332
7	354	324	324	340	340	322
8	336	312	344	350	340	312
9	312	342	350	318	318	324
10	326	326	358	356	346	304
Average	326.2	326.8	334.2	334.6	335.6	324.0

FREQUENCIES AT y_2 (Hz)

x	50	150	250	350	450	550
1	306	314	312	314	322	310
2	306	302	314	334	338	326
3	324	316	330	312	318	324
4	310	314	342	340	322	322
5	312	318	304	324	320	324
6	310	330	312	324	326	318
7	284	324	332	326	336	334
8	332	312	316	316	324	322
9	314	340	310	328	346	326
10	304	322	314	318	322	300
Average	310.2	319.2	318.6	323.6	327.4	320.6

FREQUENCIES AT y_3 (Hz)

x	50	150	250	350	450	550
1	294	298	314	288	302	296
2	308	294	308	298	314	296
3	316	306	324	306	310	300
4	304	306	314	304	292	306
5	292	302	316	300	300	300
6	288	310	290	300	308	280
7	288	302	300	286	314	308
8	296	300	314	306	302	294
9	294	302	292	318	322	296
10	310	310	320	320	300	282
Average	299	303	309.2	302.6	306.4	295.8

Readings of Doppler Frequencies

(ii) Readings at 30 s intervals

FREQUENCIES AT y_4 (Hz)

x	50	150	250	350	450	550
1	290	290	290	290	296	298
2	276	294	288	288	294	274
3	288	288	284	300	282	300
4	300	294	278	290	290	278
5	286	292	296	298	280	300
6	300	290	296	294	286	284
7	292	288	292	306	298	284
8	296	298	296	308	296	284
9	294	288	288	290	288	300
10	296	306	300	296	302	280
Average	**291.8**	**292.8**	**290.8**	**296**	**291.2**	**288.2**

FREQUENCIES AT y_5 (Hz)

x	50	150	250	350	450	550
1	238	264	274	268	270	244
2	260	282	263	282	268	256
3	238	266	280	276	272	262
4	268	276	270	284	276	268
5	240	278	290	272	272	274
6	256	284	280	278	270	244
7	260	270	268	274	290	254
8	264	278	270	274	280	244
9	250	282	276	284	288	258
10	270	266	268	282	260	260
Average	**254.4**	**274.6**	**273.9**	**277.4**	**274.6**	**256.4**

Calculation of Flow and Doppler constant

Calculation of Flow

	V-notch	Manometer	Manometer*
Q (m^3/s)	0.02836	0.02878	0.02964

denotes calibrated value

Calculation of Doppler constant

(i)

	delta A (m^2)	f (Hz)	delta Q/K (m^3/s)
1	0.0061	328.8	2.0057
2	0.0061	333.6	2.0350
3	0.0061	343.8	2.0972
4	0.0061	346.8	2.1155
5	0.0061	331.2	2.0203
6	0.0061	327.6	1.9984
7	0.0061	307.6	1.8764
8	0.0061	319.2	1.9471
9	0.0061	324.8	1.9813
10	0.0061	318.6	1.9435
11	0.0061	322.4	1.9666
12	0.0061	316.6	1.9313
13	0.0061	298.0	1.8178
14	0.0061	301.8	1.8410
15	0.0061	306.4	1.8690
16	0.0061	304.2	1.8556
17	0.0061	303.4	1.8507
18	0.0061	297.4	1.8141
19	0.0061	293.6	1.7910
20	0.0061	286.4	1.7470
21	0.0061	290.6	1.7727
22	0.0061	289.4	1.7653
23	0.0061	291.0	1.7751
24	0.0061	286.6	1.7483
25	0.0061	255.6	1.5592
26	0.0061	276.6	1.6873
27	0.0061	278.0	1.6958
28	0.0061	275.4	1.6799
29	0.0061	275.2	1.6787
30	0.0061	261.4	1.5945
Sum			**55.4612**

(ii)

	delta A (m^2)	f (Hz)	delta Q/K (m^3/s)
1	0.0061	326.2	1.9898
2	0.0061	326.8	1.9935
3	0.0061	334.2	2.0386
4	0.0061	334.6	2.0411
5	0.0061	335.6	2.0472
6	0.0061	324.0	1.9764
7	0.0061	310.2	1.8922
8	0.0061	319.2	1.9471
9	0.0061	318.6	1.9435
10	0.0061	323.6	1.9740
11	0.0061	327.4	1.9971
12	0.0061	320.6	1.9557
13	0.0061	299.0	1.8239
14	0.0061	303.0	1.8483
15	0.0061	309.2	1.8861
16	0.0061	302.6	1.8459
17	0.0061	306.4	1.8690
18	0.0061	295.8	1.8044
19	0.0061	291.8	1.7800
20	0.0061	292.8	1.7861
21	0.0061	290.8	1.7739
22	0.0061	296.0	1.8056
23	0.0061	291.2	1.7763
24	0.0061	288.2	1.7580
25	0.0061	254.4	1.5518
26	0.0061	274.6	1.6751
27	0.0061	273.9	1.6708
28	0.0061	277.4	1.6921
29	0.0061	274.6	1.6751
30	0.0061	256.4	1.5640
Sum			**55.3825**

Now the sum of the delta Q's must equal the Q as calculated by the V-notch.

i.e. for (i) 55.4612/K = 0.02836 — (ii) 55.3825/K = 0.02836

K = 1955.6 — **K = 1952.8**

B.3.

Experiment 3

Readings of flow and water depth

Flow: Zero-datum: 31.75 cm

V-notch	Manometer	Mercury	Remarks
(cm)	(cm)	(mm)	
49.07*	8.2 - 8.4	N/A	Check
54.57	32.4 - 33.1**	N/A	V-notch drowned

V-notch not drowned.

** *Water column oscillated between these 2 values*

Channel width: 600 mm

Doppler Meter:

flow depth (d)	Channel bottom
(cm)	(cm)
45.7	15.96

* *Reading when the probe is flush with the bottom of the channel.*

this level.

Divide *d* into 10 blocks, each 4.57 cm deep.

Take readings in the centre of these blocks, i.e. at y_1 = 2.285 cm, y_2 = 6.855 cm, etc above the bottom

y_1 reading on needle	y_2 reading on needle	y_3 reading on needle	y_4 reading on needle	y_5 reading on needle
(cm)	(cm)	(cm)	(cm)	(cm)
17.85	22.42	26.99	31.56	36.13

y_6 reading on needle	y_7 reading on needle	y_8 reading on needle	y_9 reading on needle	y_{10} reading on needle
(cm)	(cm)	(cm)	(cm)	(cm)
40.70	45.27	49.84	54.41	58.98

Also divide the width of channel into blocks each 100 mm wide and take readings at centre of each block, I.e. at

x_1 = 50
x_2 = 150
x_3 = 250
x_4 = 350
x_5 = 450
x_6 = 550

Readings of Doppler Frequencies

All readings were taken at 10 second intervals

FREQUENCIES AT y_1 (Hz)

x	50	150	250	350	450	550
1	364	346	404	324	346	374
2	354	360	358	360	386	370
3	334	356	324	348	386	368
4	352	352	326	330	388	382
5	328	328	374	378	378	358
6	354	366	382	364	372	380
7	390	378	392	360	352	388
8	372	364	356	330	358	350
9	356	360	316	394	348	406
10	366	392	378	374	344	362
Average	357.0	360.2	361.0	356.2	365.8	373.8

FREQUENCIES AT y_2 (Hz)

x	50	150	250	350	450	550
1	312	348	362	352	332	324
2	324	338	364	360	366	336
3	322	304	386	328	378	340
4	378	308	346	386	316	358
5	360	322	352	332	350	316
6	358	308	344	350	346	356
7	366	354	380	330	348	352
8	372	378	334	290	362	366
9	324	354	368	330	342	372
10	354	324	344	346	324	366
Average	347.0	333.8	358.0	340.4	346.4	348.6

FREQUENCIES AT y_3 (Hz)

x	50	150	250	350	450	550
1	316	306	322	318	342	344
2	330	322	330	344	320	328
3	342	310	312	336	344	348
4	350	320	350	354	324	376
5	318	342	324	322	324	362
6	342	324	332	330	324	368
7	330	336	350	338	332	348
8	352	348	336	370	352	320
9	322	342	336	332	308	338
10	358	340	328	328	356	322
Average	336.0	329.0	332.0	337.2	332.6	345.4

Readings of Doppler Frequencies

All readings were taken at 10 seconds intervals

FREQUENCIES AT y_4 (Hz)

x	50	150	250	350	450	550
	314	330	346	278	336	338
	352	340	338	344	312	352
	384	346	342	322	336	326
	350	340	328	384	336	348
	334	314	298	332	340	330
	314	334	316	330	326	314
	314	322	322	332	332	328
	316	328	334	312	312	350
	292	308	342	306	290	330
	320	336	298	338	274	300
	329	**329.8**	**326.4**	**327.8**	**319.4**	**331.6**

FREQUENCIES AT y_5 (Hz)

x	50	150	250	350	450	550
	312	344	330	344	336	328
	310	334	332	324	322	300
	322	302	312	320	328	318
	332	328	310	338	330	338
	308	332	328	320	308	306
	308	304	298	326	352	342
	304	306	298	348	346	342
	324	344	330	318	314	320
	338	336	320	316	310	306
	324	310	308	286	336	290
	318.2	**324.0**	**316.6**	**324.0**	**328.2**	**319.0**

FREQUENCIES AT y_6 (Hz)

x	50	150	250	350	450	550
	310	290	344	332	326	294
	360	334	296	324	308	296
	344	338	302	310	314	342
	338	322	320	302	316	338
	324	352	290	322	312	328
	316	328	302	332	342	352
	302	280	330	322	314	328
	302	302	316	288	322	372
	286	292	320	360	304	342
	334	284	326	328	294	300
	321.6	**312.2**	**314.6**	**322.0**	**315.2**	**329.2**

Readings of Doppler Frequencies

All readings were taken at 10 second intervals

FREQUENCIES AT y_7 (Hz)

x	50	150	250	350	450	550
	324	304	296	312	292	316
	304	328	316	274	336	310
	288	298	308	278	318	328
	318	302	320	294	304	310
	316	288	336	332	318	286
	324	304	314	320	296	304
	296	314	286	326	300	308
	312	320	338	320	342	336
	288	350	312	312	300	342
	318	306	318	324	334	310
	308.8	**311.4**	**314.4**	**309.2**	**314.0**	**315.0**

FREQUENCIES AT y_8 (Hz)

x	50	150	250	350	450	550
	288	306	288	274	326	300
	328	304	302	300	314	322
	318	324	298	314	312	314
	300	322	268	310	274	294
	284	298	322	272	292	316
	282	272	312	278	292	302
	304	332	302	312	310	294
	334	310	312	292	302	284
	318	312	310	328	330	306
	320	330	304	302	326	302
	307.6	**311.0**	**301.8**	**298.2**	**307.8**	**303.4**

FREQUENCIES AT y_9 (Hz)

x	50	150	250	350	450	550
	282	310	310	292	312	288
	270	300	310	290	284	278
	270	274	280	296	272	256
	290	306	294	266	292	274
	302	276	286	286	290	306
	310	280	278	310	296	286
	288	294	294	282	286	308
	290	302	290	278	324	294
	302	286	286	306	294	306
	306	304	324	314	288	278
	291.0	**293.2**	**295.2**	**292.0**	**293.8**	**287.4**

Readings of Doppler Frequencies

All readings were taken at 10 second intervals

FREQUENCIES AT y_{10} (Hz)

x	50	150	250	350	450	550
	264	250	256	272	266	264
	274	272	254	278	264	244
	294	260	260	280	268	256
	260	262	272	248	272	254
	268	252	264	276	250	258
	250	268	278	264	264	268
	242	262	288	278	256	274
	232	266	280	282	260	256
	248	260	252	268	264	282
	270	272	264	258	280	262
	260.2	262.4	266.8	270.4	264.4	261.8

Calculation of Flow and Doppler constant

Calcualtion of Flow

	V-notch	Manometer	Manometer
Q (m^3/s)	N/A	0.0337	0.0347

* *denotes calibrated value*

Calculation of Doppler constant

	delta A	f	delta Q/K		delta A	f	delta Q/K
	(m^2)	(Hz)	(m^3/s)		(m^2)	(Hz)	(m^3/s)
1	0.00457	357.0	1.6315	31	0.00457	321.6	1.4697
2	0.00457	360.2	1.6461	32	0.00457	312.2	1.4268
3	0.00457	361.0	1.6498	33	0.00457	314.6	1.4377
4	0.00457	356.2	1.6278	34	0.00457	322.0	1.4715
5	0.00457	365.8	1.6717	35	0.00457	315.2	1.4405
6	0.00457	378.8	1.7311	36	0.00457	329.2	1.5044
7	0.00457	347.0	1.5858	37	0.00457	308.8	1.4112
8	0.00457	333.8	1.5255	38	0.00457	311.4	1.4231
9	0.00457	358.0	1.6361	39	0.00457	314.4	1.4368
10	0.00457	340.4	1.5556	40	0.00457	309.2	1.4130
11	0.00457	346.4	1.5830	41	0.00457	314.0	1.4350
12	0.00457	348.6	1.5931	42	0.00457	315.0	1.4396
13	0.00457	336.0	1.5355	43	0.00457	307.6	1.4057
14	0.00457	329.0	1.5035	44	0.00457	311.0	1.4213
15	0.00457	332.0	1.5172	45	0.00457	301.8	1.3792
16	0.00457	337.2	1.5410	46	0.00457	298.2	1.3628
17	0.00457	332.6	1.5200	47	0.00457	307.8	1.4066
18	0.00457	345.4	1.5785	48	0.00457	303.4	1.3865
19	0.00457	329.0	1.5035	49	0.00457	291.0	1.3299
20	0.00457	329.8	1.5072	50	0.00457	293.2	1.3399
21	0.00457	326.4	1.4916	51	0.00457	295.2	1.3491
22	0.00457	327.8	1.4980	52	0.00457	292.0	1.3344
23	0.00457	319.4	1.4597	53	0.00457	293.8	1.3427
24	0.00457	331.6	1.5154	54	0.00457	287.4	1.3134
25	0.00457	318.2	1.4542	55	0.00457	260.2	1.1891
26	0.00457	324.0	1.4807	56	0.00457	262.4	1.1992
27	0.00457	316.6	1.4469	57	0.00457	266.8	1.2193
28	0.00457	324.0	1.4807	58	0.00457	270.4	1.2357
29	0.00457	328.2	1.4999	59	0.00457	264.4	1.2083
30	0.00457	319.0	1.4578	60	0.00457	261.8	1.1964
			46.4285	**Sum**			**87.3574**

Now the sum of the delta Q's must equal the Q as calculated by the V-notch.

i.e. 87.3574/K = 0.0342

K = 2514.9

B.4.

Experiment 4

Reading of flow and water depth

Flow: Zero-datum: 31.69 cm

V-notch	Manometer	Mercury	Remarks
(cm)	(cm)	(mm)	
50.0*	10.7 - 10.9**	N/A	Check
55.75*	42.6 - 43.2**	N/A	

** V-notch not drowned.*

*** Water column oscillated between these 2 values*

Channel width: 600 mm

Doppler Meter:

flow depth (d)	Channel bottom*
(cm)	(cm)
26.6	15.98

** Reading when the probe is flush with the bottom of the channel.*

Divide *d* into 8 blocks, each 3.325 cm deep.
Take readings in the centre of these blocks, i.e. at y_1 = 1.66 cm, y_2 = 4.99 cm, etc above the bottom of the channel.

y_1 reading on needle	y_2 reading on needle	y_3 reading on needle	y_4 reading on needle	y_5 reading on needle
(cm)	(cm)	(cm)	(cm)	(cm)
17.25	20.57	23.89	27.22	30.54

y_6 reading on needle	y_7 reading on needle	y_8 reading on needle
(cm)	(cm)	(cm)
33.87	37.19	40.52

Also divide the width of channel into blocks each 75 mm wide and take readings at centre of each block, I.e. at

x_1 = 37.5 x_5 = 337.5

x_2 = 112.5 x_6 = 412.5

x_3 = 187.5 x_7 = 487.5

x_4 = 262.5 x_8= 562.5

Readings of Doppler Frequencies

All readings were taken at 10second intervals

FREQUENCIES AT y_1 (Hz)

x	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
1	348	350	356	352	368	374	360	334
2	338	352	364	366	368	358	360	340
3	328	342	350	350	358	344	348	340
4	342	356	364	372	372	370	362	348
5	340	346	334	366	372	376	364	350
6	340	360	354	370	364	378	356	348
7	334	356	360	372	360	362	356	346
8	340	352	368	366	364	358	346	344
9	338	348	342	362	370	366	364	330
10	328	352	364	370	356	354	364	340
Average	337.6	351.4	355.6	364.6	365.2	364.0	358.0	342.0

FREQUENCIES AT y_2 (Hz)

x	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
1	346	364	384	374	374	372	360	358
2	352	370	374	374	364	380	378	362
3	358	360	380	368	384	388	376	368
4	364	364	362	372	368	388	366	372
5	360	378	360	372	368	374	376	356
6	346	376	392	370	370	376	372	340
7	340	366	354	364	380	380	384	360
8	344	378	370	382	386	376	372	364
9	344	378	380	376	380	368	382	354
10	362	366	374	384	368	366	360	364
Average	351.6	370.0	373.0	373.6	374.2	376.8	372.6	359.8

FREQUENCIES AT y_3 (Hz)

x	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
1	342	374	382	360	370	380	376	360
2	370	388	378	386	368	380	384	366
3	344	374	372	370	368	378	372	366
4	352	380	380	376	376	370	370	366
5	358	372	380	384	384	376	386	356
6	362	380	364	380	374	370	372	366
7	364	386	376	376	382	382	382	358
8	368	384	384	376	392	386	378	370
9	340	378	380	376	378	388	376	364
10	362	374	390	376	380	362	370	378
Average	356.2	379.0	380.6	376.0	377.2	377.2	376.6	365.0

Readings of Doppler Frequencies

All readings were taken at 10 second intervals

FREQUENCIES AT y_4 (Hz)

x	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
1	364	360	382	376	380	386	392	364
2	328	362	380	376	368	376	384	360
3	338	364	376	386	378	370	382	350
4	350	362	368	354	374	398	388	366
5	342	372	362	390	372	378	372	368
6	340	370	372	364	380	366	370	372
7	362	372	378	370	382	368	388	380
8	362	356	366	382	386	366	398	356
9	362	374	368	362	378	388	374	354
10	352	366	370	366	384	380	382	350
Average	350.0	365.8	372.2	372.6	378.2	377.6	383.0	362.0

FREQUENCIES AT y_5 (Hz)

x	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
1	364	366	372	368	378	366	352	370
2	364	364	368	384	376	376	370	352
3	330	362	374	370	374	382	372	356
4	360	378	376	372	366	388	380	386
5	370	366	382	376	372	362	380	360
6	354	358	372	360	378	370	362	362
7	352	368	374	388	370	376	384	364
8	350	370	370	376	368	366	374	356
9	360	376	376	362	378	358	386	338
10	356	358	356	364	370	370	378	342
Average	356.0	366.6	372.0	372.0	373.0	371.4	373.8	358.6

FREQUENCIES AT y_6 (Hz)

x	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
1	338	362	354	370	366	364	362	346
2	350	374	356	370	368	364	394	362
3	346	356	364	382	360	366	360	344
4	352	360	354	362	370	370	376	364
5	348	350	348	376	364	348	360	348
6	342	366	362	360	368	358	366	344
7	356	350	366	372	364	366	366	372
8	358	376	366	368	380	362	362	366
9	352	338	362	372	366	362	384	362
10	340	372	362	348	364	366	358	350
Average	348.2	360.4	359.4	368.0	367.0	362.6	368.8	355.8

Readings of Doppler Frequencies

All readings were taken at 10 second intervals

FREQUENCIES AT y_7 (Hz)

x	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
1	342	358	352	358	358	368	374	336
2	324	344	370	366	370	366	358	332
3	372	344	362	354	344	376	364	330
4	338	360	350	372	364	366	376	338
5	342	348	358	366	350	354	366	346
6	340	340	370	352	364	348	362	328
7	322	350	366	342	346	362	352	348
8	312	358	348	360	362	346	368	334
9	348	358	360	364	358	362	340	340
10	346	360	358	368	370	356	348	334
Average	338.6	352.0	359.4	360.2	358.6	360.4	360.8	336.6

FREQUENCIES AT y_8 (Hz)

x	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
1	316	326	342	366	348	362	342	326
2	306	348	378	352	362	360	348	312
3	338	348	342	350	350	366	366	328
4	356	350	352	344	362	336	338	322
5	310	372	342	368	366	358	346	326
6	300	356	390	362	382	352	334	316
7	292	344	350	348	358	366	342	304
8	306	352	344	362	350	332	336	316
9	322	354	352	346	352	334	342	318
10	328	350	358	378	364	350	346	304
Average	317.4	350.0	355.0	357.6	359.4	351.6	344.0	317.2

Calculation of Flow and Doppler constant

Calculation of Flow

	V-notch	Manometer	Manometer*
Q (m^3/s)	0.0390	0.0386	0.0398

* *denotes calibrated value*

Calculation of Doppler constant

	delta A (m^2)	f (Hz)	delta Q/K (m^3/s)		delta A (m^2)	f (Hz)	delta Q/K (m^3/s)
1	0.00249	337.6	0.8406	33	0.00249	356.0	0.8864
2	0.00249	351.4	0.8750	34	0.00249	366.6	0.9128
3	0.00249	355.4	0.8849	35	0.00249	372.0	0.9263
4	0.00249	364.6	0.9079	36	0.00249	372.0	0.9263
5	0.00249	365.2	0.9093	37	0.00249	373.0	0.9288
6	0.00249	364.0	0.9064	38	0.00249	371.4	0.9248
7	0.00249	358.0	0.8914	39	0.00249	373.8	0.9308
8	0.00249	342.0	0.8516	40	0.00249	358.6	0.8929
9	0.00249	351.6	0.8755	41	0.00249	348.2	0.8670
10	0.00249	370.0	0.9213	42	0.00249	360.4	0.8974
11	0.00249	373.0	0.9288	43	0.00249	359.4	0.8949
12	0.00249	373.6	0.9303	44	0.00249	368.0	0.9163
13	0.00249	374.2	0.9318	45	0.00249	367.0	0.9138
14	0.00249	376.8	0.9382	46	0.00249	362.6	0.9029
15	0.00249	372.6	0.9278	47	0.00249	368.8	0.9183
16	0.00249	359.8	0.8959	48	0.00249	355.8	0.8859
17	0.00249	356.2	0.8869	49	0.00249	338.6	0.8431
18	0.00249	379.0	0.9437	50	0.00249	352.0	0.8765
19	0.00249	380.6	0.9477	51	0.00249	359.4	0.8949
20	0.00249	376.0	0.9362	52	0.00249	360.2	0.8969
21	0.00249	377.2	0.9392	53	0.00249	358.6	0.8929
22	0.00249	377.2	0.9392	54	0.00249	360.4	0.8974
23	0.00249	376.6	0.9377	55	0.00249	360.8	0.8984
24	0.00249	365.0	0.9089	56	0.00249	336.6	0.8381
25	0.00249	350.0	0.8715	57	0.00249	317.4	0.7903
26	0.00249	365.8	0.9108	58	0.00249	350.0	0.8715
27	0.00249	372.2	0.9268	59	0.00249	355.0	0.8840
28	0.00249	372.6	0.9278	60	0.00249	357.6	0.8904
29	0.00249	378.2	0.9417	61	0.00249	359.4	0.8949
30	0.00249	377.6	0.9402	62	0.00249	351.6	0.8755
31	0.00249	383.0	0.9537	63	0.00249	344.0	0.8566
32	0.00249	362.0	0.9014	64	0.00249	317.2	0.7898
			29.2301	Sum			**57.6470**

Now the sum of the delta Q's must equal the Q as calculated by the V-notch.
i.e. 57.647/K = 0.039

K = 1476.3

Experiment 5

Readings of flow and water depth

Flow: Zero-datum: 31.69 cm

V-notch	Manometer	Mercury	Remarks
(cm)	(cm)	(mm)	
50.0*	10.7 - 10.9**	N/A	Check
55.75*	42.6 - 43.2**	N/A	

V-notch not drowned. Value in brackets is value measured before it drowned

** *Water column oscillated between these 2 values*

Channel width: 600 mm

Doppler Meter:

flow depth (d)	Channel bottom*
(cm)	(cm)
14.2	15.98

* *Reading when the probe is flush with the bottom of the channel.*

Divide *d* into 3 blocks, each 4.73 cm deep.

Take readings in the centre of these blocks, i.e. at y_1 = 2.365 cm, y_2 = 7.095 cm, etc above the bottom of the channel.

y_1 reading on needle	y_2 reading on needle	y_3 reading on needle
(cm)	(cm)	(cm)
17.95	22.68	27.41

Also divide the width of channel into blocks each 120 mm wide and take readings at centre of each block, I.e. at

x_1 = 60

x_2 = 180

x_3 = 300

x_4 = 420

x_5 = 540

Readings of Doppler Frequencies

All readings were taken at 10 second intervals

FREQUENCIES AT y_1 (Hz)

x	60	180	300	420	540
1	560	658	560	586	646
2	648	608	608	564	554
3	612	612	616	620	556
4	620	616	552	620	532
5	556	588	604	560	680
6	688	610	568	546	636
7	712	618	606	560	602
8	682	582	598	640	640
9	628	582	656	636	546
10	510	612	610	580	614
Average	**621.6**	**608.6**	**597.8**	**591.2**	**600.6**

FREQUENCIES AT y_2 (Hz)

x	60	180	300	420	540
1	726	710	632	678	748
2	616	736	638	730	680
3	692	698	640	632	480
4	566	642	656	668	552
5	586	632	668	618	754
6	598	752	622	612	534
7	718	644	640	564	648
8	790	694	688	624	692
9	760	622	682	648	598
10	630	588	736	668	662
Average	**668.2**	**671.8**	**660.2**	**644.2**	**634.8**

FREQUENCIES AT y_3 (Hz)

x	60	180	300	420	540
1	712	772	694	730	616
2	690	650	726	682	724
3	564	656	708	638	488
4	658	678	698	666	560
5	658	618	670	778	572
6	606	736	718	666	738
7	620	728	728	680	602
8	554	680	768	680	670
9	540	704	768	690	580
10	624	766	738	684	640
Average	**622.6**	**698.8**	**721.6**	**689.4**	**619.0**

Calculation of Flow and Doppler constant

Calculation of Flow

	V-notch	Manometer	Manometer*
Q (m^3/s)	0.0390	0.0386	0.0398

** denotes calibrated value*

Calculation of Doppler constant

	delta A	f	delta Q/K
	(m^2)	(Hz)	(m^3/s)
1	0.00568	621.6	3.5307
2	0.00568	608.6	3.4568
3	0.00568	597.8	3.3955
4	0.00568	591.2	3.3580
5	0.00568	600.6	3.4114
6	0.00568	668.2	3.7954
7	0.00568	671.8	3.8158
8	0.00568	660.2	3.7499
9	0.00568	644.2	3.6591
10	0.00568	634.8	3.6057
11	0.00568	622.6	3.5364
12	0.00568	698.8	3.9692
13	0.00568	721.6	4.0987
14	0.00568	689.4	3.9158
15	0.00568	619.0	3.5159
Sum			**54.8143**

Now the sum of the delta Q's must equal the Q as calculated by the V-notch.

i.e. 54.8143/K = 0.039

K = 1403.8

B.6.

Experiment 6

Readings of flow and water depth

Flow: Zero-datum: 31.50 cm

V-notch	Manometer	Mercury	Remarks
(cm)	(cm)	(mm)	
49.32*	9.1	N/A	

*V-notch not drowned.

Channel width: 600 mm

Doppler Meter:

flow depth (d)	Channel bottom*
(cm)	(cm)
18.40	15.98

Reading when the probe is flush with the bottom of the channel.

Divide *d* into 5 blocks, each 3.68 cm deep.
Take readings in the centre of these blocks, i.e. at y_1 = 1.84 cm, y_2 = 5.52 cm, etc above the bottom of the channel.

y_1 reading on needle	y_2 reading on needle	y_3 reading on needle	y_4 reading on needle	y_5 reading on needle
(cm)	(cm)	(cm)	(cm)	(cm)
17.42	21.10	24.78	28.46	32.14

y_6 reading on needle	y_7 reading on needle	y_8 reading on needle
(cm)	(cm)	(cm)
N/A	N/A	N/A

Also divide the width of channel into blocks each 75 mm wide and take readings at centre of each block, I.e. at

x_1 = 37.5 x_5 = 337.5
x_2 = 112.5 x_6 = 412.5
x_3 = 187.5 x_7 = 487.5
x_4 = 262.5 x_8= 562.5

Readings of Doppler Frequencies

All readings were taken at 10 second intervals

FREQUENCIES AT y_1 (Hz)

x	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
1	258	260	268	276	282	266	270	256
2	258	264	266	266	272	262	272	258
3	252	268	264	272	276	266	274	262
4	262	270	270	272	272	264	282	246
5	258	268	266	268	280	270	278	262
6	242	262	278	284	280	272	268	262
7	252	274	274	282	278	274	270	262
8	254	266	268	284	282	270	282	254
9	246	258	274	270	272	274	284	254
10	244	272	274	276	286	272	276	246
Average	**252.6**	**266.2**	**270.2**	**275.0**	**278.0**	**269.0**	**275.6**	**256.2**

FREQUENCIES AT y_2 (Hz)

x	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
1	264	274	280	274	294	290	272	264
2	268	274	280	280	284	282	266	280
3	270	292	276	286	286	282	276	268
4	268	286	270	284	284	280	274	276
5	268	282	278	278	276	296	276	276
6	268	278	272	278	278	286	272	272
7	254	268	282	282	280	288	274	264
8	252	270	272	290	282	266	272	270
9	256	266	278	274	284	276	286	272
10	264	272	266	278	272	284	266	272
Average	**263.2**	**276.2**	**275.4**	**280.4**	**282.0**	**283.0**	**273.4**	**271.4**

FREQUENCIES AT y_3 (Hz)

x	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
1	262	276	272	278	274	276	262	270
2	264	278	272	270	280	274	260	262
3	270	272	268	276	278	278	276	254
4	266	282	270	288	286	268	272	270
5	270	270	282	276	272	270	274	264
6	262	278	280	276	280	266	272	264
7	250	264	282	282	288	262	270	260
8	256	264	270	278	286	268	278	264
9	258	270	280	274	278	282	288	268
10	256	288	272	280	276	276	270	260
Average	**261.4**	**274.2**	**274.8**	**277.8**	**279.8**	**272.0**	**272.2**	**263.6**

Readings of Doppler Frequencies

All readings were taken at 10 second intervals

FREQUENCIES AT y_4 (Hz)

x	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
1	250	274	270	274	270	268	262	256
2	252	268	272	278	266	266	268	246
3	240	270	270	270	274	264	258	254
4	268	250	274	272	264	270	258	248
5	262	268	276	264	276	268	258	252
6	248	270	270	274	272	270	266	250
7	260	260	268	274	266	266	266	260
8	254	278	268	278	262	272	264	250
9	246	262	268	270	276	264	262	254
10	252	272	268	280	270	268	270	270
Average	253.2	267.2	270.4	273.4	269.6	267.6	263.2	254.0

FREQUENCIES AT y_5 (Hz)

x	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
1	246	276	278	278	282	286	264	232
2	248	278	272	278	276	270	278	236
3	248	262	274	282	270	278	264	242
4	252	270	270	282	274	274	254	238
5	248	262	284	288	264	264	248	252
6	244	260	284	272	270	278	262	256
7	238	258	268	286	274	294	264	240
8	250	262	286	266	284	270	256	244
9	246	270	268	266	276	258	274	254
10	246	260	270	260	286	262	262	242
Average	246.6	265.8	275.4	275.8	275.6	273.4	262.6	243.6

Calculation of Flow and Doppler constant

Calculation of Flow

	V-notch	Manometer	Manometer*
Q (m^3/s)	0.0185	0.0178	0.0183

* *denotes calibrated value*

Calculation of Doppler constant

	delta A (m^2)	f (Hz)	delta KQ (m^3/s)		delta A (m^2)	f (Hz)	delta KQ (m^3/s)
1	0.00276	252.6	0.6972	21	0.00276	279.8	0.7722
2	0.00276	266.2	0.7347	22	0.00276	272.0	0.7507
3	0.00276	270.2	0.7458	23	0.00276	272.2	0.7513
4	0.00276	275.0	0.7590	24	0.00276	263.0	0.7259
5	0.00276	278.0	0.7673	25	0.00276	253.2	0.6988
6	0.00276	269.0	0.7424	26	0.00276	262.2	0.7237
7	0.00276	275.6	0.7607	27	0.00276	270.4	0.7463
8	0.00276	256.2	0.7071	28	0.00276	273.4	0.7546
9	0.00276	263.2	0.7264	29	0.00276	269.6	0.7441
10	0.00276	276.2	0.7623	30	0.00276	267.6	0.7386
11	0.00276	275.4	0.7601	31	0.00276	263.2	0.7264
12	0.00276	280.4	0.7739	32	0.00276	254.0	0.7010
13	0.00276	282.0	0.7783	33	0.00276	246.6	0.6806
14	0.00276	283.0	0.7811	34	0.00276	265.8	0.7336
15	0.00276	273.4	0.7546	35	0.00276	275.4	0.7601
16	0.00276	271.4	0.7491	36	0.00276	275.8	0.7612
17	0.00276	256.0	0.7066	37	0.00276	275.6	0.7607
18	0.00276	274.2	0.7568	38	0.00276	273.4	0.7546
19	0.00276	274.8	0.7584	39	0.00276	262.6	0.7248
20	0.00276	277.8	0.7667	40	0.00276	243.6	0.6723
			14.9885	Sum			**29.6700**

Now the sum of the delta Q's must equal the Q as calculated by the V-notch.

i.e. 29.67/K = 0.0185

K = 1604.6

B.7.

Experiment 7

Readings of flow and water depth

Flow: Zero-datum: 31.50 cm

V-notch	Manometer	Mercury	Remarks
(cm)	(cm)	(mm)	
39.98*	N/A	N/A	

V-notch not drowned.

Channel width: 600 mm

Doppler Meter:

flow depth (d)	Channel bottom*
(cm)	(cm)
2.60	15.98

* *Reading when the probe is flush with the bottom of the channel.*

Divide *d* into 1 block. The flow just covers the probe.

Also divide the width of channel into blocks each 60 mm wide and take readings at centre of each block, i.e. at

$x_1 = 30$ $x_6 = 330$

$x_2 = 90$ $x_7 = 390$

$x_3 = 150$ $x_8 = 450$

$x_4 = 210$ $x_9 = 510$

$x_5 = 270$ $x_{10} = 570$

Readings of Doppler Frequencies

All readings were taken at 10 second intervals

FREQUENCIES AT y (Hz)

x	30	90	150	210	270	330	390	450	510	570
1	222	252	276	302	320	330	320	306	250	248
2	228	258	254	318	322	324	322	294	262	250
3	220	266	270	298	328	318	314	302	262	236
4	226	272	270	310	320	330	320	288	298	250
5	246	252	282	308	324	332	324	300	260	246
6	232	248	260	308	320	316	310	292	260	256
7	232	256	274	316	328	318	314	292	268	254
8	226	266	276	304	324	322	310	288	292	248
9	234	266	256	320	318	324	304	280	272	266
10	234	270	262	314	312	322	306	282	254	260
Average	230.0	260.6	268.0	309.8	321.6	323.6	314.4	292.4	267.8	251.4

Calculation of Flow and Doppler constant

Calculation of Flow

	V-notch	Manometer	Manometer*
Q (m^3/s)	0.0029	N/A	N/A

** denotes calibrated value*

Calcualtion of Doppler constant

	delta A (m^2)	f (Hz)	delta Q/K (m^3/s)
1	0.00156	230.0	0.3588
2	0.00156	260.6	0.4065
3	0.00156	268.0	0.4181
4	0.00156	309.8	0.4833
5	0.00156	321.6	0.5017
6	0.00156	323.6	0.5048
7	0.00156	314.4	0.4905
8	0.00156	292.4	0.4561
9	0.00156	267.8	0.4178
10	0.00156	251.4	0.3922
Sum			**4.4298**

Now the sum of the delta Q's must equal the Q as calculated by the V-notch.

i.e. 4.4298/K = 0.0029

K = 1513.7

APPENDIX C

Calculation of theoretical and Doppler velocities in all segments that were used for the calibration of the Doppler meter

Table 1: CALCULATION OF ENERGY GRADIENTS FOR DIFFERENT EXPERIMENTS

Experiment	Depth (m)	Flow (m^3/s)	Velocity (m/s)	R (m)	C	s	K
1	0.277	0.025890	**0.155776**	0.144021	67.72457	**3.6735E-05**	**1909.3**
2	0.305	0.028360	**0.154973**	0.151240	68.10710	**3.4234E-05**	**1955.8**
3	0.457	0.034200	**0.124726**	0.181110	69.51681	**1.7774E-05**	**2514.9**
4	0.266	0.039000	**0.244361**	0.140989	67.55818	**9.2794E-05**	**1476.3**
5	0.142	0.039000	**0.457746**	0.096380	64.58302	**0.00052123**	**1403.8**
6	0.184	0.018500	**0.167572**	0.114050	65.89963	**5.6695E-05**	**1604.6**
7	0.026	0.002900	**0.185897**	0.023926	53.68527	**0.00050114**	**1513.7**

Table 2: CALCULATION OF THEORETICAL VELOCITY GRADIENT AND POINT VELOCITY

Experiment 1

Depth	y(m)	dv/dy	dy(m)	dv(m/s)	R_o(m)	y_o(m)	v(m/s)
0.277	0.06925	0.36165	0.1385	0.05009	0.00015	1.0135E-05	0.2211
0.277	0.20775	0.12055	0.1385	0.01670	0.00015	1.0135E-05	0.2486

Experiment 2

Depth	y(m)	dv/dy	dy(m)	dv(m/s)	R_o(m)	y_o(m)	v(m/s)
0.305	0.0305	0.83177	0.061	0.05074	0.00015	1.0135E-05	0.2032
0.305	0.0915	0.27726	0.061	0.01691	0.00015	1.0135E-05	0.2311
0.305	0.1525	0.16635	0.061	0.01015	0.00015	1.0135E-05	0.2440
0.305	0.2135	0.11882	0.061	0.00725	0.00015	1.0135E-05	0.2526
0.305	0.2745	0.09242	0.061	0.00564	0.00015	1.0135E-05	0.2589

Experiment 3

Depth	y(m)	dv/dy	dy(m)	dv(m/s)	R_o(m)	y_o(m)	v(m/s)
0.457	0.02285	0.97925	0.0457	0.04475	0.00015	1.0135E-05	0.1728
0.457	0.06855	0.32642	0.0457	0.01492	0.00015	1.0135E-05	0.1973
0.457	0.11425	0.19585	0.0457	0.00895	0.00015	1.0135E-05	0.2088
0.457	0.15995	0.13989	0.0457	0.00639	0.00015	1.0135E-05	0.2163
0.457	0.20565	0.10881	0.0457	0.00497	0.00015	1.0135E-05	0.2219
0.457	0.25135	0.08902	0.0457	0.00407	0.00015	1.0135E-05	0.2264
0.457	0.29705	0.07533	0.0457	0.00344	0.00015	1.0135E-05	0.2302
0.457	0.34275	0.06528	0.0457	0.00298	0.00015	1.0135E-05	0.2334
0.457	0.38845	0.05760	0.0457	0.00263	0.00015	1.0135E-05	0.2362
0.457	0.43415	0.05154	0.0457	0.00236	0.00015	1.0135E-05	0.2386

Experiment 4

Depth	y(m)	dv/dy	dy(m)	dv(m/s)	R_o(m)	y_o(m)	v(m/s)
0.266	0.0166	2.34973	0.03325	0.07813	0.00015	1.0135E-05	0.2887
0.266	0.0499	0.78167	0.03325	0.02599	0.00015	1.0135E-05	0.3316
0.266	0.0832	0.46910	0.03325	0.01560	0.00015	1.0135E-05	0.3515
0.266	0.1164	0.33510	0.03325	0.01114	0.00015	1.0135E-05	0.3647
0.266	0.1497	0.26064	0.03325	0.00867	0.00015	1.0135E-05	0.3745
0.266	0.1829	0.21326	0.03325	0.00709	0.00015	1.0135E-05	0.3823
0.266	0.2162	0.18046	0.03325	0.00600	0.00015	1.0135E-05	0.3888
0.266	0.2494	0.15640	0.03325	0.00520	0.00015	1.0135E-05	0.3944

Experiment 5

Depth	y(m)	dv/dy	dy(m)	dv(m/s)	R_o(m)	y_o(m)	v(m/s)
0.142	0.0237	2.85595	0.0473	0.13509	0.00015	1.0135E-05	0.5238
0.142	0.0710	0.95198	0.0473	0.04503	0.00015	1.0135E-05	0.5980
0.142	0.1183	0.57119	0.0473	0.02702	0.00015	1.0135E-05	0.6325

Experiment 6

Depth	y(m)	dv/dy	dy(m)	dv(m/s)	R_o(m)	y_o(m)	v(m/s)
0.184	0.0184	4.17858	0.0368	0.15377	0.00015	1.0135E-05	0.1903
0.184	0.0552	1.39286	0.0368	0.05126	0.00015	1.0135E-05	0.2181
0.184	0.0920	0.83572	0.0368	0.03075	0.00015	1.0135E-05	0.2311
0.184	0.1288	0.59694	0.0368	0.02197	0.00015	1.0135E-05	0.2396
0.184	0.1656	0.46429	0.0368	0.01709	0.00015	1.0135E-05	0.2460

Experiment 7

Depth	y(m)	dv/dy	dy(m)	dv(m/s)	R_o(m)	y_o(m)	v(m/s)
0.026	0.004	2.38300	0.026	0.06196	0.00015	1.0135E-05	0.16941

Table 3: MEASURED FREQUENCIES in Hz

Experiment 1

y	50	150	250	350	450	550
0.06925	315.6	314.4	324.2	321.2	315.0	321.0
0.20775	264.4	275.2	273.8	280.8	278.0	285.4

Experiment 2

y	50	150	250	350	450	550
0.0305	328.8	333.6	343.8	346.8	331.2	327.6
0.0915	307.6	319.2	324.8	318.6	322.4	316.6
0.1525	298.0	301.8	306.4	304.2	303.4	297.4
0.2135	293.6	286.4	290.6	289.4	291.0	286.6
0.2745	255.6	276.6	278.0	275.4	275.2	261.4

Experiment 3

y	50	150	250	350	450	550
0.02285	357.0	360.2	361.0	356.2	365.8	373.8
0.06855	347.0	333.8	358.0	340.4	346.4	348.6
0.11425	336.0	329.0	332.0	337.2	332.6	345.4
0.15995	329.0	329.8	326.4	327.8	319.4	331.6
0.20565	318.2	324.0	316.6	324.0	328.2	319.0
0.25135	321.6	312.2	314.6	322.0	315.2	329.2
0.29705	308.8	311.4	314.4	309.2	314.0	315.0
0.34275	307.6	311.0	301.8	298.2	307.8	303.4
0.38845	291.0	293.2	295.2	292.0	293.8	287.4
0.43415	260.2	262.4	266.8	270.4	264.4	261.8

Experiment 4

y	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
0.0166	337.6	351.4	355.6	364.6	365.2	364.0	358.0	342.0
0.0499	351.6	370.0	373.0	373.6	374.2	376.8	372.6	359.8
0.0832	356.2	379.0	380.6	376.0	377.2	377.2	376.6	365.0
0.1164	350.0	365.8	372.2	372.6	378.2	377.6	383.0	362.0
0.1497	356.0	366.6	372.0	372.0	373.0	371.4	373.8	358.6
0.1829	348.2	360.4	359.4	368.0	367.0	362.6	368.8	355.8
0.2162	338.6	352.0	359.4	360.2	358.6	360.4	360.8	338.6
0.2494	317.4	350.0	355.0	357.6	359.4	351.6	344.0	317.2

Experiment 5

y	60	180	300	420	540
0.0237	621.6	608.6	597.8	591.2	600.6
0.0710	668.2	671.8	660.2	644.2	634.8
0.1183	622.6	698.8	721.6	689.4	619.0

Experiment 6

y	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
0.0184	252.6	266.2	270.2	275.0	278.0	269.0	275.6	256.2
0.0552	263.2	276.2	275.4	280.4	282.0	283.0	273.4	271.4
0.0920	261.4	274.2	274.8	277.8	279.8	272.0	272.2	263.6
0.1288	253.2	267.2	270.4	273.4	269.6	267.6	263.2	254.0
0.1656	246.6	265.8	275.4	275.8	275.6	273.4	262.6	243.6

Experiment 7

y	30	90	150	210	270	330	390	450	510	570
0.004	230	260.6	268	309.8	321.6	323.6	314.4	292.4	267.8	251.4

Table 4A: DOPPLER CONSTANT (K) DERIVED FROM THEORETICAL VELOCITY

Experiment 1

y	50	150	250	350	450	550
0.0693	1427.2	1421.8	1466.1	1452.6	1424.5	1451.7
0.2078	1063.4	1106.8	1101.2	1129.3	1118.1	1147.8

Experiment 2

y	50	150	250	350	450	550
0.0305	1618.2	1641.8	1692.0	1706.8	1630.0	1612.3
0.0915	1331.2	1381.4	1405.7	1378.8	1395.3	1370.2
0.1525	1221.2	1236.8	1255.6	1246.6	1243.3	1218.7
0.2135	1162.5	1134.0	1150.6	1145.9	1152.2	1134.8
0.2745	987.1	1068.2	1073.6	1063.6	1062.8	1009.5

Experiment 3

y	50	150	250	350	450	550
0.0229	2066.5	2085.0	2089.6	2061.8	2117.4	2163.7
0.0686	1758.4	1691.5	1814.1	1724.9	1755.3	1766.5
0.1143	1609.4	1575.9	1590.3	1615.2	1593.1	1654.5
0.16	1521.0	1524.7	1509.0	1515.5	1476.7	1533.1
0.2057	1433.8	1460.0	1426.6	1460.0	1478.9	1437.4
0.2514	1420.4	1378.9	1389.5	1422.2	1392.1	1454.0
0.2971	1341.7	1353.0	1366.1	1343.5	1364.3	1368.7
0.3428	1318.2	1332.7	1293.3	1277.9	1319.0	1300.2
0.3885	1232.3	1241.6	1250.0	1236.5	1244.1	1217.0
0.4342	1090.3	1099.6	1118.0	1133.1	1107.9	1097.0

Experiment 4

y	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
0.0166	1169.4	1217.2	1231.8	1263.0	1265.0	1260.9	1240.1	1184.7
0.0499	1060.3	1115.7	1124.8	1126.6	1128.4	1136.3	1123.6	1085.0
0.0832	1013.3	1078.1	1082.7	1069.6	1073.0	1073.0	1071.3	1038.3
0.1164	959.8	1003.1	1020.7	1021.8	1037.1	1035.5	1050.3	992.7
0.1497	950.7	979.0	993.4	993.4	996.1	991.8	998.3	957.7
0.1829	910.8	942.8	940.1	962.6	960.0	948.5	964.7	930.7
0.2162	870.9	905.4	924.4	926.5	922.3	927.0	928.0	865.7
0.2494	804.8	887.5	900.2	906.7	911.3	891.5	872.3	804.3

Experiment 5

y	60	180	300	420	540
0.0237	1186.7	1161.9	1141.3	1128.7	1146.6
0.0710	1117.4	1123.4	1104.0	1077.2	1061.5
0.1183	984.3	1104.8	1140.8	1089.9	978.6

Experiment 6

y	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
0.0184	1327.5	1399.0	1420.0	1445.2	1461.0	1413.7	1448.4	1346.4
0.0552	1206.5	1266.1	1262.5	1285.4	1292.7	1297.3	1253.3	1244.1
0.0920	1131.1	1186.5	1189.1	1202.1	1210.8	1177.0	1177.9	1140.6
0.1288	1056.6	1115.1	1128.4	1140.9	1125.1	1116.7	1098.4	1060.0
0.1656	1002.4	1080.5	1119.5	1121.1	1120.3	1111.4	1067.5	990.2

Experiment 7

y	30	90	150	210	270	330	390	450	510	570
0.004	1357.6	1538.2	1581.9	1828.7	1898.3	1910.1	1855.8	1725.9	1580.7	1483.9

Table 4B: AVERAGE THEORETICAL DOPPLER CONSTANT FOR EACH EXPERIMENT

		Average K*
Experiment 1		1287.3
Experiment 2		1311.9
Experiment 3		1481.9
Experiment 4		1035.2
Experiment 5		1128.7
Experiment 6		1240.5
Experiment 7		1904.2

* The values shown here denote the averages of the shaded blocks in Table 4A.

Table 5: VELOCITY DERIVED FROM MEASURERMENTS in (m/s)

Experiment 1

y	50	150	250	350	450	550
0.06925	0.165	0.165	0.170	0.168	0.165	0.168
0.20775	0.138	0.144	0.143	0.147	0.146	0.149

Experiment 2

y	50	150	250	350	450	550
0.0305	0.168	0.171	0.176	0.177	0.169	0.168
0.0915	0.157	0.163	0.166	0.163	0.165	0.162
0.1525	0.152	0.154	0.157	0.156	0.155	0.152
0.2135	0.150	0.146	0.149	0.148	0.149	0.147
0.2745	0.131	0.141	0.142	0.141	0.141	0.134

Experiment 3

y	50	150	250	350	450	550
0.02285	0.142	0.143	0.144	0.142	0.145	0.149
0.06855	0.138	0.133	0.142	0.135	0.138	0.139
0.11425	0.134	0.131	0.132	0.134	0.132	0.137
0.15995	0.131	0.131	0.130	0.130	0.127	0.132
0.20565	0.127	0.129	0.126	0.129	0.131	0.127
0.25135	0.128	0.124	0.125	0.128	0.125	0.131
0.29705	0.123	0.124	0.125	0.123	0.125	0.125
0.34275	0.122	0.124	0.120	0.119	0.122	0.121
0.38845	0.116	0.117	0.117	0.116	0.117	0.114
0.43415	0.103	0.104	0.106	0.108	0.105	0.104

Experiment 4

y	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
0.0166	0.229	0.238	0.241	0.247	0.247	0.247	0.242	0.232
0.0499	0.238	0.251	0.253	0.253	0.253	0.255	0.252	0.244
0.0832	0.241	0.257	0.258	0.255	0.256	0.256	0.255	0.247
0.1164	0.237	0.248	0.252	0.252	0.256	0.256	0.259	0.245
0.1497	0.241	0.248	0.252	0.252	0.253	0.252	0.253	0.243
0.1829	0.236	0.244	0.243	0.249	0.249	0.246	0.250	0.241
0.2162	0.229	0.238	0.243	0.244	0.243	0.244	0.244	0.228
0.2494	0.215	0.237	0.240	0.242	0.243	0.238	0.233	0.215

Experiment 5

y	60	180	300	420	540
0.0237	0.443	0.434	0.426	0.421	0.428
0.0710	0.476	0.479	0.470	0.459	0.452
0.1183	0.444	0.498	0.514	0.491	0.441

Experiment 6

y	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
0.0184	0.157	0.166	0.168	0.171	0.173	0.168	0.172	0.160
0.0552	0.164	0.172	0.172	0.175	0.176	0.176	0.170	0.169
0.0920	0.163	0.171	0.171	0.173	0.174	0.170	0.170	0.164
0.1288	0.158	0.167	0.169	0.170	0.168	0.167	0.164	0.158
0.1656	0.154	0.166	0.172	0.172	0.172	0.170	0.164	0.152

Experiment 7

y	30	90	150	210	270	330	390	450	510	570
0.004	0.152	0.172	0.177	0.205	0.212	0.214	0.208	0.193	0.177	0.166

Table 6: % OF MEASURED VS THEORETICAL VELOCITY

Experiment 1

y	50	150	250	350	450	550
0.06925	74.752	74.468	76.789	76.078	74.610	76.031
0.20775	55.695	57.970	57.675	59.149	58.560	60.118

Experiment 2

y	50	150	250	350	450	550
0.0305	82.737	83.945	86.511	87.266	83.341	82.435
0.0915	68.066	70.633	71.872	70.500	71.341	70.058
0.1525	62.440	63.236	64.200	63.739	63.571	62.314
0.2135	59.439	57.981	58.831	58.588	58.912	58.022
0.2745	50.472	54.618	54.895	54.381	54.342	51.617

Experiment 3

y	50	150	250	350	450	550
0.02285	82.169	82.906	83.090	81.985	84.195	86.036
0.06855	69.919	67.259	72.135	68.589	69.798	70.241
0.11425	63.996	62.662	63.234	64.224	63.348	65.786
0.1600	60.481	60.628	60.003	60.261	58.716	60.959
0.20565	57.014	58.053	56.727	58.053	58.805	57.157
0.25135	56.480	54.829	55.251	56.550	55.356	57.815
0.29705	53.351	53.800	54.319	53.420	54.250	54.422
0.34275	52.415	52.994	51.426	50.813	52.449	51.699
0.38845	48.998	49.368	49.705	49.166	49.469	48.392
0.43415	43.355	43.722	44.455	45.055	44.055	43.622

Experiment 4

y	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
0.0166	79.214	82.452	83.438	85.549	85.690	85.409	84.001	80.247
0.0499	71.819	75.577	76.190	76.313	76.435	76.966	76.108	73.494
0.0832	68.636	73.030	73.338	72.451	72.683	72.683	72.567	70.332
0.1164	65.015	67.950	69.139	69.213	70.253	70.142	71.145	67.244
0.1497	64.399	66.316	67.293	67.293	67.474	67.184	67.618	64.869
0.1829	61.698	63.860	63.683	65.206	65.029	64.250	65.348	63.045
0.2162	58.992	61.326	62.615	62.755	62.476	62.790	62.859	58.643
0.2494	54.516	60.115	60.974	61.420	61.729	60.390	59.084	54.481

Experiment 5

y	60	180	300	420	540
0.0237	84.535	82.767	81.298	80.401	81.679
0.0710	79.596	80.025	78.643	76.738	75.618
0.1183	70.119	78.701	81.269	77.642	69.714

Experiment 6

y	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
0.0184	82.730	87.184	88.494	90.066	91.049	88.101	90.263	83.909
0.0552	75.193	78.907	78.678	80.107	80.564	80.850	78.107	77.536
0.0920	70.493	73.945	74.107	74.916	75.455	73.352	73.405	71.086
0.1288	65.850	69.491	70.324	71.104	70.116	69.595	68.451	66.058
0.1656	62.473	67.337	69.769	69.870	69.819	69.262	66.526	61.713

Experiment 7

y	30	90	150	210	270	330	390	450	510	570
0.004	89.689	101.621	104.507	120.807	125.408	126.188	122.601	114.022	104.429	98.034

Table 7: FLOW THROUGH EACH BLOCK in (m^3/s)

Experiment 1

y	50	150	250	350	450	550
0.06925	0.00229	0.00228	0.00235	0.00233	0.00228	0.00233
0.20775	0.00192	0.00200	0.00199	0.00204	0.00202	0.00207

Experiment 2

y	50	150	250	350	450	550
0.0305	0.00103	0.00104	0.00107	0.00108	0.00103	0.00102
0.0915	0.00096	0.00100	0.00101	0.00099	0.00101	0.00099
0.1525	0.00093	0.00094	0.00096	0.00095	0.00095	0.00093
0.2135	0.00092	0.00089	0.00091	0.00090	0.00091	0.00089
0.2745	0.00080	0.00086	0.00087	0.00086	0.00086	0.00082

Experiment 3

y	50	150	250	350	450	550
0.02285	0.00065	0.00065	0.00066	0.00065	0.00066	0.00068
0.06855	0.00063	0.00061	0.00065	0.00062	0.00063	0.00063
0.11425	0.00061	0.00060	0.00060	0.00061	0.00060	0.00063
0.15995	0.00060	0.00060	0.00059	0.00060	0.00058	0.00060
0.20565	0.00058	0.00059	0.00058	0.00059	0.00060	0.00058
0.25135	0.00058	0.00057	0.00057	0.00059	0.00057	0.00060
0.29705	0.00056	0.00057	0.00057	0.00056	0.00057	0.00057
0.34275	0.00056	0.00057	0.00055	0.00054	0.00056	0.00055
0.38845	0.00053	0.00053	0.00054	0.00053	0.00053	0.00052
0.43415	0.00047	0.00048	0.00048	0.00049	0.00048	0.00048

Experiment 4

y	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
0.0166	0.00057	0.00059	0.00060	0.00062	0.00062	0.00061	0.00060	0.00058
0.0499	0.00059	0.00063	0.00063	0.00063	0.00063	0.00064	0.00063	0.00061
0.0832	0.00060	0.00064	0.00064	0.00064	0.00064	0.00064	0.00064	0.00062
0.1164	0.00059	0.00062	0.00063	0.00063	0.00064	0.00064	0.00065	0.00061
0.1497	0.00060	0.00062	0.00063	0.00063	0.00063	0.00063	0.00063	0.00061
0.1829	0.00059	0.00061	0.00061	0.00062	0.00062	0.00061	0.00062	0.00060
0.2162	0.00057	0.00059	0.00061	0.00061	0.00061	0.00061	0.00061	0.00057
0.2494	0.00054	0.00059	0.00060	0.00060	0.00061	0.00059	0.00058	0.00054

Experiment 5

y	60	180	300	420	540
0.0237	0.00251	0.00246	0.00242	0.00239	0.00243
0.0710	0.00270	0.00272	0.00267	0.00260	0.00257
0.1183	0.00252	0.00283	0.00292	0.00279	0.00250

Experiment 6

y	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
0.0184	0.00043	0.00046	0.00046	0.00047	0.00048	0.00046	0.00047	0.00044
0.0552	0.00045	0.00048	0.00047	0.00048	0.00049	0.00049	0.00047	0.00047
0.0920	0.00045	0.00047	0.00047	0.00048	0.00048	0.00047	0.00047	0.00045
0.1288	0.00044	0.00046	0.00047	0.00047	0.00046	0.00046	0.00045	0.00044
0.1656	0.00042	0.00046	0.00047	0.00047	0.00047	0.00047	0.00045	0.00042

Experiment 7

y	30	90	150	210	270	330	390	450	510	570
0.004	0.00024	0.00027	0.00028	0.00032	0.00033	0.00033	0.00032	0.00030	0.00028	0.00026

Table 8: % OF FLOW PASSING THROUGH EACH BLOCK

Experiment 1

y	50	150	250	350	450	550
0.06925	8.84261	8.80899	9.08357	8.99951	8.82580	8.99391
0.20775	7.40807	7.71067	7.67144	7.86757	7.78912	7.99646

Experiment 2

y	50	150	250	350	450	550
0.0305	3.61602	3.66881	3.78099	3.81398	3.64242	3.60282
0.0915	3.38287	3.51044	3.57203	3.50385	3.54564	3.48185
0.1525	3.27729	3.31909	3.36967	3.34548	3.33668	3.27070
0.2135	3.22890	3.14972	3.19591	3.18271	3.20031	3.15192
0.2745	2.81099	3.04194	3.05734	3.02875	3.02655	2.87478

Experiment 3

y	50	150	250	350	450	550
0.02285	1.89687	1.91387	1.91812	1.89262	1.94363	1.98613
0.06855	1.84374	1.77360	1.90218	1.80867	1.84055	0.32100
0.11425	1.78529	1.74810	1.76404	1.79167	1.76722	1.83524
0.15995	1.74810	1.75235	1.73428	1.74172	1.69709	1.76191
0.20565	1.69071	1.72153	1.68221	1.72153	1.74385	1.69496
0.25135	1.70878	1.65883	1.67158	1.71090	1.67477	1.74916
0.29705	1.64077	1.65458	1.67052	1.64289	1.66840	1.67371
0.34275	1.63439	1.65246	1.60357	1.58444	1.63545	1.61207
0.38845	1.54619	1.55788	1.56850	1.55150	1.56107	1.52706
0.43415	1.38254	1.39423	1.41760	1.43673	1.40485	1.39104

Experiment 4

y	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
0.0166	1.46223	1.52200	1.54019	1.57918	1.58177	1.57658	1.55059	1.48129
0.0499	1.52287	1.60256	1.61556	1.61816	1.62076	1.63202	1.61383	1.55839
0.0832	1.54279	1.64155	1.64848	1.62855	1.63375	1.63375	1.63115	1.58091
0.1164	1.51594	1.58437	1.61209	1.61383	1.63808	1.63548	1.65887	1.56791
0.1497	1.54193	1.58784	1.61123	1.61123	1.61556	1.60863	1.61902	1.55319
0.1829	1.50814	1.56098	1.55665	1.59390	1.58957	1.57051	1.59737	1.54106
0.2162	1.46656	1.52460	1.55665	1.56012	1.55319	1.56098	1.56272	1.45790
0.2494	1.37474	1.51594	1.53760	1.54886	1.55665	1.52287	1.48995	1.37387

Experiment 5

y	60	180	300	420	540
0.0237	6.44442	6.30964	6.19767	6.12924	6.22670
0.0710	6.92754	6.96486	6.84460	6.67872	6.58127
0.1183	6.45478	7.24478	7.48116	7.14733	6.41746

Experiment 6

y	37.5	112.5	187.5	262.5	337.5	412.5	487.5	562.5
0.0184	2.34857	2.47502	2.51221	2.55684	2.58473	2.50105	2.56242	2.38204
0.0552	2.44713	2.56800	2.56056	2.60705	2.62192	2.63122	2.54196	2.52337
0.0920	2.43039	2.54940	2.55498	2.58287	2.60147	2.52895	2.53081	2.45085
0.1288	2.35415	2.48432	2.51407	2.54196	2.50663	2.48804	2.44713	2.36159
0.1656	2.29279	2.47130	2.56056	2.56428	2.56242	2.54196	2.44155	2.26489

Experiment 7

y	30	90	150	210	270	330	390	450	510	570
0.004	8.17362	9.26107	9.52405	11.0095	11.4289	11.4999	11.173	10.3912	9.51694	8.93413

APPENDIX D

Readings of sets of Doppler frequencies at random time intervals

Frequency readings taken again at random at various locations

Readings were taken at random

	x/y 49.84/150	x/y 17.85/350	x/y 36.12/550
1	306	324	328
2	304	360	300
3	324	348	318
4	322	330	338
5	298	378	306
6	272	364	342
7	332	360	342
8	310	330	320
9	312	394	306
10	330	374	290
Mean	**311.0**	**356.2**	**319.0**
1	304	346	314
2	306	368	320
3	288	354	324
4	292	394	318
5	280	368	306
6	290	376	312
7	288	370	306
8	318	390	322
9	326	418	306
10	318	342	336
Mean	**301.0**	**372.6**	**316.4**
1	322	342	322
2	300	392	342
3	306	368	318
4	304	376	320
5	286	378	328
6	330	364	328
7	312	346	292
8	308	346	334
9	302	370	322
10	288	336	314
Mean	**305.8**	**361.8**	**322.0**
1	300	352	322
2	298	372	292
3	332	372	306
4	324	340	308
5	320	368	344
6	312	366	326
7	312	352	362
8	290	366	326
9	274	380	322
10	320	354	320
Mean	**308.2**	**362.2**	**322.8**

APPENDIX E

Effect of different time intervals between readings on the average Doppler frequency for the whole set of readings

Readings and calculation of difference between observed frequencies for different time intervals

Vertical	Horizontal	10s	30s	% Difference	Average
y_1	50	328.8	326.2	0.8	
	150	333.6	326.8	2.0	
	250	343.8	334.2	2.8	
	350	346.8	334.6	3.5	
	450	331.2	335.6	-1.3	
	550	327.6	324.0	1.1	1.5
y_2	50	307.6	310.2	-0.8	
	150	319.2	319.2	0.0	
	250	324.8	318.6	1.9	
	350	318.6	323.6	-1.6	
	450	322.4	327.4	-1.6	
	550	316.6	320.6	-1.3	-0.6
y_3	50	298.0	299.0	-0.3	
	150	301.8	303.0	-0.4	
	250	306.4	309.2	-0.9	
	350	304.2	302.6	0.5	
	450	303.4	306.4	-1.0	
	550	297.4	295.8	0.5	-0.3
y_4	50	293.6	291.8	0.6	
	150	286.4	292.8	-2.2	
	250	290.6	290.8	-0.1	
	350	289.4	296.0	-2.3	
	450	291.0	291.2	-0.1	
	550	286.6	288.2	-0.6	-0.8
y_5	50	255.6	254.4	0.5	
	150	276.6	274.6	0.7	
	250	278.0	273.9	1.5	
	350	275.4	277.4	-0.7	
	450	275.2	274.6	0.2	
	550	261.4	256.4	1.9	0.7

APPENDIX F

Comparison and calculation of differences in the measured flow velocities between an electromagnetic flowmeter and the Doppler meter

F.1.

K = 1403.8

Horizontal (mm)	Doppler frequency (Hz)	Doppler velocity (m/s)	Electro Magn. Vel. (m/s)
300	700	0.50	0.49
	646	0.46	0.45
	630	0.45	0.47
	694	0.49	0.46
	676	0.48	0.5
	662	0.47	0.47
	646	0.46	0.46
	712	0.51	0.5
	688	0.49	0.47
	706	0.50	0.46
		0.482	**0.473**

K = 1476.3

Horizontal (mm)	Doppler frequency (Hz)	Doppler velocity (m/s)	Electro Magn. Vel. (m/s)
300	370	0.25	0.27
	386	0.26	0.27
	384	0.26	0.26
	386	0.26	0.27
	358	0.24	0.26
	374	0.25	0.26
	378	0.26	0.26
	382	0.26	0.26
	382	0.26	0.26
	360	0.24	0.27
		0.255	**0.264**

F.2.

K = 1459.5

Horizontal (mm)	Doppler frequency (Hz)	Doppler velocity (m/s)	Electro Magn. Vel. (m/s)
300	700	0.48	0.49
	646	0.44	0.45
	630	0.43	0.47
	694	0.48	0.46
	676	0.46	0.5
	662	0.45	0.47
	646	0.44	0.46
	712	0.49	0.5
	688	0.47	0.47
	706	0.48	0.46
		0.463	**0.473**

K = 1459.5

Horizontal (mm)	Doppler frequency (Hz)	Doppler velocity (m/s)	Electro Magn. Vel. (m/s)
300	370	0.25	0.27
	386	0.26	0.27
	384	0.26	0.26
	386	0.26	0.27
	358	0.25	0.26
	374	0.26	0.26
	378	0.26	0.26
	382	0.26	0.26
	382	0.26	0.26
	360	0.25	0.27
		0.258	**0.264**

APPENDIX G

Change in the Doppler constant with possible error in the measured flow rate

Change in Doppler constant with change in flow

Experiment	delta KQ	% change in Q	Q	K	% Change in K
1	49.4307	-10	0.02330	2121	11.11
		-5	0.02459	2010	5.26
		0	0.02589	1909	0.00
		5	0.02718	1818	-4.76
		10	0.02848	1736	-9.09
2	55.4612	-10	0.02552	2173	11.11
		-5	0.02694	2059	5.26
		0	0.02836	1956	0.00
		5	0.02978	1862	-4.76
		10	0.03120	1778	-9.09
3	87.3574	-10	0.03127	2794	11.11
		-5	0.03300	2647	5.26
		0	0.03474	2515	0.00
		5	0.03648	2395	-4.76
		10	0.03821	2286	-9.09
4	57.6470	-10	0.03510	1642	11.11
		-5	0.03705	1556	5.26
		0	0.03900	1478	0.00
		5	0.04095	1408	-4.76
		10	0.04290	1344	-9.09
5	54.8143	-10	0.03510	1562	11.11
		-5	0.03705	1479	5.26
		0	0.03900	1405	0.00
		5	0.04095	1339	-4.76
		10	0.04290	1278	-9.09
6	29.6700	-10	0.01665	1782	11.11
		-5	0.01758	1688	5.26
		0	0.01850	1604	0.00
		5	0.01943	1527	-4.76
		10	0.02035	1458	-9.09
7	4.42980	-10	0.00263	1682	11.11
		-5	0.00278	1594	5.26
		0	0.00293	1514	0.00
		5	0.00307	1442	-4.76
		10	0.00322	1376	-9.09

APPENDIX H

Readings of sediment concentration tests

Table 1: CALCULATION OF SEDIMENT INFLOW RATE

Lid	Mass* (g)			Av. mass sand (g)	Time interval (s)	Inflow Rate (g/s)
1	180	175	177	**82.33**	30	**2.74**
2	267	264	258	**168.00**	30	**5.60**
3	271	277	272	**178.33**	30	**5.94**
4	421	415		**323.00**	30	**10.77**
5	525	495	513	**416.00**	30	**13.87**
6	353	346		**254.50**	30	**8.48**
7	375	370		**277.50**	30	**9.25**
8	464	460		**367.00**	30	**12.23**
9	669	711	684	**593.00**	30	**19.77**
10	906	916		**816.00**	15	**54.40**
11	1089	1123		**1011.00**	30	**33.70**
12	581	588		**489.50**	30	**16.32**
13	856	872		**769.00**	30	**25.63**

* Mass of container and sand after 30 seconds

Table 2: MEASURED AND AVERAGE DOPLLER FREQUENCIES

											Av.
Clean	630	632	650	654	672	670	644	644	638	660	**649.4**

Lid	i	ii	iii	iv	v	vi	vii	viii	ix	x	Av.
1	676	682	672	690	696	686	696	658	650	656	**676.2**
2	670	700	686	712	682	680	700	664	648	666	**680.8**
3	648	708	678	656	676	664	676	680	668	656	**671.0**
4	668	680	694	688	682	688	700	678	668	688	**683.4**
5	664	674	696	672	684	644	660	674	690	694	**675.2**
6	664	668	652	658	688	660	690	672	668	696	**671.6**
7	660	660	680	674	690	670	662	672	642	698	**670.8**
8	664	658	666	660	674	666	672	676	672	674	**668.2**
9	694	698	672	672	676	678	660	654	672	670	**674.6**
10	Funnel emtied too quickly and tests with this lid were terminated										
11	672	644	674	642	692	668	638	680	672	650	**663.2**
12	672	708	684	674	680	660	684	684	670	702	**681.8**
13	638	680	666	678	688	670	688	694	700	694	**679.6**
Clean	628	662	648	650	672	676	656	650	654	648	**654.4**

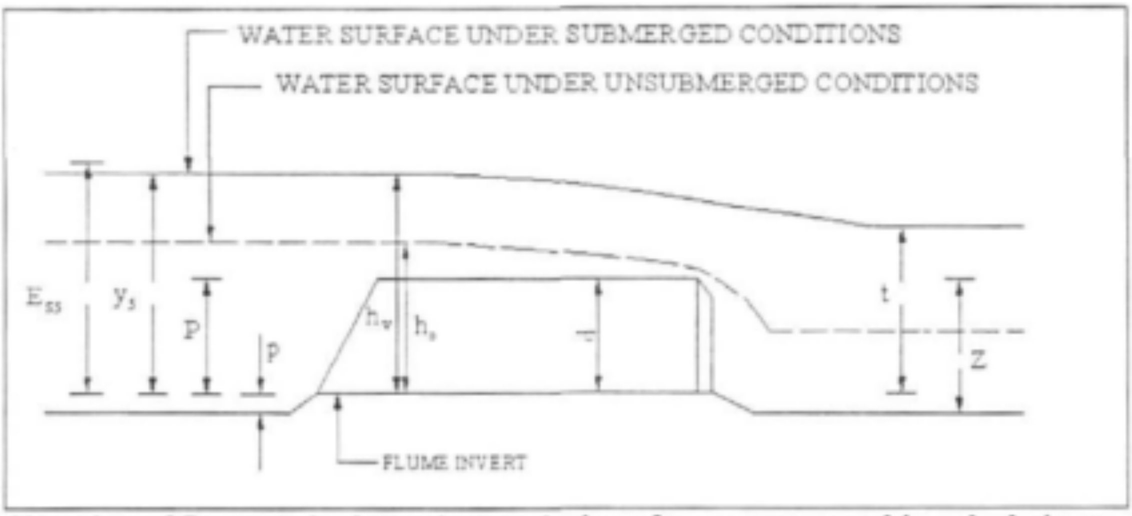
Lid	i	ii	iii	iv	v	vi	vii	viii	ix	x	Av.
1	690	660	666	670	672	652	690	660	698	700	**675.8**
2	672	676	670	676	662	656	686	670	694	672	**673.4**
3	680	640	688	712	662	678	662	666	698	678	**676.4**
4	700	664	664	696	690	666	660	656	684	664	**674.4**
5	710	702	682	670	640	688	678	660	682	670	**678.2**
6	672	680	660	690	660	668	682	680	698	688	**677.8**
7	692	650	682	676	696	670	666	682	662	670	**674.6**
8	690	700	690	676	680	680	652	690	652	692	**680.2**
9	676	666	684	666	662	668	676	664	668	678	**670.8**
10	Funnel emtied too quickly and tests with this lid were terminated										
11	680	658	660	668	658	674	666	686	680	678	**670.8**
12	688	656	686	664	668	684	668	682	674	690	**676**
13	668	674	662	666	674	678	676	706	694	656	**675.4**
Clean	628	658	640	632	664	622	656	640	664	640	**644.4**

Clean	642	662	628	636	656	636	664	678	654	660	**651.6**

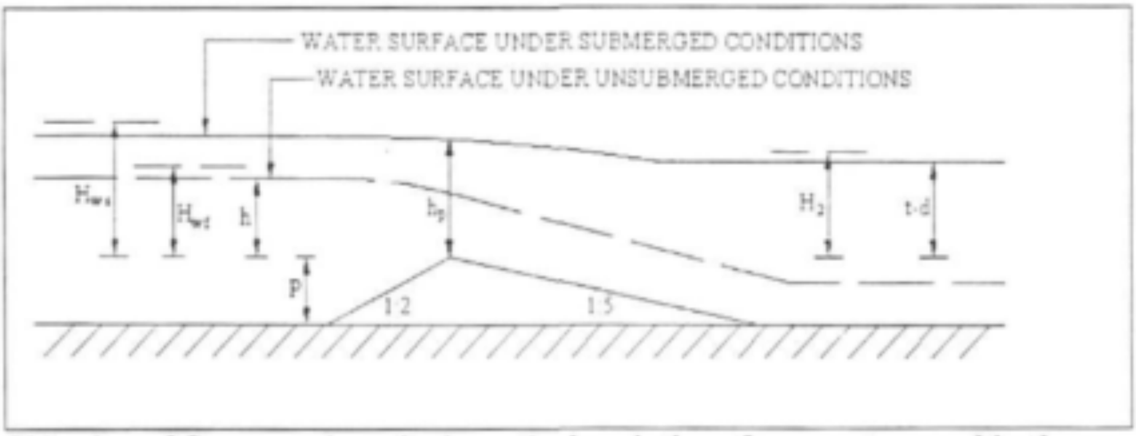
APPENDIX I

Readings and calculations of tests of Doppler meter in combination with Crump weir

Definition sketches of parameters used in calculation. For a detailed description of the symbols and the method of calculation, refer to ***The Rating of Sluicing Flumes in Combination with Sharp-Crested and Crump Weirs under Modular and Non-Modular Flow Conditions, Bruce, 2000***



Side view of flume and schematic description of parameters used in calculations of the flow.



Side view of Crump weir and schematic description of parameters used in the calculation of the flow.

READINGS OF MANOMETER AND WATER LEVELS FOR MODULAR EXPERIMENTS

Manometer

Test Nr.	Reading 1 (cm)	Reading 2 (cm)	hmanometer (cm)	Qlab (m3/s)
F1	13.4		13.4	0.0404
F2	15.7		15.7	0.0437
F3	22.4		22.4	0.0522
F4	31.5		31.5	0.0620
F5	40.7		40.7	0.0704
F6	47.4	49.0	48.2	0.0766
F7	53.5	54.9	54.2	0.0813
F8	61.5	62.7	62.1	0.0870
F9	67.1	68.2	67.7	0.0908
F10	88.0	91.0	89.5	0.1044
F11	99.5	103.0	101.3	0.1111
F12	111.0	117.0	114.0	0.1179
F13	121.0	127.0	124.0	0.1229
F14	131.0	138.0	134.5	0.1280
F15	169.0	176.0	172.5	0.1450

WATER LEVELS

	Readings				Water levels relative to invert		
Test Nr.	2.1 (m)	2.3 (m)	4 (m)	6 (m)	2.1 (m)	2.3 (m)	hv (m)
F1	0.7434	0.7371	0.7594	0.7592	0.1373	0.1311	0.1342
F2	0.7473	0.7414	0.7631	0.7624	0.1412	0.1354	0.1383
F3	0.7564	0.7506	0.7705	0.7699	0.1503	0.1446	0.1475
F4	0.7644	0.7583	0.7777	0.7771	0.1583	0.1523	0.1553
F5	0.7700	0.7645	0.7835	0.7834	0.1639	0.1585	0.1612
F6	0.7737	0.7683	0.7877	0.7875	0.1676	0.1623	0.1650
F7	0.7769	0.7714	0.7907	0.7904	0.1708	0.1654	0.1681
F8	0.7807	0.7769	0.7941	0.7940	0.1746	0.1709	0.1728
F9	0.7848	0.7793	0.7969	0.7963	0.1787	0.1733	0.1760
F10	0.7915	0.7935	0.8040	0.8036	0.1854	0.1875	0.1865
F11	0.7959	0.7968	0.8083	0.8080	0.1898	0.1908	0.1903
F12	0.8000	0.8006	0.8117	0.8114	0.1939	0.1946	0.1943
F13	0.8027	0.8033	0.8148	0.8144	0.1966	0.1973	0.1970
F14	0.8047	0.8059	0.8174	0.8167	0.1986	0.1999	0.1993
F15	0.8140	0.8148	0.8264	0.8261	0.2079	0.2088	0.2084

READINGS OF DOPPLER FREQUENCIES FOR MODULAR EXPERIMENTS

Test Nr.	1	2	3	4	5	6	7	8	9	10	Av.
F1	112	112	106	110	112	110	112	108	106	116	**110.4**
F2	122	122	120	120	126	120	122	116	120	120	**120.8**
F3	152	152	150	154	150	152	152	148	150	150	**151.0**
F4	184	190	182	186	186	182	182	186	184	188	**185.0**
F5	216	210	206	208	212	212	208	208	210	210	**210.0**
F6	226	222	224	228	224	228	224	226	222	230	**225.4**
F7	228	236	238	226	212	208	222	238	242	238	**228.8**
F8	258	252	252	250	246	254	244	254	254	244	**250.8**
F9	262	272	270	266	252	244	246	252	266	258	**258.8**
F10	292	298	302	298	300	290	300	298	294	286	**295.8**
F11	316	320	318	318	306	302	310	330	304	316	**314.0**
F12	312	332	340	338	330	320	322	330	328	326	**327.8**
F13	322	342	324	344	314	304	334	334	332	334	**328.4**
F14	324	332	332	324	322	306	322	338	348	354	**330.2**
F15	380	378	386	384	366	378	372	376	370	376	**376.6**

CALCULATION RESULTS OF MODULAR EXPERIMENTS

Test Nr.	H_{wf} (m)	y (m)	Q_{wf} (m3/s)	v_{wf} (m/s)	v_{Dop} (m/s)	h (m)
F1	0.0158	0.1871	0.0053	0.0211	0.0756	0.0158
F2	0.0198	0.1906	0.0074	0.0289	0.0828	0.0193
F3	0.0287	0.1980	0.0129	0.0487	0.1035	0.0267
F4	0.0365	0.2052	0.0185	0.0673	0.1268	0.0339
F5	0.0424	0.2113	0.0232	0.0820	0.1439	0.0400
F6	0.0462	0.2154	0.0264	0.0915	0.1544	0.0441
F7	0.0494	0.2184	0.0292	0.0998	0.1568	0.0471
F8	0.0542	0.2219	0.0335	0.1128	0.1718	0.0506
F9	0.0576	0.2244	0.0367	0.1221	0.1773	0.0531
F10	0.0686	0.2316	0.0477	0.1536	0.2027	0.0603
F11	0.0726	0.2360	0.0520	0.1645	0.2151	0.0647
F12	0.0769	0.2394	0.0566	0.1765	0.2246	0.0681
F13	0.0798	0.2424	0.0599	0.1843	0.2250	0.0711
F14	0.0823	0.2449	0.0627	0.1910	0.2262	0.0736
F15	0.0922	0.2541	0.0744	0.2184	0.2580	0.0828

Exp	v_{app}	v_{Dop}	v_{Dop} (regres.)	% error
F1	0.0211	0.0756	0.0828	-8.7
F2	0.0289	0.0828	0.0899	-7.9
F3	0.0487	0.1035	0.1077	-3.9
F4	0.0673	0.1268	0.1244	1.9
F5	0.0820	0.1439	0.1376	4.5
F6	0.0915	0.1544	0.1462	5.7
F7	0.0998	0.1568	0.1537	2.0
F8	0.1128	0.1718	0.1654	3.9
F9	0.1221	0.1773	0.1737	2.1
F10	0.1536	0.2027	0.2021	0.3
F11	0.1645	0.2151	0.2119	1.5
F12	0.1765	0.2246	0.2227	0.8
F13	0.1843	0.2250	0.2297	-2.1
F14	0.1910	0.2262	0.2358	-4.1
F15	0.2184	0.2580	0.2605	-0.9
			Average	-0.3
			Std. Dev.	4.3
			Max	5.7
			Min	-8.7

WATER LEVEL READINGS FOR NON-MODULAR EXPERIMENTS

	Readings						Water levels relative to flume invert							
Test Nr	2.1	2.3	4	6	7	9	2.1	2.3	4	6	7	9	h_v	t
	(m)													
D1	0.7560	0.7565	0.7708	0.7712			0.7560	0.7565	0.7708	0.7712			0.7563	
D1.1	0.7622	0.7625	0.7722	0.7728	0.7399	0.7380	0.7622	0.7625	0.7722	0.7728	0.7399	0.7380	0.7624	0.7390
D1.2	0.7670	0.7669	0.7767	0.7753	0.7565	0.7566	0.7670	0.7669	0.7767	0.7753	0.7565	0.7566	0.7670	0.7566
D1.3	0.7761	0.7762	0.7815	0.7825	0.7728	0.7712	0.7761	0.7762	0.7815	0.7825	0.7728	0.7712	0.7762	0.7720
D1.4	0.7795	0.7794	0.7838	0.7829	0.7756	0.7749	0.7795	0.7794	0.7838	0.7829	0.7756	0.7749	0.7795	0.7753
D1.5	0.7884	0.7886	0.7910	0.7917	0.7862	0.7853	0.7884	0.7886	0.7910	0.7917	0.7862	0.7853	0.7885	0.7858
D1.6	0.8011	0.8016	0.8043	0.8036	0.8009	0.7995	0.8011	0.8016	0.8043	0.8036	0.8009	0.7995	0.8014	0.8002
D1.7	0.7571	0.7578	0.7709	0.7707	0.6865	0.6856	0.7571	0.7578	0.7709	0.7707	0.6865	0.6856	0.7575	0.6861
D2	0.7744	0.7755	0.7864	0.7882			0.7744	0.7755	0.7864	0.7882			0.7750	
D2.1	0.7751	0.7760	0.7900	0.7869	0.6723	0.6724	0.7751	0.7760	0.7900	0.7869	0.6723	0.6724	0.7756	0.6724
D2.2	0.7756	0.7763	0.7893	0.7882	0.6975	0.6941	0.7756	0.7763	0.7893	0.7882	0.6975	0.6941	0.7760	0.6958
D2.3	0.7756	0.7762	0.7889	0.7889	0.7184	0.7151	0.7756	0.7762	0.7889	0.7889	0.7184	0.7151	0.7759	0.7168
D2.4	0.7768	0.7775	0.7897	0.7888	0.7370	0.7350	0.7768	0.7775	0.7897	0.7888	0.7370	0.7350	0.7772	0.7360
D2.5	0.7790	0.7800	0.7904	0.7895	0.7559	0.7543	0.7790	0.7800	0.7904	0.7895	0.7559	0.7543	0.7795	0.7551
D2.6	0.7863	0.7863	0.7943	0.7940	0.7751	0.7748	0.7863	0.7863	0.7943	0.7940	0.7751	0.7748	0.7863	0.7750
D2.7	0.7951	0.7962	0.8003	0.8001	0.7912	0.7898	0.7951	0.7962	0.8003	0.8001	0.7912	0.7898	0.7957	0.7905
D2.8	0.8110	0.8112	0.8141	0.8137	0.8090	0.8079	0.8110	0.8112	0.8141	0.8137	0.8090	0.8079	0.8111	0.8085
D2.9	0.7767	0.7767	0.7895	0.7897			0.7767	0.7767	0.7895	0.7897			0.7767	
D3	0.7875	0.7893	0.7993	0.8000			0.7875	0.7893	0.7993	0.8000			0.7884	
D3.1	0.7880	0.7857	0.8004	0.8003	0.7462	0.7150	0.7880	0.7857	0.8004	0.8003	0.7462	0.7150	0.7869	0.7306
D3.2	0.7900	0.7902	0.8005	0.8002	0.7340	0.7319	0.7900	0.7902	0.8005	0.8002	0.7340	0.7319	0.7901	0.7330
D3.3	0.7908	0.7900	0.8019	0.8011	0.7608	0.7611	0.7908	0.7900	0.8019	0.8011	0.7608	0.7611	0.7904	0.7610
D3.4	0.7937	0.7935	0.8020	0.8025	0.7744	0.7763	0.7937	0.7935	0.8020	0.8025	0.7744	0.7763	0.7936	0.7754
D3.5	0.8021	0.8032	0.8100	0.8099	0.7975	0.7960	0.8021	0.8032	0.8100	0.8099	0.7975	0.7960	0.8027	0.7968
D3.6	0.8168	0.8171	0.8210	0.8211	0.8154	0.8140	0.8168	0.8171	0.8210	0.8211	0.8154	0.8140	0.8170	0.8147
D4	0.7993	0.8003	0.8117	0.8111			0.7993	0.8003	0.8117	0.8111			0.7998	
D4.1	0.8006	0.8014	0.8125	0.8118	0.7466	0.7447	0.8006	0.8014	0.8125	0.8118	0.7466	0.7447	0.8010	0.7457
D4.2	0.8010	0.8017	0.8127	0.8120	0.7548	0.7529	0.8010	0.8017	0.8127	0.8120	0.7548	0.7529	0.8014	0.7539
D4.3	0.8016	0.8022	0.8125	0.8125	0.7621	0.7615	0.8016	0.8022	0.8125	0.8125	0.7621	0.7615	0.8019	0.7618
D4.4	0.8020	0.8027	0.8130	0.8121	0.7701	0.7697	0.8020	0.8027	0.8130	0.8121	0.7701	0.7697	0.8024	0.7699
D4.5	0.8031	0.8036	0.8135	0.8121	0.7825	0.7812	0.8031	0.8036	0.8135	0.8121	0.7825	0.7812	0.8034	0.7819
D4.6	0.8068	0.8075	0.8161	0.8160	0.7945	0.7942	0.8068	0.8075	0.8161	0.8160	0.7945	0.7942	0.8072	0.7944
D4.7	0.8150	0.8156	0.8224	0.8216	0.8105	0.8098	0.8150	0.8156	0.8224	0.8216	0.8105	0.8098	0.8153	0.8102

DOPPLER READINGS AT CRUMP CREST FOR NON-MODULAR EXPERIMENTS

Test Nr	Doppler Readings (Hz)										
	1	2	3	4	5	6	7	8	9	10	Av
D1	145	152	146	146	142	155	151	148	144	149	**147.8**
D1.1	140	138	138	140	134	140	136	138	140	134	**137.8**
D1.2	140	144	148	142	148	152	146	140	150	144	**145.4**
D1.3	164	152	148	154	162	162	158	154	154	164	**157.2**
D1.4	170	176	170	160	152	166	164	164	166	146	**163.4**
D1.5	166	150	158	162	172	176	172	174	152	174	**165.6**
D1.6	168	158	174	174	164	152	154	140	154	154	**159.2**
D1.7	132	130	130	134	130	136	132	128	130	128	**131.0**
D2	198	206	210	230	230	230	230	224	218	198	**217.4**
D2.1	230	234	230	230	232	222	218	218	212	226	**225.2**
D2.2	228	222	224	226	224	220	212	218	210	212	**219.6**
D2.3	234	230	230	230	226	222	224	226	224	216	**226.2**
D2.4	208	212	218	206	212	218	206	220	210	216	**212.6**
D2.5	218	198	214	208	222	202	218	210	216	222	**212.8**
D2.6	222	224	222	228	224	218	218	216	214	226	**221.2**
D2.7	218	202	188	216	210	214	210	214	226	214	**211.2**
D2.8	232	218	208	228	224	220	218	224	228	234	**223.4**
D2.9	218	220	224	220	220	218	222	222	224	208	**219.6**
D3	276	262	264	270	271	258	266	266	268	284	**268.5**
D3.1	254	242	246	256	240	228	230	244	238	216	**239.4**
D3.2	274	258	252	246	270	264	264	260	272	256	**261.6**
D3.3	266	286	284	270	270	272	274	262	268	268	**272.0**
D3.4	246	252	234	232	240	260	244	238	242	238	**242.6**
D3.5	220	250	236	240	246	236	238	248	226	218	**235.8**
D3.6	248	236	256	240	246	242	240	254	236	264	**246.2**
D4	290	310	320	316	316	306	316	284	282	294	**303.4**
D4.1	268	274	268	266	256	252	264	242	256	244	**259.0**
D4.2	250	250	262	274	258	266	250	234	266	248	**255.8**
D4.3	240	250	288	262	256	274	250	250	252	274	**259.6**
D4.4	268	292	270	288	276	284	278	274	278	268	**277.6**
D4.5	236	246	216	250	222	220	228	230	250	236	**233.4**
D4.6	204	222	230	248	232	248	246	248	232	240	**235.0**
D4.7	292	298	302	286	284	260	274	292	300	300	**288.8**

APPENDIX J

Readings of tests to establish the minimum and maximum levels where the Doppler meter can be expected to give reliable readings

READINGS OF MIN. AND MAX. RELIABLE DEPTHS FOR MEASUREMENTS

Datum(Doppler): 12.83 cm
Datum(Point 4): 57.38 cm
Datum(Point6): 57.06 cm

Test Nr.	Reading Height (m)	Doppler Frequencies										Av.	V_{Dop}
		1	2	3	4	5	6	7	8	9	10		
M1.1	0.0100	154	172	168	170	160	164	168	144	152	164	**162**	**0.111**
M1.2	0.0217	164	172	164	200	182	192	190	180	180	170	**179**	**0.123**
M1.3	0.0417	168	200	186	190	202	196	192	194	202	184	**191**	**0.131**
M1.4	0.0517	190	190	188	178	190	190	186	176	190	170	**185**	**0.127**
M1.5	0.0817	204	200	196	190	194	192	186	202	210	194	**197**	**0.135**
M1.6	0.1017	196	186	190	188	194	176	190	192	186	190	**189**	**0.129**
M1.7	0.1217	192	200	198	188	184	196	174	190	190	188	**190**	**0.130**
M1.8	0.1417	190	188	184	180	190	180	194	194	190	198	**189**	**0.129**
M1.9	0.1617	194	194	196	196	190	200	194	194	190	196	**194**	**0.133**
M1.10	0.1817	188	190	190	198	196	198	200	192	192	190	**193**	**0.133**
M1.11	0.2017	198	190	198	196	196	186	198	204	208	200	**197**	**0.135**
M2.1	0.0100	222	220	224	208	202	230	220	236	206	236	**220**	**0.151**
M2.2	0.0217	240	254	234	250	226	230	230	230	242	212	**235**	**0.161**
M2.3	0.0417	234	232	238	264	252	242	252	250	240	240	**244**	**0.167**
M2.4	0.0617	240	262	256	260	254	264	258	258	254	244	**255**	**0.175**
M2.5	0.0817	258	260	258	256	262	256	266	254	258	260	**259**	**0.177**
M2.6	0.1017	256	252	266	254	264	252	264	256	244	254	**256**	**0.176**
M2.7	0.1217	262	258	260	246	252	250	228	250	260	260	**253**	**0.173**
M2.8	0.1417	250	250	262	254	262	258	256	252	260	254	**256**	**0.175**
M2.9	0.1617	240	242	256	266	250	258	254	260	254	250	**253**	**0.173**
M2.10	0.1817	250	254	264	260	254	258	262	244	254	248	**255**	**0.175**
M2.11	0.2017	250	266	258	264	256	264	260	246	262	260	**259**	**0.177**
M2.12	0.2217	280	276	274	276	278	280	278	280	268	274	**276**	**0.189**
M3.1	0.0100	284	312	312	280	274	284	312	304	298	282	**294**	**0.202**
M3.2	0.0217	308	306	304	300	300	306	308	304	310	304	**305**	**0.209**
M3.3	0.0417	302	346	318	326	328	330	324	322	314	314	**322**	**0.221**
M3.4	0.0617	316	324	338	322	326	304	314	338	334	318	**323**	**0.222**
M3.5	0.0817	336	336	336	334	330	316	330	336	316	314	**328**	**0.225**
M3.6	0.1017	326	324	328	334	328	312	334	340	342	336	**330**	**0.226**
M3.7	0.1217	338	338	340	334	342	330	336	334	322	324	**334**	**0.229**
M3.8	0.1417	340	338	342	326	334	340	342	330	336	332	**336**	**0.230**
M3.9	0.1617	338	324	330	324	330	342	324	338	334	334	**332**	**0.227**
M3.10	0.1817	340	336	350	336	326	332	334	324	340	342	**336**	**0.230**
M3.11	0.2017	342	336	354	336	340	340	344	332	338	334	**340**	**0.233**
M3.12	0.2217	336	348	330	332	338	348	350	344	344	336	**341**	**0.233**
M3.13	0.2417	366	368	344	364	364	358	358	360	358	362	**360**	**0.247**

Test	Readings					
	Manometer	2.1	2.3	4	6	y
	(cm)	(cm)				(m)
M1	34.65	76.65	76.48	77.98	77.99	0.208
M2	68.90	78.49	78.40	79.73	79.68	0.225
M3	135.00	80.55	80.51	81.75	81.80	0.246

APPENDIX K

Readings of tests to establish the influence of the probe angle relative to the horizontal on the Doppler readings

Readings of Doppler frequencies with different probe angles relative to the horizontal

Angle with horizontal (Degrees)	Reading (Hz)										
	1	2	3	4	5	6	7	8	9	10	Av
-60	122	120	118	116	120	120	120	120	122	118	**120**
-40	200	200	204	204	198	200	202	202	202	198	**201**
-20	224	238	246	252	260	250	254	246	254	258	**248**
0	250	250	244	248	234	234	252	244	236	244	**244**
20	250	244	240	242	244	248	240	242	238	246	**243**
35	222	220	216	220	220	216	222	220	224	216	**220**
55	168	174	172	172	174	170	174	176	170	176	**173**
70	112	108	110	106	108	112	110	110	108		**109**
90	48	56	52	52	66	72	102	82	92	82	70

APPENDIX L

Tests to establish the minimum velocity the Doppler meter can detect accurately

Readings for tests to establish the minimum velocity that can be measured accurately

Manometer

Test Nr	Reading 1 (cm)	Reading 2 (cm)	h (cm)	Q_{Lab} (m^3/s)	A (m^2)	v (m/s)
V1	2.2	2.1	2.2	0.0162	0.550	0.029449
V2	5.0	4.8	4.9	0.0244	0.570	0.042859
V3	12.3	11.9	12.1	0.0384	0.596	0.064467
V4	16.8	16.5	16.7	0.0450	0.647	0.069615
V5	24.2	24.7	24.5	0.0546	0.618	0.088275
V6	32.0	35.3	33.7	0.0640	0.632	0.101395

Water levels

	Readings at position		
Test Nr	4 (m)	6 (m)	Av. (m)
V1	0.847	0.847	0.847
V2	0.857	0.857	0.857
V3	0.870	0.870	0.870
V4	0.875	0.875	0.875
V5	0.881	0.882	0.881
V6	0.888	0.888	0.888

Datum (upstream):

4	0.5738m
6	0.5706m

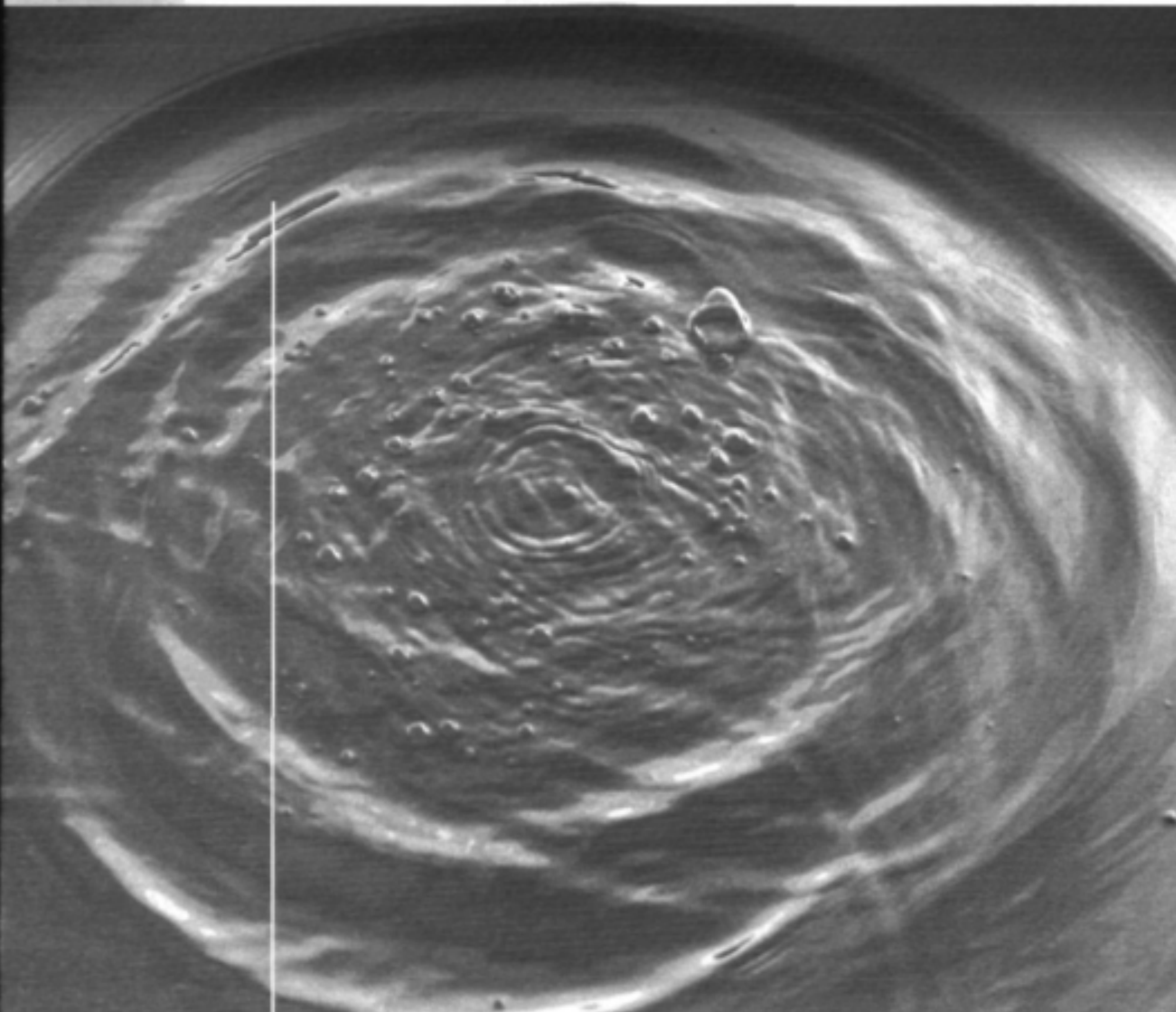
Readings for tests to establish the minimum velocity that can be measured accurately (continued)

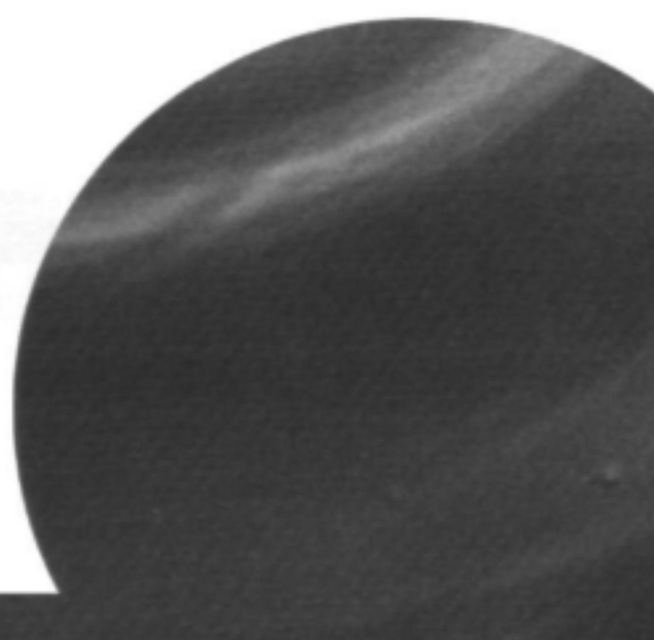
Doppler Frequencies

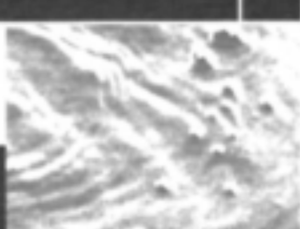
Test Nr	1	2	3	4	5	6	7	8	9	10	Average
V1	0	0	0	0	0	0	0	0	0	0	0.0
V2	18	4	6	16	11	14	10	6	20	2	10.7
V3	38	51	41	32	48	34	38	40	32	46	40.0
V4	49	66	56	90	76	48	68	51	76	92	67.2
V5	88	100	84	94	74	102	88	84	100	106	92.0
V6	108	102	89	112	116	108	102	104	122	116	107.9

Test Nr	Av. Freq. (Hz)	V_{Dop} (m/s)	Y (m)	A (m2)	Q_{Dop} (m3/s)
V1	0.0	0.000	0.275	0.550	0.000
V2	10.7	0.007	0.285	0.570	0.004
V3	40.0	0.027	0.298	0.596	0.016
V4	67.2	0.046	0.324	0.647	0.030
V5	92.0	0.063	0.309	0.618	0.039
V6	107.9	0.074	0.316	0.632	0.047

B = 2 m







Water Research Commission

PO Box 824, Pretoria, 0001, South Africa

Tel: +27 12 330 0340, Fax: +27 12 331 2565

Web: http://www.wrc.org.za

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