CURRENT MEASUREMENTS
IN KNIGHT INLET
1956

by

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ABSTRACT

Current measurements were made in Knight Inlet during the period, July 4th to 11th, 1956. A current drag, designed at the Chesapeake Bay Institute, was employed for current measurements in the upper 20 meters of the water column. An Ekman current meter was used at depths below 20 meters. Corrections for ship motion were applied to the Ekman current meter readings.

This investigation consists of:

(1) a general analysis of the techniques used in the collection and treatment of the data,

(2) a description of the currents obtained from the above treatment of the data.

Currents at every depth of measurement showed oscillating or fluctuating components superimposed on a net current. Tidal forces appear to act at all depths. The direct effect of wind stress on currents is apparent to depths of at least 10 meters. Indirect wind effects are indicated at greater depths.

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I INTRODUCTION

The Institute of Oceanography of the University of British Columbia has carried out a study of the coastal inlets of British Columbia over several years. These inlets are deep indentations in the shoreline. They are long and narrow with steep sides. The bottom topography is characterized by a deep basin that is often two to three times the depth of the outside passages and coastal shelf regions through which they have access to the sea. The deep basin of the inlet and the shallower passages beyond the inlet mouth are usually separated by a sill, or shallower section where the depth is about one half that of the outside passages. In these inlets the distribution of properties such as salinity, temperature and oxygen content has been determined.

The salinity distribution provides some information about circulation in the inlets. The circulation or water movements within the inlets, if fully understood, would help in understanding the sources and movement of nutrients for biological activity. It also would assist in determining the distribution of particulate material and possible pollutants.

The first fact provided by observation of the salinity distribution is that all fresh water emptied into an inlet by rivers (principally at the head of the inlet) stays in the surface layers. The fresh water flows out over higher salinity sea water. The salinity of the surface layer increases from the head to the mouth. Therefore salt water must be mixed upward into the surface layer and carried seaward. In order that there be continuity of the fresh water flow, the speed of the down-inlet flow of the surface layer must increase towards the mouth. In order to replace the salt carried seaward in the surface layer there must be up-inlet flow of sea water at depths below the surface layer (see figure 1). Extensive surveys of a shallow east coast estuary (Pritchard, 1952) where the water is slightly less stratified bears out these ideas. Dynamical studies of deep inlets are based on this (Cameron, 1951 and Stommel, 1951). However, in deep inlets the distribution of net currents (non-periodic) and also of tidal currents (periodic) is unknown and these can be obtained only by direct measurements.

There are some difficulties in carrying out a current measurement programme in these deep inlets and experiments were made in 1952, 1953 and 1955 in order to find a suitable position for measurements; to determine the best technique for anchoring; to determine the magnitude of currents to be measured, and to experiment with current measuring devices.

The 1956 data from Knight Inlet, with which this thesis is concerned, represents the most recent experiment in this series. The data serves as the basis for an analysis of the techniques employed and for an analysis of the currents in order to determine the influence of tide, wind and runoff.

II INLET DESCRIPTION

The data treated in this thesis was obtained in Knight Inlet. In general characteristics this inlet is typical of those in British Columbia (see figure 2,3 and 4). It is a long, narrow deep coastal indentation with a length of 102 kilometers (55 nautical miles) and an average width of 3 kilometers (1.6 nautical miles). The average mid-inlet depth is 420 meters (1380 feet) and the maximum is 550 meters (1800 feet). It has two sills in its length, 74 and 110 kilometers from the head of the inlet. The basin (designated as the outer basin) between these two sills has irregular topography but does not exceed 250 meters in depth. The inner basin inside the inner sill is deeper and contains the maximum depth (Pickard, 1956). The outer sill depth is 67 meters and the inner sill depth is 63 meters.

This inlet is a positive, fjord-type estuary (Pritchard, 1952) in consideration of its depth, sills and average salt content (less than the adjacent sea). The fresh water is supplied largely by river runoff introduced at the head by the Klinaklini River.

This river runoff is at a maximum in June or July due to melting of the snow and ice at higher altitudes. An estimate of the mean monthly runoff has been made from rainfall and watershed data (Pickard and Trites,1957). For June and July the values are 790 and 616 cubic meters per second respectively.

A series of salinity profiles down the length of the inlet is plotted in figure 2. These are taken from data obtained during the two days following the last current measurement. The inlet begins as a highly stratified, two-layer system at the head and grades to near homogeneous in the outer basin. The fresh water is concentrated in the upper 20 meters, though there is still a gradient in salinity below this. The fresh water has salt water mixed upward into it as it moves down the inlet. The upper layer eventually reaches a salinity close to that of the sea water at the mouth.

As indicated in the introduction this implies an outflow in the surface layer to provide continuity of fresh water flow, and inflow at depth to balance the salt carried out with the fresh water. Just where this inflow takes place is undetermined. However, in view of the fair stability of the upper 50 meters of water and the fact that salt is being supplied at the lower boundary of the surface layer (at a depth of about 15 meters) it seems likely that up-inlet flow will be concentrated just below the upper layer.

Tides in this region are of the semi-diurnal mixed type with a maximum range of about 5 meters. The nearest continuously recording tide station to Knight Inlet is at Alert Bay, about 40 miles from the region where this data was obtained. Alert Bay is in the network of channels into which the inlet empties.

The two current stations at which measurements were made were 5 and $3^1/2$. The nearest tide station referred to the Alert Bay tide predictions is Glendale Cove, about 5 miles up-inlet from station 5 (see figure 2). For Glendale Cove there is no time difference from Alert Bay in high or low water, but there is a mean ratio of rise for high tide given as 1.15 (Tide tables, 1956). The predicted tides for Alert Bay are those which are indicated on the various graphs.

The state of the tide at station 5 from July 4th to 6th was in the transition from neap to spring tides with marked inequality. The range of tide for successive high to low waters differed by a factor of two, while the range of tide for successive low to high waters was very nearly the same. For the period from July 6th to 8th on station $3^1/2$ the tide was near springs, still with the factor of 2 between successive high to low water ranges. The time spent on station 5 from

July 8th to 11th was during spring tides with the factor defined before being only 1.6.

The two stations on which current measurements were made are in the straight reach of the inlet (see figure 2). A straight reach was chosen for the current measurements because previous measurements in a sinuous inlet (Bute Inlet in particular) were difficult to interpret. Station $3^1/2$ was on the inner sill, or slightly up-inlet from the shallowest part (see figure 4). Station 5 was situated 15 kilometers (8 nautical miles) up-inlet from station $3^1/2$ over the deeper basin inside the inner sill. Transverse profiles of the inlet at these stations are shown in figure 3. Apart from the depth difference between these two stations there is a difference in the symmetry about the centre-line of the inlet. The anchoring position corresponds roughly with the centre-line. At station 5 there are steep sides and a level bottom and little asymmetry about the centre-line. At station $3^1/2$ there is a steep side and a level bottom to the south of the centre-line. To the north it is shallower and the grade is less than that of the steep southern slope.

During the period of these observations the prevailing winds and the strongest winds were westerly, or up-inlet. The one exception was the first 24 hours on station 5 when a steady 10 knot wind blew down the inlet. The up-inlet winds followed approximately a diurnal cycle with a minimum from 0600 to 1200 hours and a maximum at 1600 to 2000 hours. The maximum up-inlet wind in each case was over 20 knots.

III EXPERIMENTAL PROCEDURE

General Description

Measurements were taken from the research vessel, H.M.C.S. Cedarwood, a wooden ship of 51 meters length, 9.2 meters beam and 4.5 meter draft. A single anchor was used as previous attempts in 1952 - 3 to anchor bow and stern were unsuccessful. The ship motion was monitored during current measurements (in a way which is described below) to permit correction for the swing of the vessel on its anchor cable.

Current profiles were obtained from the surface to 20 meters every half hour with a C.B.I. current drag (description in section on instrumentation) for the first and second anchorages and every hour on the third anchorage. Measurements with the Ekman current meter were taken in the remainder of the water column every hour. At station 5 the Ekman current meter measurement depths were 50, 100, 200 and 300 meters. At station $3^1/2$ the depths were 10, 20, 40, 60 and 70 meters. It will be noted that there is an overlap of C.B.I drag and Ekman meter measurements at the 10 and 20 meter depths on station $3^1/2$. These measurements served to compare the two instruments.

The periods of observation consisted of 48 hours on station 5 from July 4th to 6th; 48 hours on station $3^1/2$ from July 6th to 8th and another 68 hours on station 5 from July 8th to 11th. The following table summarizes the amount of data obtained.

Station	5	$3^1/2$	5
Duration of anchorage	1500 July 4th to 1500 July 6th	1800 July 6th to 1800 July 8th	2100 July 8th to 1600 July 11th
No.of C.B.I.drag profiles to 20m.	90	96	64
No.of Ekman meter profiles	48	48	63

A bathythermograph cast to 270 meters was made hourly at station 5 and to 75 meters hourly at station $3^1/2$. The occasional 20 meter cast was made to determine the surface temperature structure in more detail.

Hourly meteorological observations included the wind velocity, air temperature (wet and dry bulb thermometers), barometric pressure, cloud type and cloud cover, visibility and sea state.

At the beginning and end of each Ekman current reading a 3-point fix with a sextant was taken on shore stations. The position of these shore stations were determined several times during the anchorages with radar ranging and gyro compass bearing. These shore stations were usually prominent racks whitewashed for daylight visibility and marked by oil lanterns at night. Only when rain was heavy were these stations not visible.

On the two days following the last current station, oceanographic stations were taken along the length of the inlet to determine the water structure.

In numerous instances below there will be reference to a'calculated' tidal current as opposed to the observed currents. This 'calculated' current is deduced from predicted tides, several assumptions being made, namely:

(1) that the real tide was as predicted,

(2) that the whole water surface of the inlet rises and falls uniformly,

(3) that the tidal current necessary to provide the water for filling (or emptying) the tidal prism is uniform across the entire section of the inlet,

(4) that the tidal current varies sinusoidally.

The close correspondence of the actual tide records and predicted tide heights at Alert Bay lend support to the first assumption. Early investigations by Dawson (1920) support the second. There is less justification for the final two assumptions. A more detailed account of this tide current calculation appears in the discussion.

Current Measuring Devices

1. The Ekman Current Meter.

The Ekman current meter is an integrating, propellor-type device which is activated and deactivated by messengers. During the activation period the number of revolutions of the propellor is metered. Also, for every 33 turns of the propellor, a small phosphor-bronze ball is released to fall into a compass-directed trough directing the ball into a 10° segmented cup.

After deactivation the meter is raised. Both the number of revolutions made by the propellor, and the number of balls in each 10° segmented cup are noted.

The number of revolutions made, combined with the activation period gives the average revolutions per minute. Comparison with a calibration curve gives the current measured. A weighted mean of the angles indicated by the balls determines the current direction.

The period of activation was usually 2 minutes, though periods of 1 and 4 minutes were used when the current was very large or very small, respectively.

For the meter used in this experiment the threshold velocity required to overcome friction was 1.8 centimeters per second. Experience with calibration of these instruments shows a possible error of about 3 per cent in readings. The accuracy in the direction indication is about $\pm$ 5 degrees for reasonably large currents, but there is a larger uncertainty in small currents (Tabata and Groll, 1956).

Error in indication of the water current is introduced by horizontal ship drift during the current measurement. The Ekman meter reads the vector sum of the water current relative to the earth and the ship velocity relative to the current. Since the ship velocity is a significant percentage of this reading (see discussion of ship motion) the ship's movement was monitored to correct for this.

The major disadvantage in using the Ekman current meter is the slowness with which measurements are made. This is because the meter has to be recovered after each measurement. It takes approximately one half hour to take 4 measurements at 50, 100, 200 and 300 meters.

2. The C.B.I. Current Drag:

Currents in the upper layer (zero to 20 meters) are of special interest in estuaries. Experience has indicated that they vary markedly with depth and time. This detail must be provided by frequent readings at several levels. Preferably the readings for all depths should be made simultaneously. As indicated before, the Ekman current meter is too slow for this, even though the depth is only 20 meters. Another objection is that the magnetic effects of the ship may appreciably affect current direction indications at these small depths (Sverdrup, et al, 1942). A C.B.I. current drag can provide the type of measurement required.

The design used was that described by Burt and Pritchard (1951) of the Chesapeake Bay Institute (hence C.B.I. drag). Readings can be obtained at one depth in about 15 seconds and the drag can be quickly lowered or raised to successive depths.

This device is a negatively buoyant, weighted biplane (see figure 5) suspended by a light, steel wire. The current exerts a force on the biplane, and the wire angle from the vertical is a measure of the magnitude of the current. The direction of the current is given by an estimate of the angle at which the wire streams away from the ship, combined with the ship's heading.

The sizes of the biplane and weights used are determined by the magnitude of the currents to be measured, in consideration of the optimum, angle-measuring range (3 degrees to 45 degrees) and the Reynolds number restriction for the equation used to calibrate the drag.

The restriction on the Reynolds number is that it be greater than 1000 for flow past the drag, in order that the drag coefficient for the biplane be constant.

In this experiment a 1.5 by 1.0 foot biplane was used with 10, 20 or 40 pound weights. With these combinations the lower limit of a speed measurement is 0.3 centimeters per second. This is highly satisfactory in the current range of zero to 150 centimeters per second, encountered.

The equation of the C.B.I. drag is

$$v = (2W / C_d A \rho)^{1/2} (\tan \theta)^{1/2} = k (\tan \theta)^{1/2}$$

as a consequence of the balance of forces shown in figure 5. The symbols represent the following:

θ = angle measured from the vertical

W = weight of the drag in water

Cd = drag coefficient of the plane

A = plane area

ρ = fluid density

The drag coefficient used by Burt and Pritchard was 1.2 .

A check of this formula was made by Burt and Pritchard by simultaneous current measurements with the drag and a von Arx recording meter. They show good agreement to a depth of 25 feet and have indicated successful use to 50 feet. The use of this drag to 20 meters or 65 feet in British Columbia inlets required a further check on its accuracy at such depths. Also, since currents in the British Columbia inlets appear to be twice those used by Burt and Pritchard for their check, there is further reason to investigate its accuracy.

Sources of error in using the above formula include:

(1) neglect of drag on the suspending wire

(2) neglect of lift on the wire

(3) neglect of wire curvature.

Error in the direction estimation may be caused by current directing of the ship's hull if the hull does not line up parallel to the surface current. The fact that part of the direction measurement involves an eye estimation of angle probably introduces an average error of $\pm$ 10 degrees even with the most experienced operator.

In reading the wire angle there was a possible error of $\pm$ 1/2 degree. The accuracy in angle required for a 0.05 knot (2.5 centimeters per second) accuracy in current is given by Burt and Pritchard as:

Measuring Angle

	at 3°	at 10°	at 20°
15 lb.weight	1°	$1\ 1/2^{\circ}$	2°
30 lb.weight	$1/2^{\circ}$	1°	$1\ 1/2^{\circ}$

A point of distinction between drag measurements and Ekman meter measurements is that the Ekman measurements are values integrated over 2 minutes (in most cases) whereas drag measurements are obtained in about 15 seconds. The latter more closely approximate instantaneous readings.

IV DATA TREATMENT

Ship Motion:

The sextant headings on shore stations and the data determining the shore station positions were used to calculate the ship's velocity during current measurements. These were also used to determine the large scale movements of the ship from hour to hour.

The shore stations were arranged as shown in figure 6, so that one angle (θ_1) was measured between two stations on one shore, and the other (θ_2) on two stations one on either shore. The relative positions of these stations were determined from the gyro compass fixes and radar ranging.

A three-armed protractor is usually used to plot ship movement or position, but for short period movements the proctractor is not as sensitive as the accuracy of the sextant readings warrants. By short term is meant the ship movement in the period of a current measurement (usually 2 minutes). The following describes the manner in which the ship movement was determined.

A change in θ_1 is a measure of the cross-inlet movement and a change in θ_2 is a measure of the along-inlet movement. The movement, $\triangle S$, is related to the mean of the two fixes on the same stations, $\bar{\theta}$, the distance between the two shore stations, L , and the change in angle, $\triangle\theta$, by the following equation:

$$\triangle S = \frac{L}{4} \left(\operatorname{cosec}^2 \frac{\bar{\theta}}{2}\right) (\triangle\theta)$$

This equation applies to only one of the components of movement (either cross or along the inlet) and is based on two assumptions:

(1) that $\triangle S$ is small compared to L, and

(2) that the ship (point of observation) is fairly close to the right bisector of the line joining the two shore stations. Any more rigorous formula to fit the actual situation of stations requires an uneconomical amount of labour for reducing the data.

The ship's velocity during current measurements was determined from the time between sextant fixes,(the activation time of the current meter) and the distance the ship had moved as determined from the fixes in the above manner. The formula above was used to determine each component of the movement and these were combined to give a vectorial displacement.

Some information regarding the extent of ship movement or the long-period movement is presented in this thesis. For this purpose the three-armed protractor was sufficiently accurate to present the picture.

Unfortunately, due to the rugged nature of the coastline in this inlet, there is not too much choice in the positioning of shore stations. Thus the conditions stated above are not exactly met. For this reason the error in the along-inlet direction is put at 5 to 10 per cent.

For the same type of reason the error invthe cross-inlet component of the ship motion must be put at 15 to 20 per cent. The reason for the large possible error in the cross-inlet component lies in the shoreline irregularities. The stations had to be placed so that, at times, the ship was far off the ideal right bisector. Thus any cross-stream currents deduced from currents corrected for ship motion may include an error of the above proportion (15 to 20 per cent) of the ship velocity.

There is the assumption implicit here that the meter moves with the ship. This is an assumption that is often made, but seldom justified. The following is an attempt to put an upper limit on the possible error that might be incurred by making the above assumption.

If the assumption does not hold, then there will be relative movement between the meter and the ship. This would result in a change in the suspending wire angle from the vertical or a change in the angle at which the wire streams away from the ship (provided the ship's heading is not changed). Only the change in wire angle from the vertical will be considered.

During current measurements this wire angle was checked. A change in angle of 5° would probably have been noticed. This angle is used as a limit of noticeable meter movement with respect to the ship. The maximum angle which would have gone unnoticed, combined with an average ship movement of 11 meters (station 5) over a meter activation interval of 2 minutes, shows that the meter must partake of at least 75% of the ship movement when it is at a depth of 50 meters; or at least 50% at a depth of 100 meters. At greater depths the above limit of detection of wire angle change (5°) gives no guarantee that the meter will move with the ship. Nevertheless the full correction for the ship velocity has has been applied throughout this data.

Due to poor visibility it was not always possible to monitor ship motion. For this reason some of the data presented is not corrected for ship motion. The Ekman reading itself was used if no correction was available. The percentage of uncorrected data for the first period at station 5 was 31%; at station $3^{1}/2$ it was 2% and in the second period of observations at station 5 it was 1%. These figures give some reason to consider the data of the first period on station 5 as less reliable than the data for the second period at the same station.

Current Measurements

The currents obtained from the C.B.I. drag and from the deeper measurements were separated into along-inlet (conveniently east-west) and cross-inlet components. For the C.B.I. drag measurements, resolution into components was carried out only for directions greater than 20° from the east-west line because of the ± 10° possible error in the direction estimate.

The C.B.I. drag measurements were first plotted as profiles to determine the current at standard depths of 2,4,6, 10, 15 and 20 meters. Ekman meter readings were taken at set depths. When the wire-angle was large, raising the meter above the set level, adjustment was made by paying out more wire.

The series of component values for each depth were then plotted on a time scale along with the tide and wind conditions.

From these plots and a smooth curve drawn through the currents obtained, a vertical current profile for the along-inlet component was constructed for each hour and the hourly profiles plotted as a series.

The net current at each depth was determined by a 25 hour average of the above hourly values. The 25 hour average was used to eliminate the tidal currents.

V RESULTS

Ships Motion:

A plot of the ships position for successive fixes on shore stations shows marked differences between anchorages (figure 7). Though movements may have been peculiar to that particular ship they will be a guide for future measurements and, of course, they are of significance in this set of measurements.

During the first period of observation on station 5, the wind was zero or down-inlet and the surface current predominantly down-inlet. The ship moved on an arc of about 500 meters length, thus describing predominant shearing (side to side) motion. On two occasions it sheared and surged (moved up on the anchor) violently off its stable arc. These two periods were initially associated with transverse, alternate bands of slick and ruffled surfaces moving up the inlet. It is believed that these bands are due to progressive, interval waves in the lower boundary of the surface layer. When the ship moved off the arc it required one to three hours to return to it.

During the second anchorage on station 5, the wind and surface current conditions were different. The wind was always up-inlet, and the surface current reversed fairly regularly. In this instance the extent of ship motion was large, covering an elliptical region of 950 by 550 meters. The elliptical pattern was formed by two arcs and paths between them. The arc on the up-inlet end of this pattern is of smaller length and of greater density of position than the ill-defined arc on the down-inlet end. When the wind and surface currents are in the same direction the ship moves on the smaller arc. The down-inlet end where wind and surface current were opposed showed an ill-defined arc as well as large movement from hour to hour.

The frequency distribution of the ship's speed for the two stations has been plotted in figure 8. The distributions are skewed as the ship's speed can apparently be great in some cases. Here, again, a difference can be seen between stations $3^1/2$ and 5. The mean ship speed at station $3^1/2$ was 4.5 centimeters per second and at station 5 about 7.5 centimeters per second. These two means have significance in evaluating the necessity for monitoring ship motion during current measurements.

In figure 9 there are plotted the Ekman readings as well as the corrected readings for both longitudinal and transverse components of a part of the series at stations $3^1/2$

and 5. The correction at station $3^1/2$ is relatively small. The correction at station 5 is larger and predominantly in the transverse component.

A comparison of mean ship speed in different wind, surface current and anchorage conditions suggests that the mean ship speed increases with:

(1) increased wind,

(2) decreased surface current,

(3) increased depth at the anchorage,

(4) light cross stream breezes (markedly),

(5) opposing wind and surface current.

Certain of these are obviously interrelated. In particular, in estuaries where tidal currents are present at the surface, a shallow region presents a smaller depth for the anchorage and usually increases the tidal currents. Both of these act in the direction towards decreased ship motion. When the wind and surface current tend towards the same direction there will also be a decrease in the ship movement. In view of the large effect of wind stress on surface currents there is an increased tendency for the wind and the surface current to be in the same direction.

Description of Currents.

(1) Station $3^1/2$, July 6th to 8th, 1956

A time series plot of the longitudinal component of the current (figure 10) shows strong oscillations up and down inlet. The times of peak currents and slack water are highly correlated with what might be deduced from the predicted tide height curve. The oscillatory currents do not show a smooth sinusoidal variation. There are large irregularities at all depths of measurement.

Though a mean amplitude of oscillation cannot have much significance since the tide is a semi-diurnal mixed type, it can be said that there was a mean range in current of about 140 to 150 centimeters per second. Comparison of the range in current at different depths shows that they were nearly constant at all depths with two exceptions and one dubious case. The dubious case involves the depth of 2 meters where the effect of the wind distorted the oscillating currents making an estimate of current range difficult. The current range at 70 meters was reduced to about 105 centimeters per second or 70% of currents above it. The flood current at 40 meters during the second half of the anchorage was remarkably reduced (figure 10 (b)) to 30 or 40% of the first flood peaks In general it appeared that the maximum flood current was more subject to large fluctuations within one flood than was the ebb.

The transverse component of the current plotted as a time series (figure 11) shows asymmetry about a mean current at all depths. In general, the south component on the flood was greater than the north component on the ebb. This statement does not apply to the measurements at 10 meters wherenet flow was northerly.

The currents on the flood and ebb did not differ in direction by 180 degrees. The mean ebb direction at all depths over a full 25 hours was between 270 and 285° true for the whole anchorage. The mean flood at 10 meters was in the direction of 104° true. At 20 and 40 meters it was about 125°, and at 60 and 70 meters it was 135° true. The last 25 hours showed some change in mean directions of the floods. Directions at both 10 and 20 meters were 103°. At 40 meters it was 155°, at 60 meters it was about 135° (as before) and at 70 meters it was 129° true. The following table summarizes this data:

	First 25 hours		Last 25 hours	
mean direction / depth	Flood	Ebb	Flood	Ebb
10 m.	104° true	286°	103°	278°
20	125	278	103	282
40	127	273	155	274
60	135	277	136	271
70	134	283	129	273

Dealing now with only the longitudinal component, it is seen that the plot of the series of hourly profiles (figure 12) is naturally divided into two periods. The first constitutes a period of no wind, and the second a period of varying up-inlet winds.

During the first period the column of water below 20 meters appeared to move as a unit with a smaller amplitude of motion at 70 meters. The region above 20 meters appears more complicated. This may be an artifact of observation since there was more detailed coverage in this region. Above 10 meters the flood current was markedly less than that of the water below 20 meters. The ebb current in the upper 20 meters was somewhat larger than the ebb below. There was a minimum in the ebb at 4 to 6 meters. This was less evident on the flood.

During the second period there were varying up-inlet winds with a maximum speed of 23 knots. There was considerable difference between the flow at the surface and at 40 meters. The near-surface current (2 meters depth) was reduced to zero on the ebb and was more than twice the deep current on the flood. On the hour between the period of zero wind and the first recorded wind a reduction appeared in the flood current at 40 meters. There appeared to be no effect on the ebb current at this depth.

There also appeared a minimum or down-inlet tendency for flow at about 10 meters which was most marked on the flood. This 'direction" of flow at this depth could be the cause of the apparent up-inlet flow at 4 to 6 meters as described for the first period. This latter flow was obliterated by the wind currents during the second half of the anchorage.

The 25 hourly-value mean for each depth is plotted in profile for the first and last 25 hours of the anchorage (figure 13). These two profiles are quite different.

Consider first the initial mean profile for which there was an average wind of 4 knots. There was net outflow at all depths of measurements down to 40 meters. The net flow at 60 and 70 meters was up-inlet. There was a significant minimum in the outflow at 4 meters or alternatively, a maximum in the outflow at 15 meters.

Turning to the final 25 hour period it should be noted first that the mean wind for this period was 12 knots up-inlet. The superimposed initial mean flow shows the great change that took place. The surface flow to 6 meters was completely reversed. The outward flow at 10 and 15 meters was virtually unchanged, but at 20 and 40 meters the outflow had increased. The inflow at 60 and 70 meters had also been reduced. This resulted in a depth of no net motion at 55 to

60 meters rather than 40 to 45 meters as occurred during the first 25 hours.

(2) Station 5, July 4th to 6th, 1956

The time series plot of the longitudinal components of the current will be considered first (figure 14). At 300 meters the oscillatory current was predominant but there were sporadic bursts super-imposed on it. The oscillatory current was what one might deduce from the tide height variation. At 200 meters the same held true with regard to the oscillatory motion and its correlation with tide. It appears that the irregularities in the flow occur usually on the flood current. At 100 meters the irregularities nearly obliterated the systematic oscillations and at 50 meters the fluctuations were incoherent but just as large as the systematic oscillating currents at 100 meters.

The mean range of currents was about 30 centimeters per second at 200 and 300 meters. This was slightly reduced to about 24 centimeters per second at 100 and 50 meters.

Before continuing with the currents in the upper 20 meters the wind conditions should be described. The anchorage can be divided into two periods; the first period characterized by a 10 knot down-inlet wind and the second period by no wind.

Currents measured in the upper 20 meters were much larger than those at the greater depths, ranging from 120 centimeters per second down-inlet to 45 centimeters per second up-inlet. It is apparent that the net flow was down-inlet at all depths, the magnitude decreasing with increasing depth.

At the 2,4 and 6 meter depths during the first half of the anchorage there were up-inlet surges in current of 60 to 90 centimeters per second, lasting from 1/2 to 1 hour in the hour before predicted high water. During the second half of the anchorage this same feature resembled a step function with the up-inlet surge lasting 2 to 3 hours in the 3 hours before predicted high water.

At 10, 15 and 20 meters there was an increasing frequency of zero currents measured as depth increased. Currents at these 3 depths were sporadic, although they tended to coincide with the extremes in current at the 2, 4 and 6 meter depths.

The current range at the 2 meter depth was larger than at other depths. At 4 and 6 meters the range was about 75% of that at 2 meters. At 10, 15 and 20 meters it was 50% of the range at 2 meters. The current range at lower depths is only 25% of that at 2 meters.

Turning to the transverse components at 50, 100, 200 and 300 meters (figure 15) it is seen that the currents were highly irregular and of the same magnitude as the longitudinal components at the same depth.

Inspection of the series of hourly profiles of the longitudinal components (figure 16) reveals some interesting features. At the depths of 50 or 100 meters the flood current appeared to start earlier and then spread downward. This early flood usually started after predicted high water and would not extend to 300 meters until predicted low water.

There were two features associated with the period between low and high water. At 300 meters in the middle of this period a down-inlet surge in the current of 1 to 2 hours duration took place in 3 cases out of 4. In the smaller depths of 5 to 15 meters there appeared an up-inlet current surge in the 1 or 2 hours before predicted high water. Again this happened in 3 cases out of 4. In this fourth case an up-inlet surge took place, but was observed at depths of 5 to 10 meters greater.

The profiles given by 25 hour means for the first and last 25 hours are shown in figure 17. The first profile corresponds to a period when there was an average down-inlet wind of 10 knots. The second period was one of no wind.

The first profile shows net currents at 100, 200, and 300 meters which were barely significant. An up-inlet flow took place at 50 meters. There was a net flow down-inlet at all depths to 20 meters with a particularly strong flow down-inlet from the surface to 5 meters. There was a significant minimum in the down-inlet flow at 10 meters, or alternatively, a maximum at 15 meters.

The final period of 25 hours showed several changes. Net down-inlet currents from the surface to 20 meters were reduced. The minimum in the down-inlet flow observed at 10 meters in the first 25 hours had disappeared in the last 25 hours. The up-inlet flow evident only at 50 meters during the first 25 hours, showed also at 15 and 20 meters in the last 25 hours. Net currents at 200 and 300 meters were again insignificant, but at 100 meters there appeared a significant net current down-inlet.

(3) Station 5, July 8th to 11th, 1956

The time series plot of the longitudinal component of currents (figure 18) shows the oscillating currents observed at the other stations. The currents at 50 meters and below were much like those measured during the first anchorage with perhaps a somewhat greater range. The oscillations were more coherent in the second half of the period than in the first. Again the currents at 100 meters were slightly less coherent than at 200 and 300 meters. Currents at 50 meters were, however, just as coherent as those at 100 meters in contrast to the first anchorage. Currents at 200 and 300 meters were those one might deduce from the predicted tide, both in magnitude and phase; that is, up-inlet flow from predicted low water to high water and down-inlet flow from predicted high water to low water. The magnitude was in reasonable agreement with the tidal prism, tide rises and the cross-section at the station assuming that the tidal flow was uniform over the whole section.

Before considering the currents in the upper 20 meters, the wind conditions should be indicated. During this complete period there was an up-inlet wind, with the diurnal cycle, to maximum speeds of 25 knots. Along with this change in wind conditions from the first anchorage there was a change in the character of the currents in the upper 20 meters. The oscillations were more nearly symmetrical about the mean current than before (compare figures 18 (a) and 14 (a)). The mean current is also seen to reverse during about 24 hours in the middle of the period. The oscillations were not those one might expect from the predicted tide, if these are defined as above. The magnitude is to great and there is a 90° phase lag.

The range of current in the longitudinal direction varied with depth. If the range at 2 meters is taken as 100 per cent, then at 4 meters it was 100 per cent, at 6 meters it was 90 per cent, at 10 meters 75 per cent, at 15 and 20 meters 50 per cent and about 25 per cent at 50 meters and below.

The transverse component at depths of 50, 100, 200 and 300 meters (figure 19) was irregular with possibly a larger amplitude at 50 meters than at the greater depths. In contrast to the first period of measurements the amplitude of fluctuations of the transverse (cross-inlet) component was one half or less that of the longitudinal component. This difference between the two periods of observation may be due to the fact that a greater percentage of measurements for the second period had data available to correct for ship motion.

Turning to the hourly profiles (figure 20) of the longitudinal component there is seen to have been a fairly consistent pattern for the first half of the period. Any time during the three hours before predicted high water there appeared a strong flood current from the surface to 20 meters. The water at 200 and 300 meters was in the last stage of flood when this surface flow began. At the same time as this flood took place at the surface there occurred a down-inlet current at 50 and 100 meters. As the predicted tide passed high water the down-inlet current spread to the 200 and 300-meter depths and the surface up-inlet flow deepened to about 50 meters. Midway between high and low water the surface up-inlet flow stopped or reversed to a small dow-inlet flow so that for the remainder of the predicted ebb the whole column was moving down the inlet. There was a fairly consistent flow for the remainder of the predicted ebb at depths of 50 meters and more. During this last period, though, the surface down-inlet currents had speeds from zero to 75 centimeters per second.

During the second half of the period the flow at 50 meters depth and greater followed the above pattern, but in the surface 20 meters the flow deviated from that described above. The up-inlet flow was late and at a greater depth. It also persisted into the second half of the ebb as calculated from the predicted tide heights.

Three 25 hour means are plotted in figure 21. These cover the first, middle and last 25 hour periods. Since there were only 68 hours of observation there is some small overlap of data in these means. In all three profiles there was a significant up-inlet flow at a depth of 300 meters. At 200 meters a net down-inlet flow became significant in the middle and last profiles. At 100 meters there was a marked down-inlet flow in all 3 profiles. At 50 meters the net flow was not significant. At some depth between 50 and 20 meters there was a 'depth of no motion'. It was probably closer to 50 meters. This 'depth of no motion' separated the net down-inlet flow at

100 meters and the net up-inlet flow at 20 meters. The upper boundary of this up-inlet flow cannot be placed too accurately as it appears that the wind has a direct effect on flow down to perhaps 15 meters, thus penetrating to the region of this boundary.

The first 25 hours was a period with a mean up-inlet wind of 14 knots. Here there was still a net down-inlet flow from 2 to 15 meters, though the flow at 20 meters was up-inlet. In the middle profile the average wind had increased slightly and had been blowing for a longer period of time. The flow in the upper 20 meters was all up-inlet although there appeared to be two flows separated by a minimum up-inlet flow at 6 meters.

Turning, then, to the last profile it is seen that the surface flow was down-inlet despite a continuing average wind of 16 knots up the inlet. The maximum down-inlet flow in this last profile was at 4 and 6 meters rather than close to the surface (2 meters) as was noted in the net currents of the first 25 hours.

VI DISCUSSION

Technique:

(1) Design of the experiment:

Primarily this experiment was carried out to determine the general characteristics of the currents in the inlet. For a given amount of time, manpower and instrumentation an optimum programme was designed. A balance was struck between the number of depths of measurement and the frequency with which measurements at one depth could be made. There was the choice of either making frequent measurements at closely spaced depths in some layer of particular interest, or of spreading the number of depths of measurement over the whole column of water. Since a general picture was desired the latter course was taken in the deeper waters. In the surface layer the former course was undertaken for two reasons. It was recognized that water in this layer often showed large variations in current within a small depth. The sharp gradients in water properties appear to be related to these variations. Perhaps the greatest impetus towards the more detailed study of the surface layer was the fact that the C.B.I current drag could provide the information easily and quickly.

In support of the large separation between measuring depths in the deeper water (100 meters at station 5) it may be said that the small and smooth gradient of water properties argues for some uniformity in water movement.

The choice of the stations to be occupied for current measurements and the choice of the position in the width of the channel present two other problems in the experiment design. Station 5 was chosen to give information about the water movement at depth behind the sill. Station $3^1/2$ is the sill position and represents a markedly different inlet characteristic from station 5. With a single ship to cover a whole cross-section of the inlet, it was logical to anchor close to mid-channel. With the choice of a long, straight reach it was hoped that eddy structures or any current pattern showing asymmetry about the inlet centre-line would be avoided. This was not entirely realized. The current data suggests that the ship position was not representing the whole cross-section. In addition, from observations of debris and foam floating on the water, it was found on occasion that the surface currents could be quite different across the inlet. In one instance it seemed that the flow across two thirds of the inlet was one direction while in the other third it was in the opposite direction.

(2) Ship Motion:

In previous data it had been recognized that ship motion might contribute a large proportion of the current meter reading. The 1956 data bears this out – especially for the deep station, number 5.

If the mean speed for ship motion is compared with the maximum half range of currents measured at each station, some idea of its importance can be determined. For station 5 the mean ship speed during current measurements was 7.5 centimeters per second compared with a half range in current of 15 centimeters per second. Here, then, was a mean ship speed that was 50 per cent of the maximum currents measured. Clearly correction must be made and the correction must also be determinded accurately. In the case of station $3^1/2$ more favourable conditions existed which put the mean ship speed at only 4.5 centimeters per second compared with a half range in currents of about 70 centimeters per second. The ship speed, therefore, averaged 7 per cent of the current speed, a factor of 7 better than the correction for station 5.

These two comparisons give rise to three conclusions. First, the Ekman current meter readings at station $3^1/2$ are little affected by ship motion. Therefore the accuracy of determination of the ship movement is not so critical. Also, data taken at this station in previous years can be used with confidence even though no ship movement was determined. Secondly, currents indicated by the Ekman meter on station 5 must be viewed critically. Then it is noted that only 69% of Ekman measurements were corrected for the first anchorage on station 5 compared with 99% on the second anchorage, it is clear that the data for the second anchorage is more reliable. Thirdly, as mentioned in the preceding paragraph, the ship movement at station 5 is a large proportion of the Ekman meter readings. Therefore the accuracy of the currents obtained by correcting the Ekman readings is largely determined by the accuracy with which the ship movement is known. Certainly the accuracy in the ship velocity calculation is much less than the Ekman current meter accuracy. In particular, the cross-stream components of currents at station 5 are in greater doubt than the longitudinal components. For this reason, little significance was placed in individual values or means of the cross-inlet component at station 5.

For the reason just stated it seems advisable to attempt to improve the technique of determining the ship movement when anchored at stations such as station 5. At such a station the speed of ship movement is of the same order as the currents to be measured.

(3) Comparison of Ekman and C.B.I. drag readings at the same depths:

As mentioned in the description of the instruments, it was not advisable to use the Ekman meter above 20 meters depth due to the possible magnetic effects of the ship on the direction indication. Also, the C.B.I. drag was used in currents and depths for which the device has not been calibrated. For these reasons it was deemed advisable to check one device against the other.

While anchored at station $3^1/2$, both Ekman meter and C.B.I. drag measurements were made at 10 and 20 meters. These measurements were not made simultaneously but merely in the regular schedule of operations as outlined in the procedure. That is, a current profile to 20 meters was taken every half hour on the hour with the C.B.I. current drag, and the Ekman meter was used at 10 and 20 meters shortly after the C.B.I. drag current profile taken on the hour.

The plot of both Ekman and C.B.I. drag measurements (the along- inlet component) are shown in figure 22. In general, the peak currents indicated by the Ekman meter were less than those indicated by the drag. Since current in the upper 20 meters is usually unidirectional, it appears that drag on the wire has introduced an appreciable error. That is, the formula based on just the drag on the biplane does not represent the total drag on the system.

The above conclusion was reached from consideration of the time-series plot of the two sets of current data. however, an effect related to this was apparent in another calculation.

In order to determine the mean current profiles,a 25 hourly-value running mean was calculated for currents at all depths. This included both Ekman meter and C.B.I. drag readings separately for the 10 and 20 meter depths where these overlapped. There was a difference in the trend of the means indicated by the C.B.I. drag and Ekman meter measurements (see figure 23). It is seen in the measurements at 20 meters that the trend of the means for the Ekman meter measurements were in opposite directions. Any conclusion as to the depth to which the wind effect had directly penetrated will perhaps hinge on which trend is the correct one.

There is no way in which to carry out any systematic error correction in Ekman meter readings as possible errors recognized cannot be evaluated. The difference between the Ekman meter and C.B.I. drag averages was in a direction indicated by the direction of the mean flow above the particular depth at which measurements were compared. The wire on which the C.B.I. drag is suspended is in this flow above the depth of measurement. There is a drag on the wire due to this flow. If this drag on the wire is significant then the C.B.I. drag measurement means would deviate from the true average in the direction of the mean flow above the depth of measurement. This is the direction in which the means of the C.B.I. drag measurements deviate from the means of the Ekman meter measurements. A correction for this wire drag can be applied to the C.B.I. drag measurements.

A formula directly relating the current at one depth to the angle measured at the surface cannot be simply stated if drag on the wire is significant. This is because the drag on the wire depends on the strength of the current between the surface and the depth of measurement.

The currents given by the equation developed by Burt and Pritchard (1951) were first plotted for each profile, Then a non-uniform grid of rectangles based on an equation developed below, provided a correction to the square of the velocity given by the simplified equation deduced by Burt and Pritchard. This correction was applied every 5 meters to successively correct the profile in 5 meter intervals from the surface down to 20 meters.

The development of the formula on which the grid was constructed is outlined below. First, the equation developed by Burt and Pritchard is reviewed. Referring to the force diagram in figure 5.

$$\tan \theta = F/W \qquad (1)$$

where F is the drag force on the biplane, W is the weight of the drag in water and θ is the angle measured at the surface. Now,

$$2F = C_{dp} A \rho v \qquad (2)$$

where C_{dp} is the drag coefficient of the biplane, A is the area of the biplane, ρ is the density of the fluid and v is the actual velocity at the depth of measurement. Hence the velocity, V, given by consideration of only the drag on the biplane is,

$$V = (2W/C_{dp} A_p \rho)^{1/2} (\tan \theta)^{1/2} \qquad (3)$$

This is not the actual velocity because the drag on the wire has not yet been considered.

In considering the drag force on the wire, there is added to F another force N, given by,

$$2N = C_{dw} \rho d \int_0^h v_z^2 \, dz \qquad (4)$$

where N is the force due to the drag on the wire, C_{dw} is the drag coefficient of the wire, d is the diameter of the wire, h is the depth of measurement and z is depth measured downward from the surface. Only the vertical projection of the wire, perpendicular to the current, is considered here.

Then as far as the angle measured at the surface is concerned the angle is given by the balance of T, W and F plus N. Hence,

$$\tan \theta = \frac{F + N}{W} \qquad (4)$$

Substitution of equations (2) and (4) into equation (5) produces,

$$\tan \theta = \frac{C_{dp}\, A \rho\, v^2}{2\, W} + \frac{C_{dw}\, \rho\, d}{2\, W} \int_0^h v_z^{\,2}\, dz \qquad (6)$$

Now θ was the angle measured and is related to V by equation (3). Therefore,

$$\frac{C_{dp}\, A \rho\, V^2}{2\, W} = \frac{1}{2W} \left(C_{dp} A \rho\, v^2 + C_{dw}\, \rho\, d \int_0^h v_z dz \right)$$

$$\therefore \quad V^2 - v^2 = \frac{C_{dw} d}{C_{dp} A} \int_0^h v_z^{\,2} dz$$

This equation provides the correction. The-drag coefficient for the 3/32 inch, stranded, steel wire used is not precisely known. However, it is known that for currents of the magnitude measured the drag coefficient for a smooth cylinder is between 1.0 and 1.1. The fact that the steel wire was stranded and therefore rougher may indicate a slightly higher drag coefficient. Lacking exact measurements, the value was put at 1.2 for the purpose of calculations. This is the same value as that used for the biplane.

This correction was carried out for the C.B.I. drag measurements and the results are shown in figure 23

There still remains some discrepancy between the Ekman averages and the corrected C.B.I. averages, though agreement is considerably improved. Other errors can possibly account for these discrepancies.

It is possible that the drag coefficient for the wire may be appreciably different from 1.2 . Weights are added to the drag and the area which they present to the current is not considered. A twenty pound weight has a cross-section of 97 square centimeters compared with 1,390 for the biplane. This is a possible 6% error.

Lift on the wire has also been neglected. It has a tendency to reduce the weight, W. An estimate of this error can be made considering an average angle measurement of 30° for measurements at station $3^1/2$. Assuming a uniform velocity from the surface to the depth of measurement the lift is found to be about 7% of the weight of the drag.

Currents.

(1) Station $3^1/2$

Currents at all depths at station $3^1/2$ showed an oscillating component superimposed on a mean flow. These oscillating currents were of the same range at all the depths of measurement with the possible exception of the depth nearest the bottom, where insufficient data provides room for uncertainty.

The oscillating currents showed peaks at times midway between predicted high and low water and, apart from net flow, showed slack water or zero current near times of predicted high and low water. These facts are strong evidence that flow at the sill is typical of channel flow and that the oscillating currents are due primarily to the rise and fall of the tide in the inlet. Further evidence for this last statement will be presented below in the discussion of transport through the section.

The general characteristics of the mean flow on which the oscillating currents were superimposed did not remain the same throughout the period of observation. Large changes took place as indicated in figure 13. In comparing the first and last 25 hours of the anchorage, significant changes are seen to have taken place at all depths except 10 and 15 meters, the flow was completely reversed, changing from down-inlet to up-inlet. This change is attributed directly to the wind stress exerted at the surface.

At 20 meters and all greater depths the change in flow was in a direction opposite to the change in surface layer. It appears that this may be an indirect effect of the wind stress. The magnitude of the change at depth is sufficient to compensate for the flow reversal in the surface. Further evidence pointing to these changes at greater depths, as an effect related to the wind, is the fact that the marked change in the flood current noted at 40 meters was highly correlated with the onset of the wind.

There is no obvious reason why this marked change in the character of the flood current should take place at 40 meters. The net currents at the greatest depths (40, 60 and 70 meters) changed in the same direction with a slightly larger change at 40 meters. Thus, although the effect at 40 meters was more noticeable, the change in the net current is comparable at all 3 of these depths.

From this period of observation it appears that there is inflow at the bottom and outflow at mid-depths. In the surface the mean current is down-inlet when there is no wind but can be reversed if a strong up-inlet wind is blowing.

When one considers the net flow deduced from the salinity structure in the inlet, it is seen that the observed net flow distribution with depth is not the same. From the salinity structure it was deduced that outflow must take place in the low salinity upper layer and inflow at some depth below this. The point at which this and the observed net flow diverge is in the fact that outflow persists down to a depth of 45 to 50 meters -- well below the low salinity upper layer. It is quite possible that the mean flow in this region near the sill, is not primarily determined by the density distribution, but more by the jet effects of a constricting cross-section and attendant amplification of tidal currents.

Topography may also influence the flow in this region. The discussion so far has dealt with only the along-inlet components of the current. However, there are large cross-inlet components of the current which, when averaged, indicate new flow towards the side of the inlet. The best demonstration of this feature is in the mean directions of the flood and ebb at the depths of 10, 20, 40, 60 and 70 meters (see table in description). The current directions on flood and ebb do not differ by 180°. Ebb directions at all depths lay between 271 and 286° true. At 10 meters on the flood it was very close to 104° (i.e. 180° different) but at 20 and 40 meters it was 125° and at 60 and 70 meters it was about 135° true. There is an increasing southward set of the flood current as the depth increases. The slight northward set of the ebb currents was consistent with the southern shoreline of the inlet from the east to Prominent Point (see figure 4).

The topography may explain the southward set of the flood currents and possibly its variation with depth. The axis of the outer basin is inclined to the axis of the inner basin A current flowing up-inlet in the outer basin region is partially trapped in the shallow of Hoeya Sound and Lull Bay (see figure 4). Water escaping from this region must flow around Boulder Point with a southward component. This would deflect the flood currents to the south.

There was a big difference between flood current directions in the first and last 25 hours at depths of 20 and 40 meters. At 20 meters it changed from 125° to 103° true. Thus it was aligned parallel to the current direction at 10 meters in the last 25 hours. This could possibly be an indication that the wind stress at the surface has a direct influence to a depth of 20 meters. The change in the magnitude of the mean current between the first and last 25 hours indicated a nearly significant change in the direction opposite to that of the wind stress, which would seem to contradict the above statement. However, the mean current applies to a complete tidal cycle, while the angles were calculated only from either the flood or ebb current velocities. It is possible that the wind stress could penetrate deeper during currents which were parallel to it (flood in this case) than during currents which opposed it.

At 40 meters the change in the flow is marked in the direction of the flood current as well as in the increase in magnitude of the mean flow down the inlet. Both of these appear to be due to only one phenomenon, a decrease in magnitude of the longitudinal component of the current on the flood. This means that the effect was probably not an intensification of the southward set of the flood, but another effect directed down-inlet along the axis of the inner basin to the west and operating only during the flood period. There is no obvious explanation for this type of effect.

(2) Station 5:

As at station $3^1/2$, the currents were characterized by an oscillating current superimposed upon a mean current. At this station, however, the currents were not nearly as regular. The magnitude of the oscillating currents at 50, 100, 200 and 300 meters were only one quarter the magnitude at 2 meters. The currents at different depths did not occur with the same phase. In general there appears to have been two differing regions, surface and deep, separated by a broad boundary region from 20 to 100 meters. The confused nature of currents at 50 meters may be due to the fact that this depth is in this transition region. As noted in the description, the currents at 50 meters were of the same magnitude as those at greater depths, but did not show any systematic oscillating component.

The deeper region will be dealt with first. The following comments apply to currents at 300 and 200 meters, and to a lesser degree to those at 100 meters. At these depths the currents were oscillatory and superimposed on a very small net current. The slack water coincided with predicted high and low tide, suggesting that these currents were caused by tidal forces. Further support for this idea is found in the magnitude of the oscillating currents. These magnitudes are in agreement with tidal currents calculated assuming lateral uniformity and

and uniformity with depth for tidal flow to fill or empty the inlet according to the predicted tide heights.

Turning to the upper layer, there was found to be an oscillating current, but the current had a range at 2 and 4 meters four times larger than the tidal currents calculated as above. The range in the oscillating currents decreased with depth. These oscillations were not in phase with movements at depth, but did occur in a systematic fashion related to the predicted tide heights. Whatever mechanism or mechanisms were present to cause the flow in the surface layer, there was certainly a strong component with a tidal period.

The vertical profiles of the net currents show three consistent features that are distributed in depth and may be related to the two flow regimes of oscillatory currents. Starting at the surface there was found to be outflow except when a strong up-inlet wind was blowing. There was inflow below this surface layer extending to below 50 meters and at 100 meters there was a down-inlet flow that slowly but steadily increased over the course of the week of measurements.

The first two have an explanation as described in the introduction. The runoff must escape in the surface layer and the return (up-inlet) flow of salt water below this apparently extends just to about 50 meters. The average transport for the two periods of current measurements for depths down to 50 meters, is distributed as follows:

Fresh water in the upper 10 m.	-	600	cu.m./sec, down-inlet
Salt water in the upper 10 m.	-	1700	" " " " "
Salt water at 10 to 50 m.	-	1200	" " " up- inlet

It is seen that there was not strict balance of salt water. There was, however, a lack of adequate coverage by measurements at depths between 20 and 50 meters where a large part of the up-inlet moving salt water appeared to be. It is felt that errors due to linear interpolation between these points may easily account for the apparent unbalance of salt.

There is no explanation for the well developed down-inlet flow observed at 100 meters. It can only be pointed out that this flow was correlated with a complete change in the wind stress at the surface, from down-inlet to up-inlet. There was also a correlation with the transition from neap to spring tides.

(3) Tides and tidal currents,

No tide stations were set up in conjunction with these current measurements. For this reason currents have been related to the predicted tide at Alert Bay. Comparison of the actual tide record at Alert Bay with the predicted tides shows excellent agreement.

Previous studies in inlets have shown virtually no time lead or lag in the tidal rise along the whole length of an inlet, though there may be a difference in the tide range (Dawson, 1920). This study is reflected in the present tide tables which give no time difference between Alert Bay and Glendale cove (see figure 2 for its position) and a mean ratio of rise of 1.15 for high tides. For these reasons it is felt that any current that is primarily tidal in character will be directly related to the rise and fall of the tide as predicted. This was the case at all depths of measurement at station $3^1/2$ and at the greater depths at station 5. A significant result of these experiments was the discovery of tidal currents well below the depth of the inner sill (67 meter sill depth) in the inner basin.

The currents at station 5 in the 20 meter surface layer appear not to have been a direct effect of the rise and fall of the tide in the inlet if the assumption of cross-section uniformity of tidal currents is correct. They were out of phase with the calculated tidal currents, though the variations were systematic and had a tidal period. Estimates have been made of the depth of tidal influence by only considering the amplitude of currents at the surface (Trites, 1955). This data suggests that this is not a valid procedure at such stations as Knight 5.

There is the question of whether tidal currents should be a smooth function of time. Tide height curves appear to be smooth in most cases, but tidal currents, (the rate of the change of tide height curve) are not necessarily so. A check was made of the slopes of the actual tide records for this period of observations. The smallest time interval over which a slope could be accurately obtained was 10 minutes and even with this 10 minute slope it was evident that tidal currents are not smooth functions of time and certainly do not adhere to a sinusoidal curve . Peaks tend to be flattened and " slack water" is a period of sharp current bursts. The data show this clearly, especially the data taken half-hourly with the C.B.I. drag (see figures 10 (a), 14 (a) and 14 (b)).

(4) Wind Effects:

There were long periods of wind during all three anchorages. It is obvious from the vertical profiles of net currents that the wind stress had a large direct effect on the surface currents. The flow of water at the surface was both accelerated and impeded - even reversed- during the period of these observations. Reversal of the surface current is shown in a comparison between the first and last 25 hours on station $3^1/2$ (figure 13) and between the first and middle 25 hours of the second anchorage on station 5 (figure 21). The acceleration of near-surface flow is clearly shown in the period of down-inlet wind (first 25 hours) on the first anchorage at station 5 (figure 17).

A comparison of the net currents at the surface in the middle and last profiles for the second anchorage at station 5 shows a limit to which wind can affect surface currents. Apparently between these two periods the flow near the surface has returned to the down-inlet direction despite the fact that a strong up-inlet wind was still blowing. Here is evidence that the wind stress can only reverse surface flow for a limited time. It appears from the data that there was a pressure gradient built up within 30 hours to balance the wind stress due to an average wind of 16 knots.

The data suggests that the depth of direct influence of the wind can be quite variable. When the magnitudes of mean currents are considered, it is found that the wind appears to have had a direct influence down to only 6 meters at station $3^1/2$. Current direction data at the same station suggests that this direct effect may have penetrated to 20 meters, though the change in magnitude of mean current at this depth, if significant, was in the opposite direction to the wind stress. Since the direction data was obtained by considering flood and ebb currents separately and the mean currents in a 25 hour period, the apparent contradiction may not exist. It seems possible that the wind stress could have had an influence to a greater depth on the flood than on the ebb. This could be due to a change in the water structure (density gradients) with the state of the tide. Turning to data from station 5, there is seen to be large direct effects down to at least 20 meters. The reason for the difference between stations $3^1/2$ and 5 is likely the difference in water structure at the two stations.

There is evidence for indirect effects of the wind stress. Some flows, such as those at 40 meters on station $3^1/2$ and at 100 meters on station 5 underwent changes that were correlated with changes in the wind stress at the water surface. The change in the flood flow at 40 meters on station $3^1/2$ is thought to be strong evidence for indirect influence of the wind. The flow at 100 meters on station 5 is not considered to be as strong evidence for this phenomenon. If flows at these depths were influenced by the wind, it appears that the flows were of a compensatory nature. That is, they changed in the direction opposite to that of the change in the wind.

(5) Hourly Transports:

The hourly current profiles obtained were used to calculate a transport through the inlet cross-sections at the stations. The assumption of lateral uniformity was made in order to calculate this. This is related to the assumption made in calculating tidal currents. In the latter case it was assumed that the tidal current would be uniform across the whole section. Then the hourly profiles plus the best cross-section profile obtainable (see figure 3) provided an estimate of the transport at every hour. A table method was used to calculate the transport from the currents at the particular depths. Linear interpolation between observed currents is implied in this method.

The results for all three anchorages are shown in figure 24. In addition to the observed points there is plotted a solid line denoting a calculated transport with which to compare the observed transports. This calculated transport was determined from the predicted tide heights, the tidal prism, and assuming that the tidal current was uniform across the section and that it varied sinusoidally. There has been support for these assumptions in the magnitude of oscillatory currents observed (see discussion of tides and tidal currents above) and there is further support for them in the observed transports at station $3^1/2$. Observed transports at station 5 do not support the above assumptions.

The figure shows a difference in agreement of observed and calculated transports between data at station $3^1/2$ and 5. For station $3^1/2$ there was very close correspondence between calculated and observed transports. This is interpreted as a reasonable assurance that currents near mid-channel at station $3^1/2$ are representative of the total cross-section. The irregularities that showed in the currents at individual depths were not evident in the observed transports. This is due to averaging over the whole water column.

The transports at station 5 are far from agreement with the calculated curve. Periods of flood and ebb can be recognized, but that is about all. The variation is not sinusoidal and shows large fluctuations. This is taken as evidence that flow across the section is not laterally uniform. There may have been concentrations of the current (to one side of the inlet or at some particular depth) within the cross section.

There has been some further evidence for both lateral uniformity and lateral non-uniformity in surface currents. Experiments with photography of lines of dye stretched across inlets (Pickard,1953) have shown a full range of conditions. Some results show a fairly uniform flow across the inlet with the exception of regions close to shore. In other instances small, localized jets have appeared. The latter could complicate transport calculations based on current measurements taken at just one position in the inlet.

If current measurements are taken in one position in the inlet there is considerable doubt whether they will be representative of currents to either side of that position. It has been noted that there were large lateral movements of the ship, encompassing about one quarter of the width of the inlet, during the second anchorage on station 5. It is therefore possible that the ship was moving in and out of current patterns. The attendant complications in the interpretation of current measurements are obvious.

(6) Fresh Water Transport:

An estimate has been made of the fresh water transport in the surface layer from the net currents and the fresh water portion of this layer. Data from both stations were used. Seven 25-hour periods were chosen respresenting the entire duration of the current measurements with as little time overlap as possible. It was found that the mean fresh water transport was 310 cubic meters per second down-inlet although it varied from 2000 cubic meters per second down-inlet to 1000 cubic meters per second up-inlet depending on the duration and direction of the wind stress.

This net fresh water transport should represent approximately the river flow into the inlet unless there is a deepening of the brackish surface layer. It is not believed that such a deepening can take place over any great period of time as evidenced by the rapid return of outflow near the surface at station 5 (second anchorage) despite a strong contrary wind.

Estimates of a mean monthly transport of fresh water into the inlet have been made (Pickard and Trites,1957). These are based on precipitation and watershed data. The values given in this paper are:

June: 27.8×10^3 cu.ft./sec. (790 cu.m./sec)
July: 21.7×10^3 " " " (615 " " ")

It is to be noted that these are mean monthly values, and daily or weekly values could differ appreciably from these. It is felt that the value of 310 cubic meters per second obtained, is in reasonable agreement with these figures.

(7) Net Transport:

The only net transport to be expected through any section of the inlet is the fresh water component of the surface layer. As noted in the previous section, this was about 300 cubic meters per second down-inlet when calculated from just the fresh water component of the surface layer. The net transport through the whole column should just equal this 300 cubic meters per second with the transports of salt water at various depths cancelling each other.

Under the assumptions made in the transport calculations it was found that the net transport did not equal the fresh water component of the surface layer transport. At both stations there was calculated a down-inlet transport in every 25 hour period. At station $3^1/2$ it was 3,700 cubic meters per second and at station 5 it was 8,500 cubic meters per second. The net transport is in the right direction, but is an order of magnitude greater than the fresh water transport.

If these values were true values, the water level in the inlet would have fallen at the rate of 2 to 3 meters per day. However, it has already been remarked that the assumptions under which these transports were calculated are in doubt.

There is the question of just how significant this net transport was in terms of the accuracy of measurements and the assumptions made in the calculations. It should be noted that despite the fact that the net transport calculated above is 10 to 20 times the fresh water transport, the net transport itself is only one tenth of the average transport required to fill or empty the tidal prism during a flood or ebb.

Nonetheless, the net transport calculated was always in one direction and it is felt that it may have been significant. Realizing that it was based on currents measured in mid-channel, two possible explanations for this net transport are suggested. It may have been that the ebb flowed preferentially in mid-channel, and the flood at the sides. There may also have been a horizontal closed circulation with its down-inlet portion in mid-channel.

At station 5, it is seen that the net flow developed at the 100 meter depth is sufficient to account for the net down-inlet transport. If the cause for this flow could be determined, the problem may be solved.

(8) Internal Waves:

One feature of the inlets which has been noted on several occasions is the existence of internal waves or waves at density discontinuities in the water structure. Alternating bands of slick and ruffled water surface observed moving up an inlet have been observed (Pickard,1954) and explained as a progressive internal wave travelling on the sharp density gradient at 10 to 15 meters which is present in these 2-layer inlets.

There is some evidence to suggest that internal waves are also present at greater depths. During this set of current measurements, bathythermogram casts were made regularly to a depth of 270 meters at station 5. From these it appears that isotherms oscillated vertically with a tidal period. In particular there was a temperature minimum which oscillated between the 75 and 150 meter depths. The minimum is thought to be the residue of severe winter cooling (G.L. Pickard, private communication). This series of bathythermograms is, at present, the subject of a separate study. The oscillation of these isotherms may be due to internal waves.

The existence of internal waves may explain one feature of the net current profiles. This feature is present in the mean current profiles for the first 25 hours on station $3^1/2$ and for the first 25 hours on station 5 (first anchorage) which are shown in figures 13 and 17. In the surface layer at station $3^1/2$ there was a minimum at 4 meters and a maximum at 15 meters in the down-inlet flow. At station 5 the minimum was at 10 meters and the maximum at 15 meters. This feature has been noted before in current measurements taken at station 4 in Knight Inlet (Trites,1955). This pattern of a minimum and maximum can be regarded as either a minimum alone, a maximum alone, or both a minimum and maximum superimposed on a net current which monotonically decreases with depth. There is no way of differentiating between these possible interpretations.

A simplified picture of an internal wave will demonstrate the possible effects of internal waves on current measurements. In the first instance, for progressive internal waves of finite amplitude there is a small transport of fluid in the direction in which the wave travels. The second effect is an apparent net flow in the direction of wave travel when current measurements are taken at a depth between the crest and trough of an internal wave which persists over any great percentage of the time.

The second effect is the one considered here. In figure 25 is shown an internal wave at a density discontinuity. It can be seen that measurements taken continuously at level A will show a net flow in the direction in which the wave is travelling. It must be emphasized that this is just a simple presentation. The effect of a density gradient (which is the usual case in an inlet) rather than a sharp density discontinuity, is that there will be several modes of oscillation possible. A complex situation could develop in reality.

Applying this to the net current profile, and in particular to the minimum and maximum near the surface, it seems possible that these may be due to internal waves in the boundary between the brackish surface layer and the denser sea water below. The fact that strong internal waves observed (by the slick and ruffled bands) have been moving up the inlet may suggest that the minimum in the down-inlet flow is the apparent flow due to a progressive internal wave.

VII CONCLUSIONS

The character of currents at all depths of measurement was that of an oscillating current or a fluctuating current superimposed on a net current. There is reason to believe that the oscillating component at all depths at station $3^1/2$ on the sill, and at 200 and 300 meters at station 5 in the inner basin was determined primarily by tidal forces. The combination of forces producing the flow at the surface at station 5 is undetermined but did contain a period related to the tide.

The wind stress exerted at the surface has a large direct effect on surface currents to at least a depth of 10 meters, and possibly to 20 meters or more. It is recognized that this depth of penetration may depend on the density structure of the water and its changes with position and state of tide.

There is also evidence that there may be indirect influences of the wind as it affects deeper flows. These flows appear to be of a compensatory nature.

In regions such as that at station $3^1/2$ it is recognized that bottom topography and an irregular shoreline may have a large effect on the direction and strength of currents.

There is reason, from the results of transport calculations, to think that there is lateral non-uniformity of currents across an inlet. The fact that the net transport was found always to be directed down-inlet for these mid-channel stations suggests that the lateral non-uniformity may be systematic in origin.

The values obtained for the net fresh water transport down the inlet are in good agreement with monthly means determined independently from precipitation and watershed data.

VIII RECOMMENDATIONS

The above conclusions about currents and the problems encountered in the interpretation of current measurements, as well as comments made about the technique, lead to recommendations for future work. These recommendations are made primarily to help reduce errors in measurements and to provide more information with which to interpret the current data.

Despite the fact that monitoring of the ship motion gives a correction for currents measured, it still seems advisable to attempt to use a multiple anchoring scheme if the time and equipment are available. The large possible error in the correction current plus the fact that the correction current (ship's speed) may be a large proportion of currents measured are the reasons why it is felt that multiple anchoring should be undertaken whenever possible.

If there is the manpower available there are several observations that could be made to facilitate the interpretation of current measurements. A tide gauge should be placed on the shore near the ship position. If possible, there should be more of these placed at various positions in the inlet.

One person in charge of a cutter or other small boat could carry out surface current measurements across the width of the inlet to determine if the flow is uniform across the inlet or not. Often the structure of the water near the surface is of interest when surface current measurements indicate the accumulation of fresh water in the inlet. Subsequent deepening of the surface layer and the location of such a deepening could be determined by measurements taken from a small boat.

There is, of course, the possibility of a multi-ship operation (apart from use of a ship's cutter). Both additional simultaneous current stations across one section of the inlet, and simultaneous oceanographic data for dynamic studies would provide considerably more information about currents and their distribution.

Instrumentation can be improved. Notably, use of a deck-reading current meter would cut down time requirements, thus providing a more detailed and more nearly synoptic picture. From the calculations of drag on the wire of the C.B.I. current drag, it is obvious that the smallest wire possible should be used to improve accuracy at the depth at which it has already been used, and to make it possible to use the drag at even greater depths.

The marked influence of wind stress on surface currents suggests the necessity for more detail concerning wind factors. Frequent wind measurements at two or more heights above the water surface would facilitate calculations of wind stress.

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———————. 1954. Oceanography of British Columbia inlets. III, Internal waves. Prog. Rep. Pacific Coast Stations Fish. Res. Bd. Canada, No.98, pp. 13 - 16.

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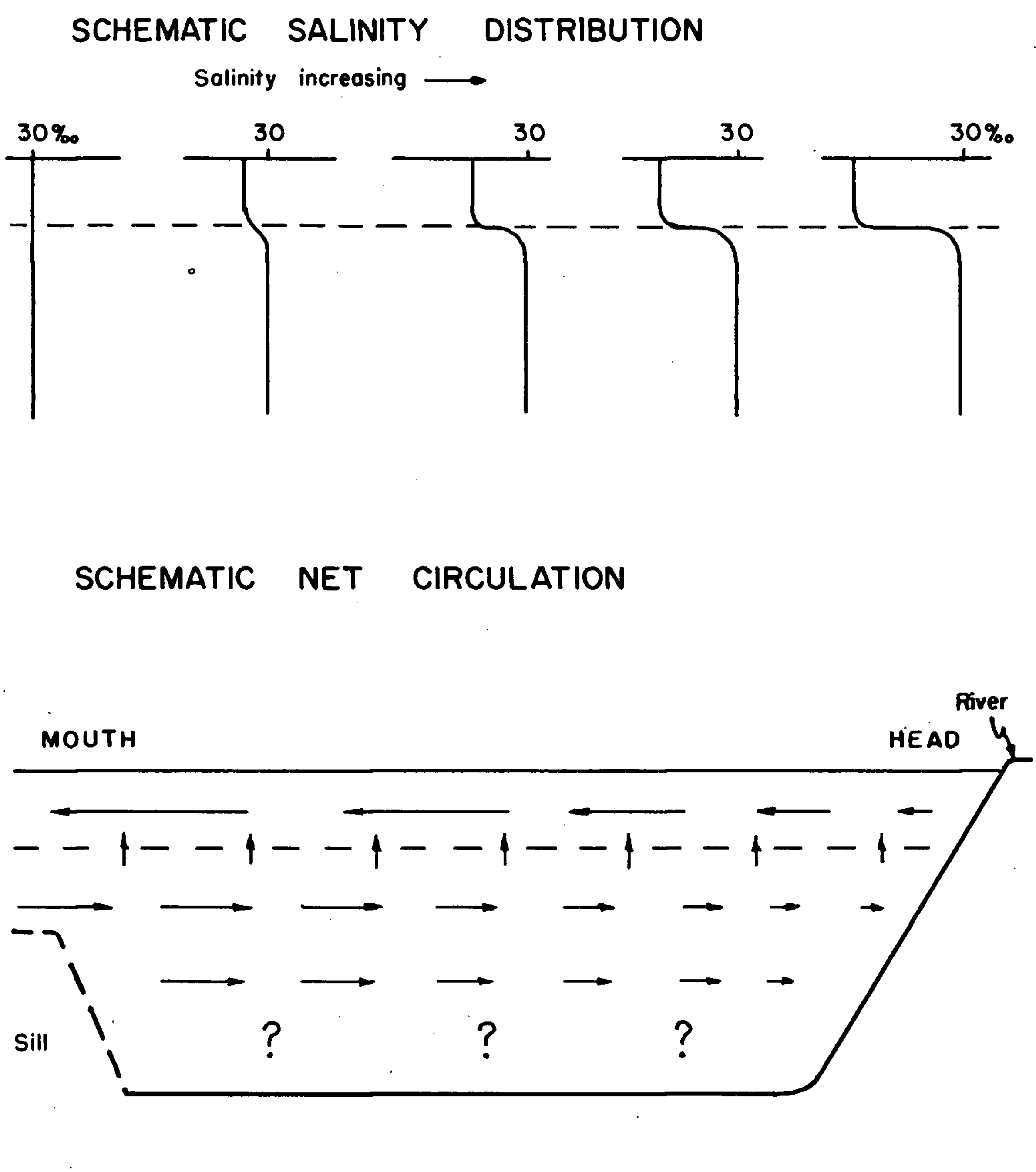


SCHEMATIC REPRESENTATION OF THE SALINITY DISTRIBUTION AND CIRCULATION IN AN INLET

Figure 1

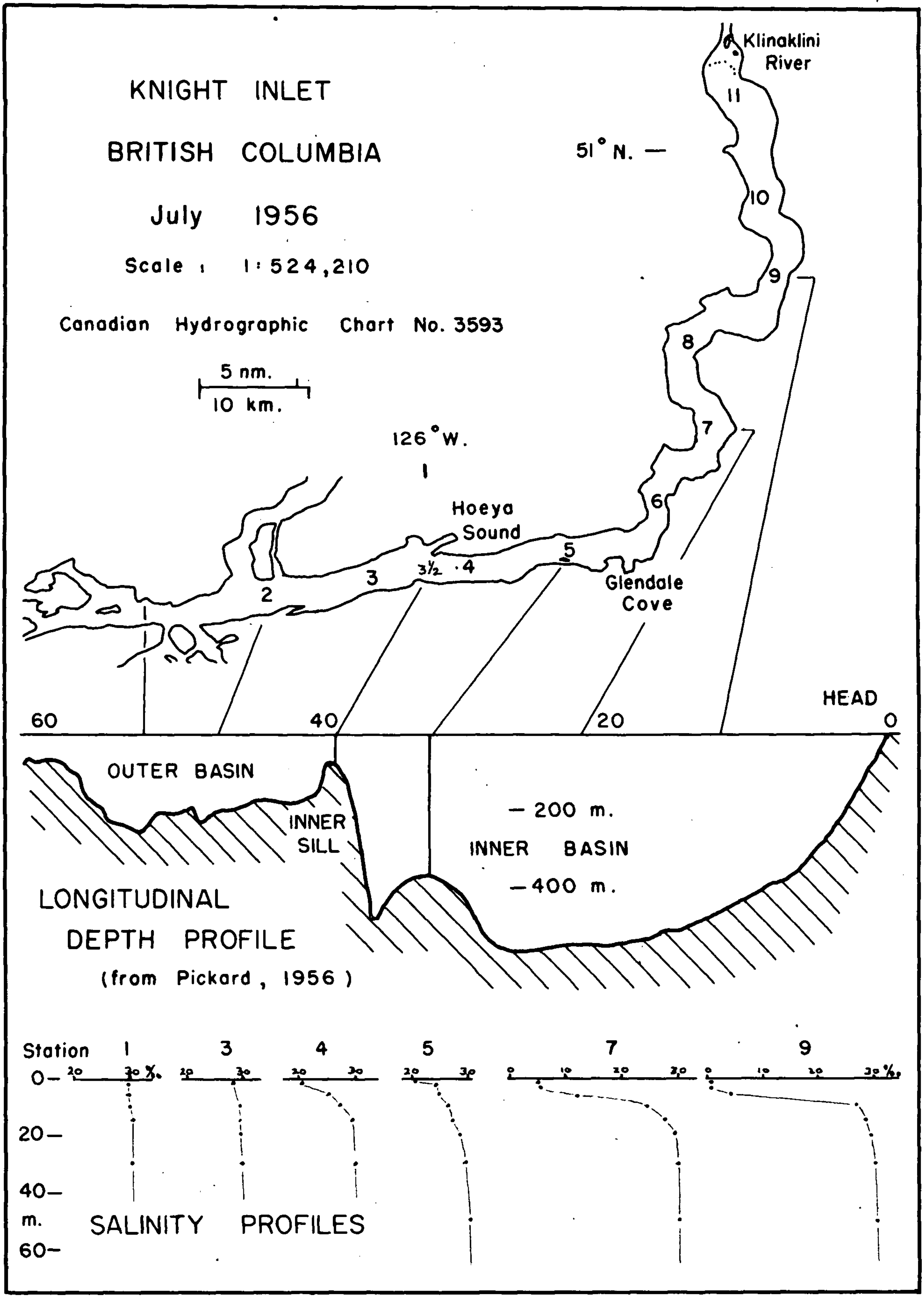
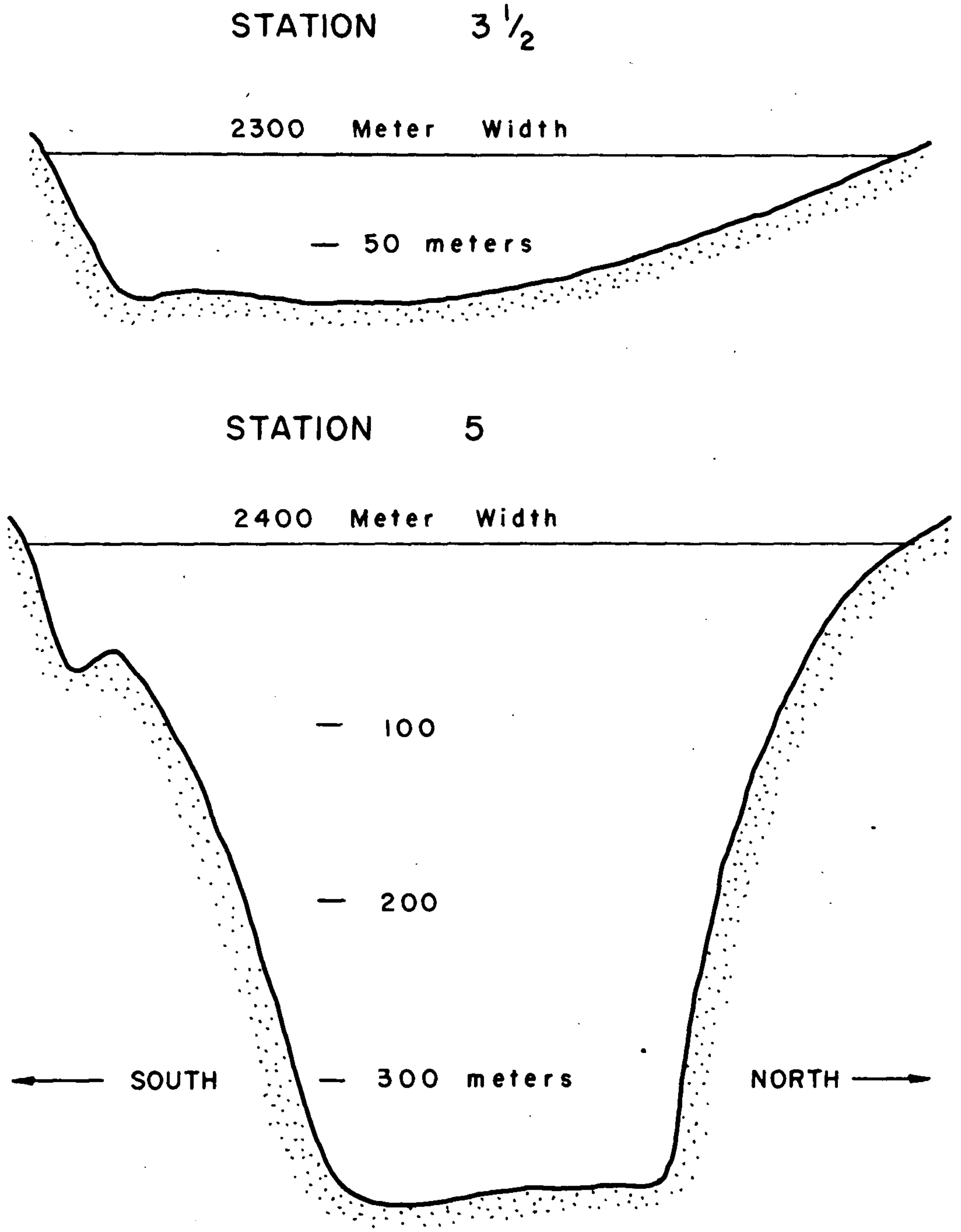
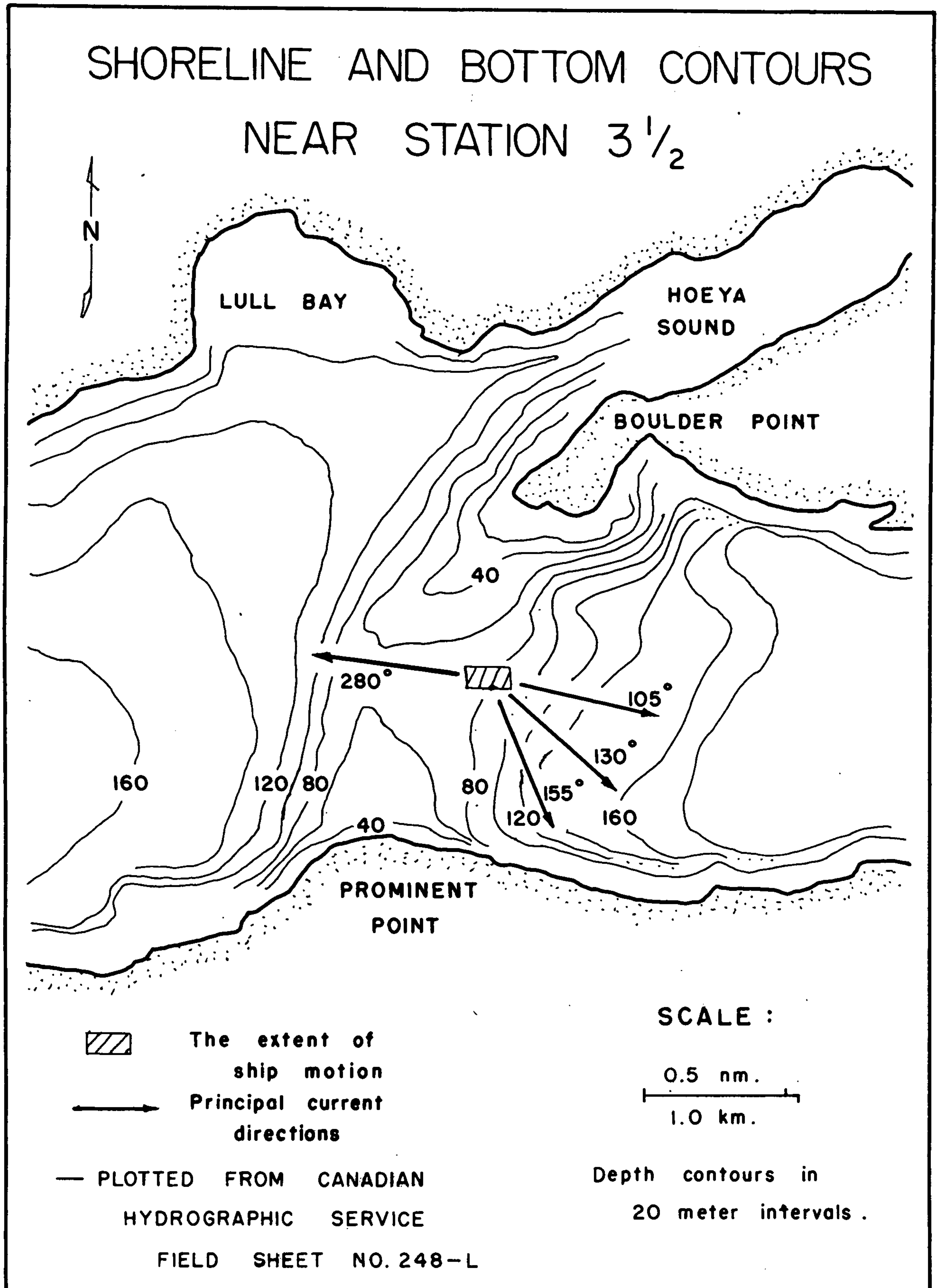

KNIGHT INLET
BRITISH COLUMBIA
July 1956
Scale : 1:524,210
Canadian Hydrographic Chart No. 3593
5 nm.
10 km.
126° W.
51° N.
Klinaklini River
Hoeya Sound
Glendale Cove
1
2
3
3½
4
5
6
7
8
9
10
11
60
40
20
HEAD
0
OUTER BASIN
INNER SILL
INNER BASIN
— 200 m.
— 400 m.
LONGITUDINAL DEPTH PROFILE
(from Pickard, 1956)
Station
0
20
40
m.
60
SALINITY PROFILES

Figure 2



TRANSVERSE SECTIONS AT THE CURRENT STATIONS

Figure 3



SHORELINE AND BOTTOM CONTOURS
NEAR STATION 3 1/2
N
LULL BAY
HOEYA
SOUND
BOULDER POINT
40
280°
105°
130°
155°
160
120
80
80
120
160
40
PROMINENT
POINT
The extent of
ship motion
Principal current
directions
— PLOTTED FROM CANADIAN
HYDROGRAPHIC SERVICE
FIELD SHEET NO. 248-L
SCALE :
0.5 nm.
1.0 km.
Depth contours in
20 meter intervals.

Figure 4

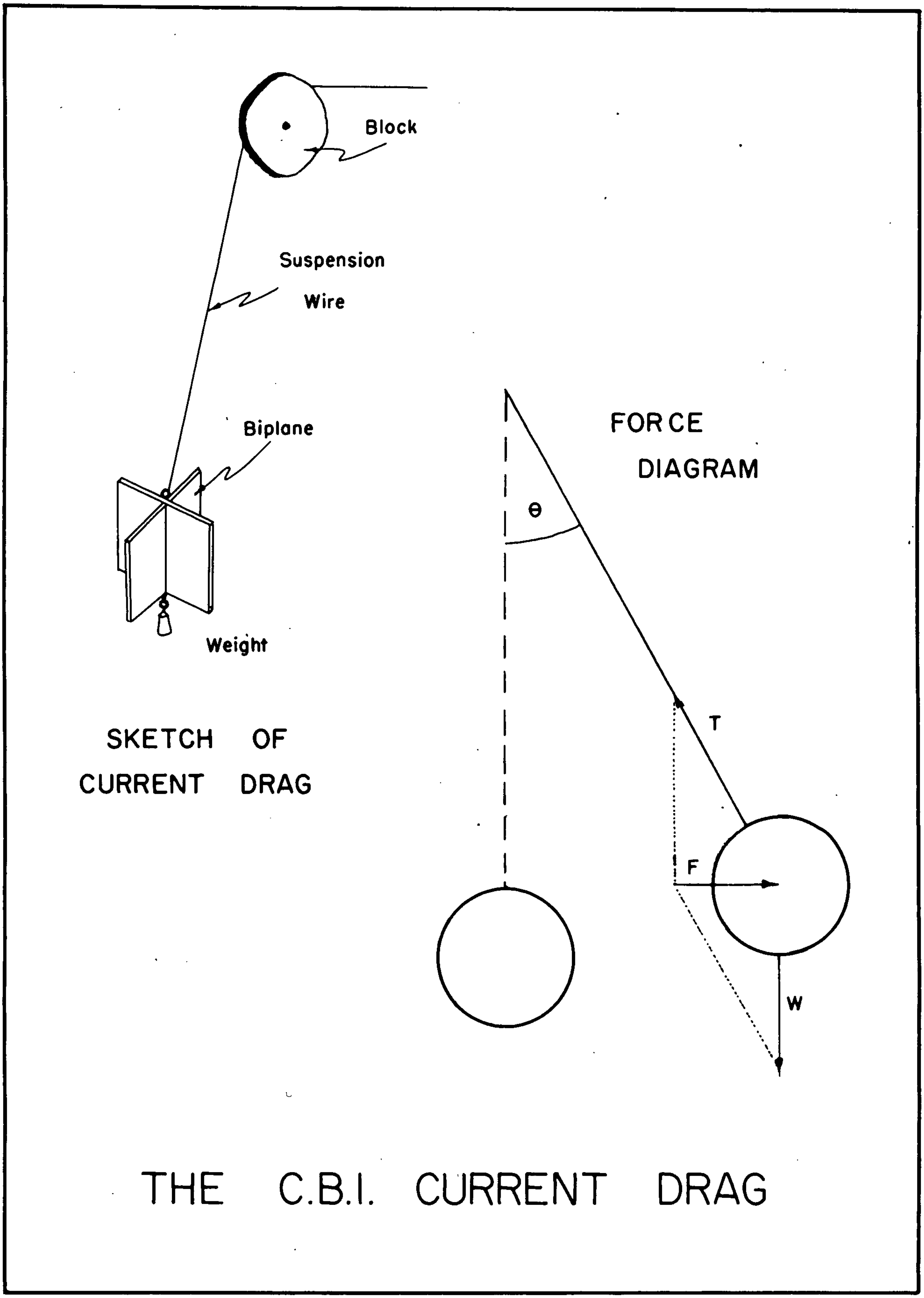
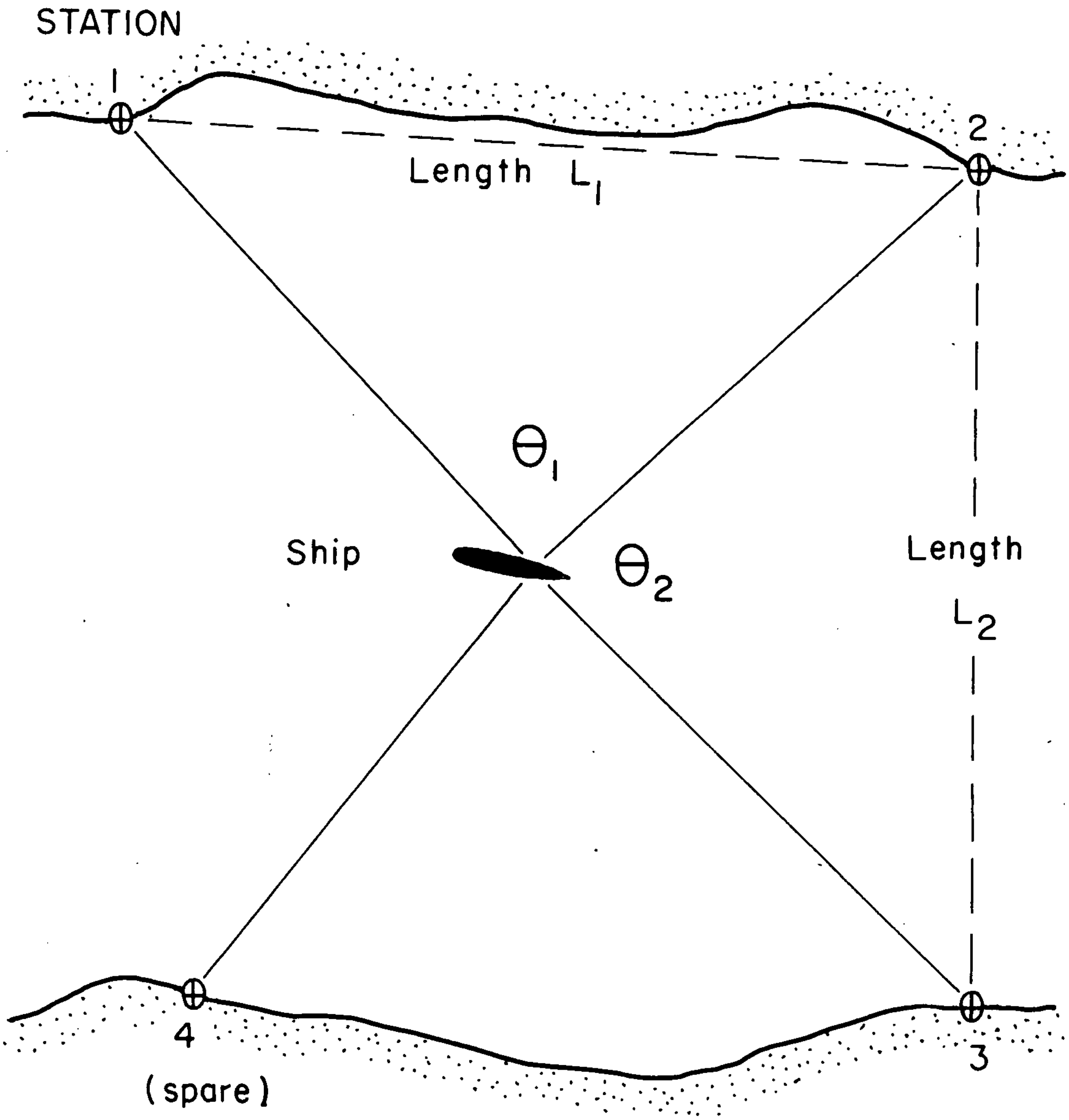
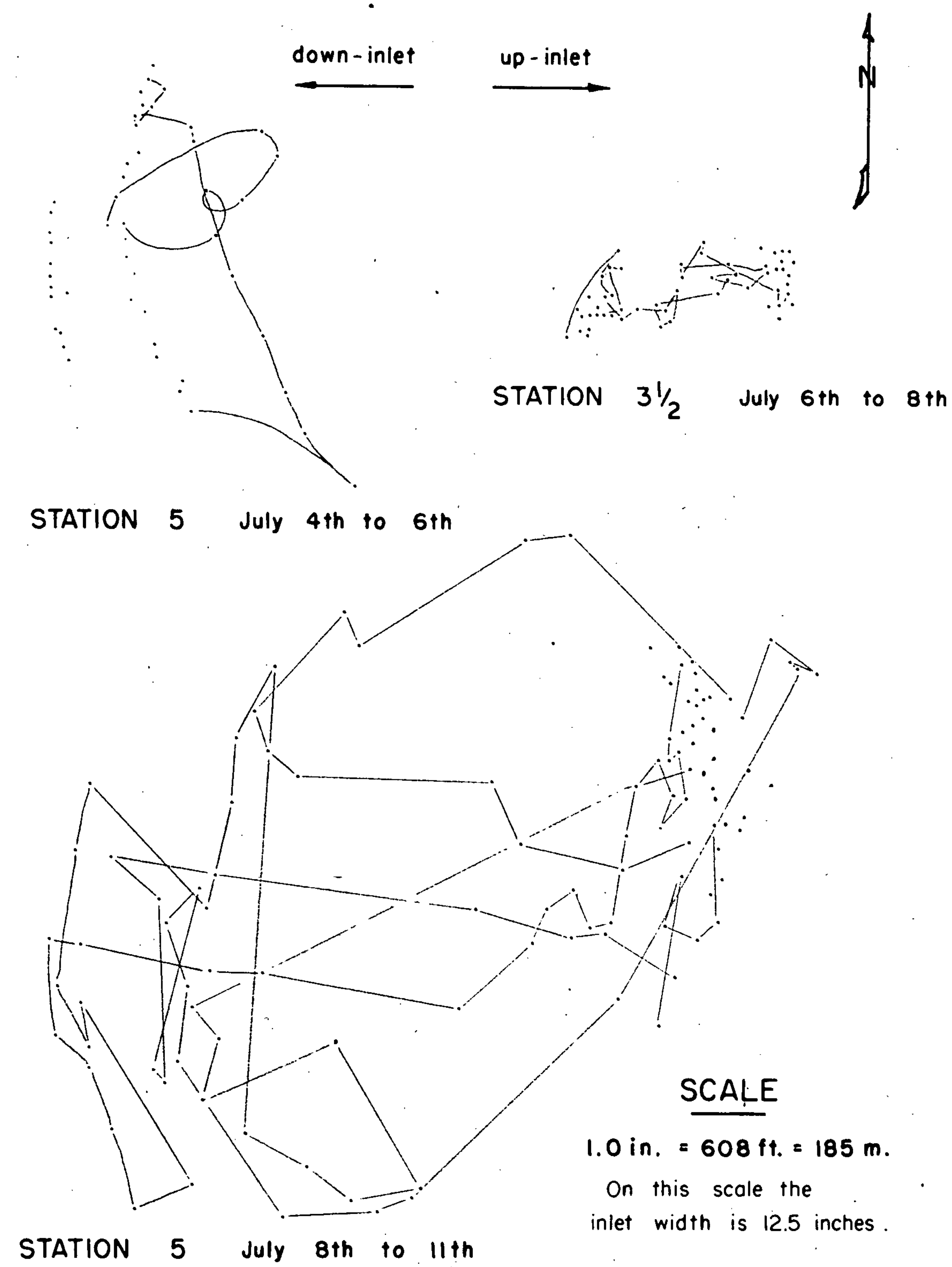

Block
Suspension
Wire
Biplane
Weight
SKETCH OF
CURRENT DRAG
FORCE
DIAGRAM
θ
T
F
W
THE C.B.I. CURRENT DRAG

Figure 5



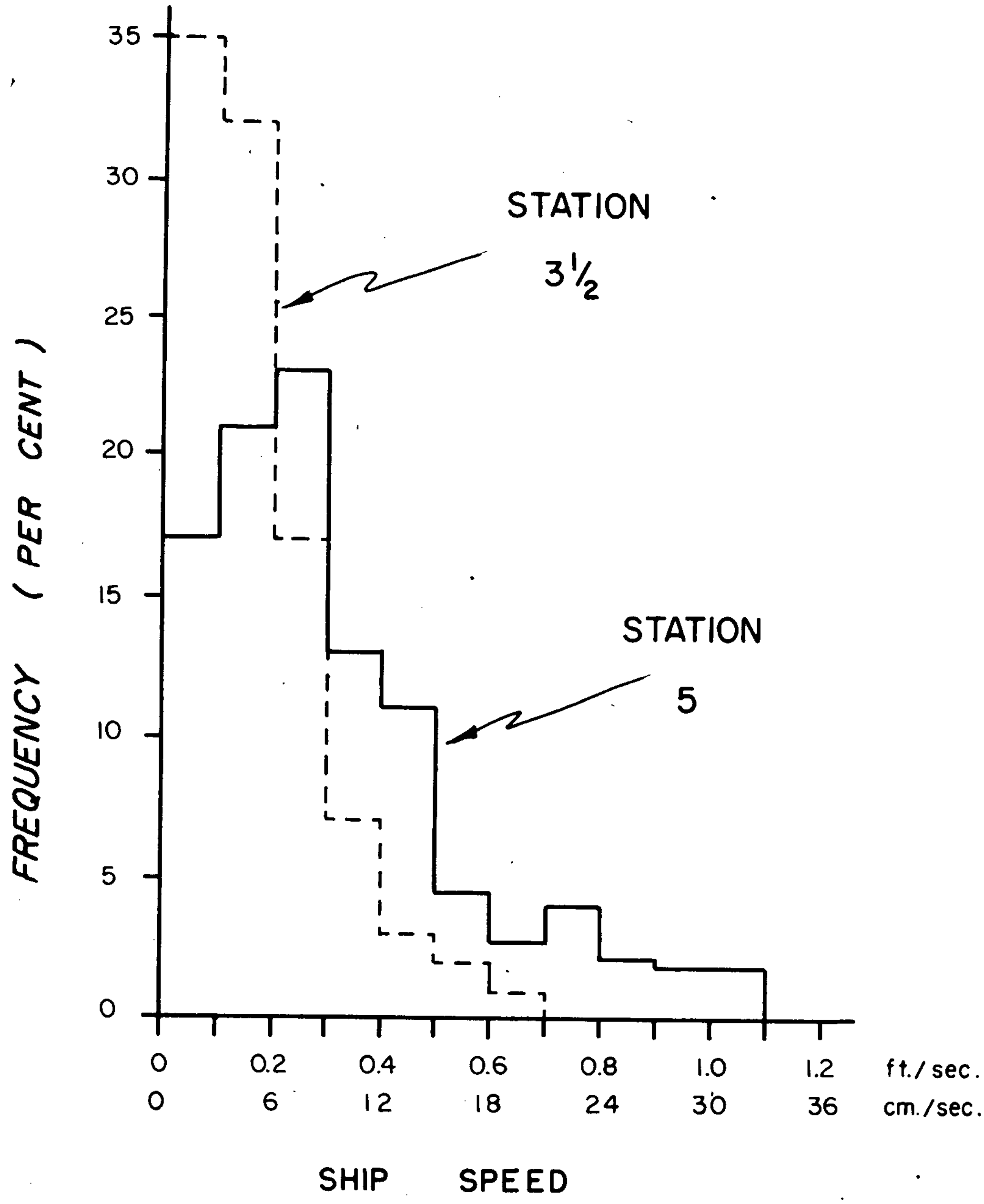
POSITIONING OF SHORE STATIONS

Figure 6



THE EXTENT OF SHIP MOTION

Figure 7



DISTRIBUTION OF SHIP SPEED
AT THE TWO CURRENT STATIONS

Figure 8

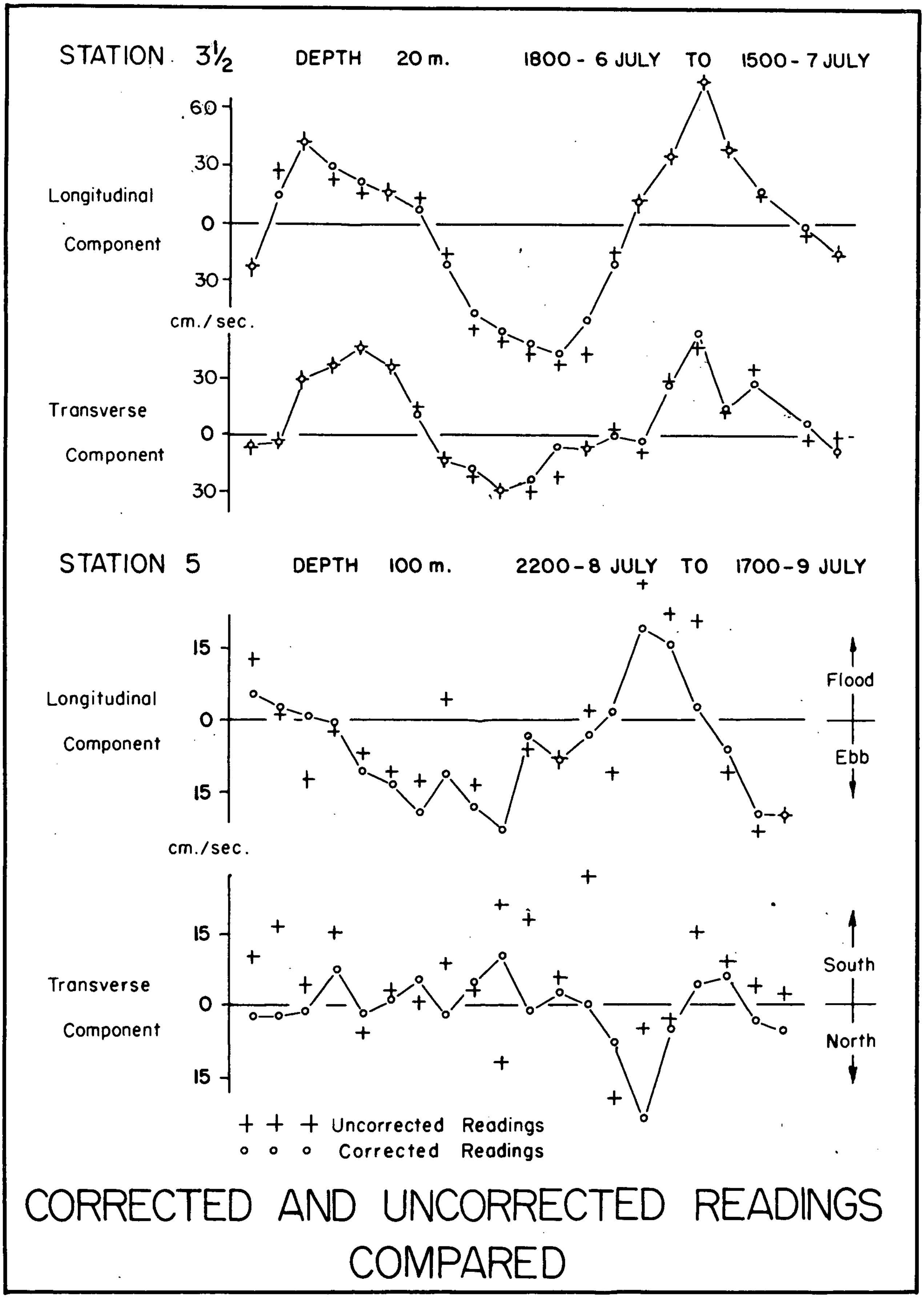
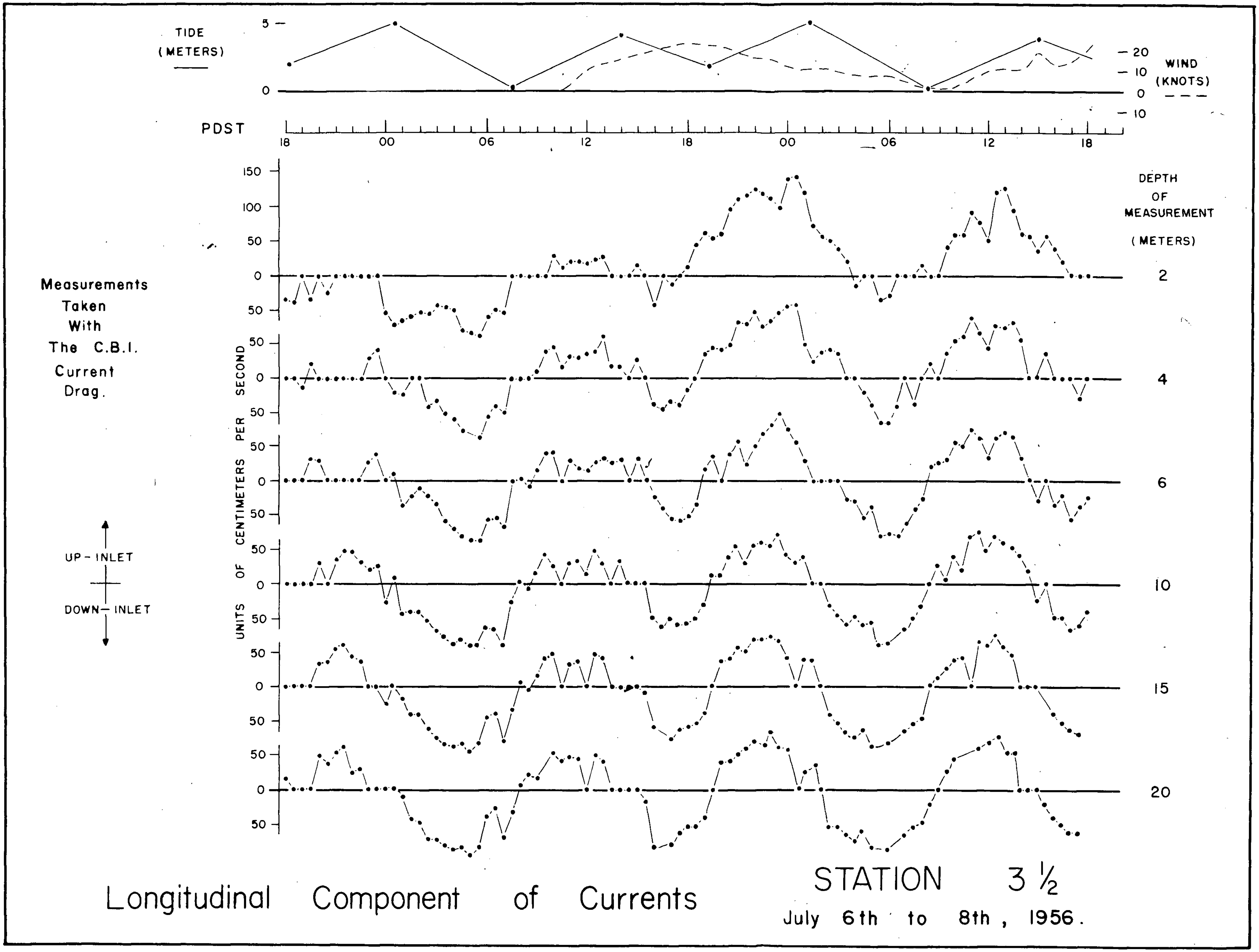
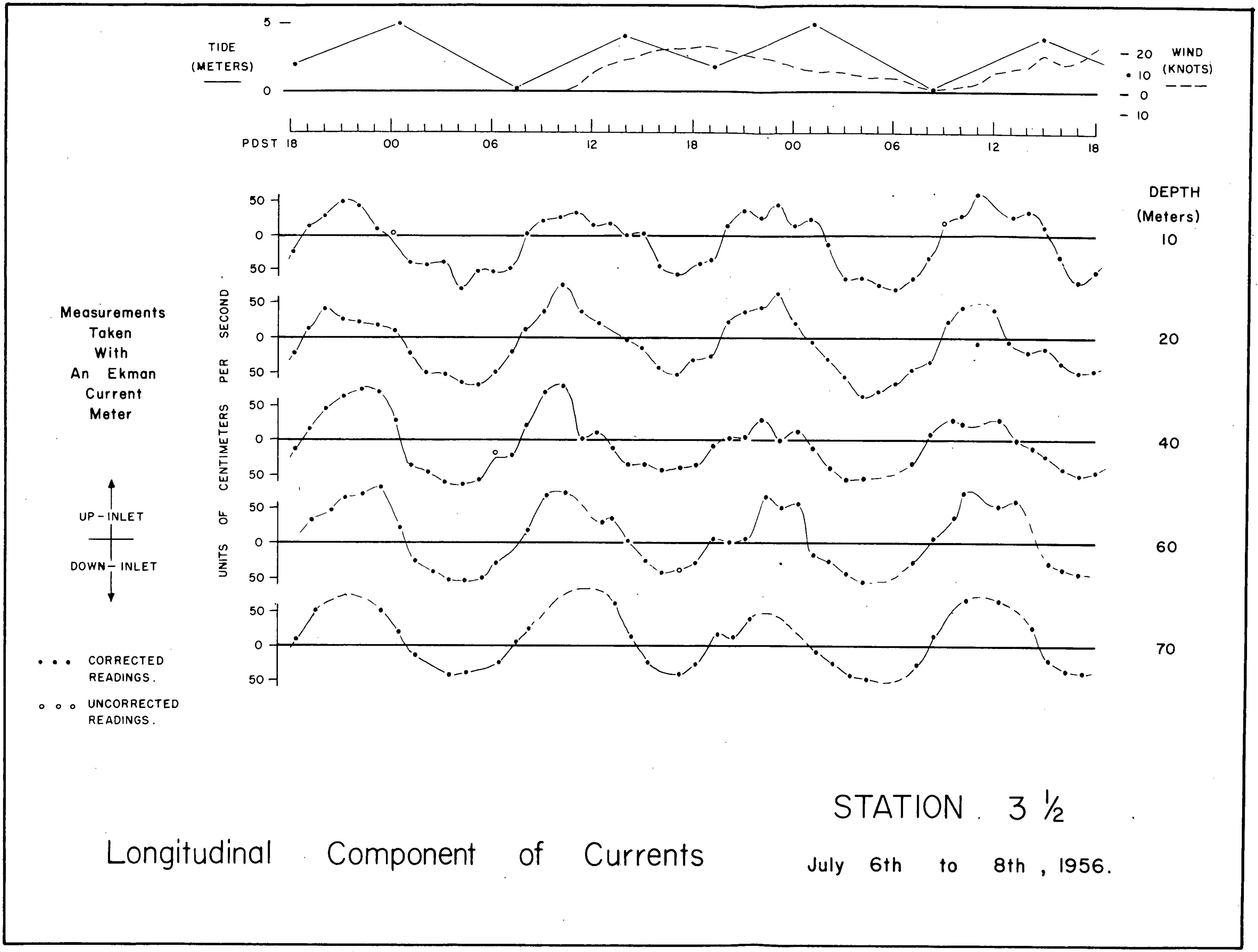

STATION 3½
DEPTH 20 m.
1800 - 6 JULY TO 1500 - 7 JULY
60
30
0
30
Longitudinal
Component
cm./sec.
30
0
30
Transverse
Component
STATION 5
DEPTH 100 m.
2200-8 JULY TO 1700-9 JULY
15
0
15
Longitudinal
Component
Flood
Ebb
cm./sec.
15
0
15
Transverse
Component
South
North
+ + + Uncorrected Readings
o o o Corrected Readings
CORRECTED AND UNCORRECTED READINGS COMPARED

Figure 9



TIDE (METERS)
WIND (KNOTS)
PDST
18 00 06 12 18 00 06 12 18
DEPTH OF MEASUREMENT (METERS)
2
4
6
10
15
20
UNITS OF CENTIMETERS PER SECOND
Measurements Taken With The C.B.I. Current Drag.
UP - INLET
DOWN - INLET
Longitudinal Component of Currents
STATION 3 ½
July 6th to 8th, 1956.

Figure 10 (a)



TIDE
(METERS)
WIND
(KNOTS)
20
10
0
10
5
0
PDST 18
00
06
12
18
00
06
12
18
DEPTH
(Meters)
10
20
40
60
70
50
0
50
UNITS OF CENTIMETERS PER SECOND
Measurements
Taken
With
An Ekman
Current
Meter
UP - INLET
DOWN - INLET
CORRECTED
READINGS.
UNCORRECTED
READINGS.
STATION 3 ½
July 6th to 8th, 1956.
Longitudinal Component of Currents

Figure 10 (b)

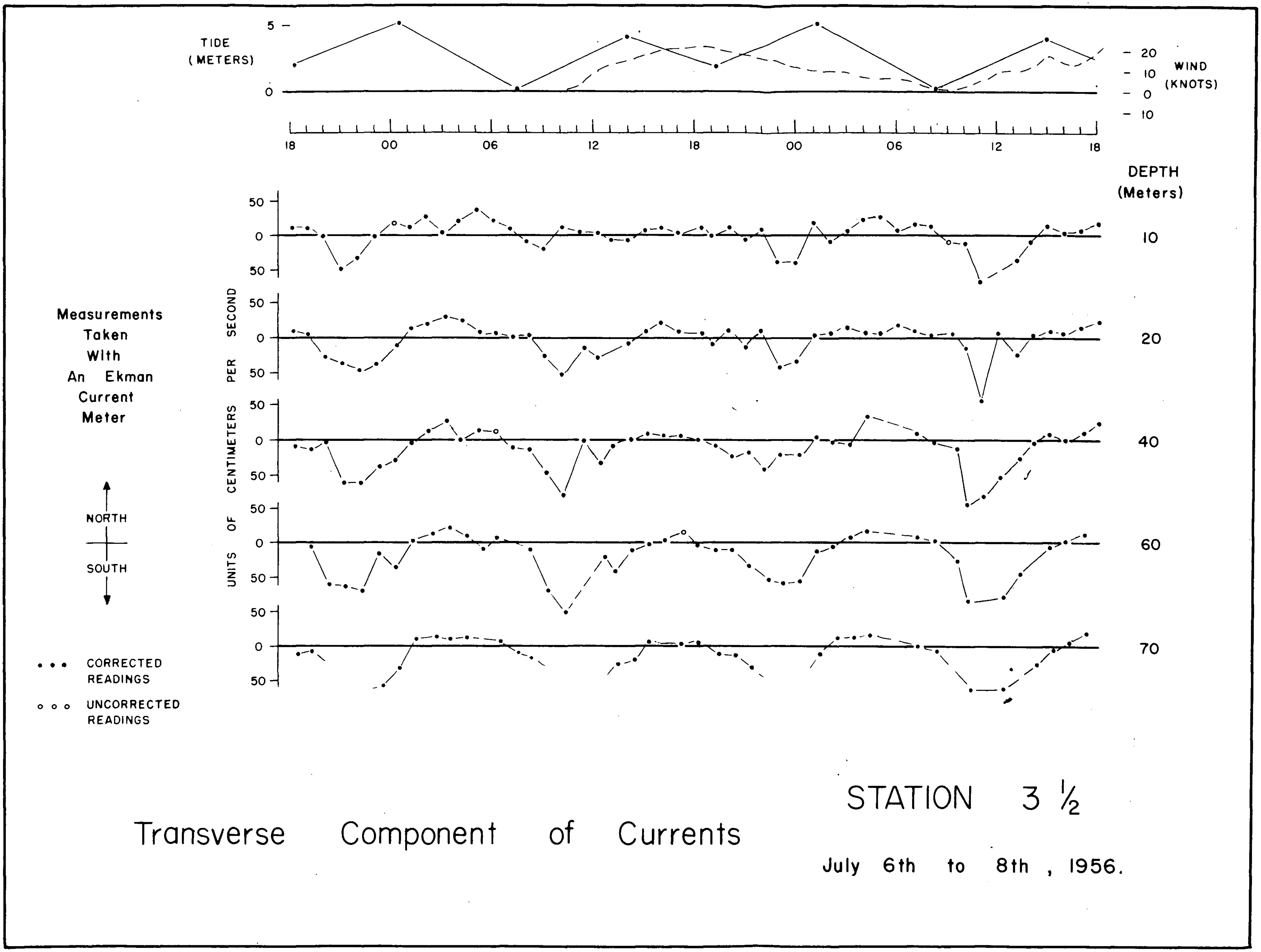

TIDE
(METERS)
5
0
20
10
0
10
WIND
(KNOTS)
18
00
06
12
18
00
06
12
18
DEPTH
(Meters)
50
0
50
10
20
40
60
70
SECOND
PER
CENTIMETERS
OF
UNITS
Measurements
Taken
With
An Ekman
Current
Meter
NORTH
SOUTH
CORRECTED
READINGS
UNCORRECTED
READINGS
STATION 3 ½
Transverse Component of Currents
July 6th to 8th, 1956.

Figure 11

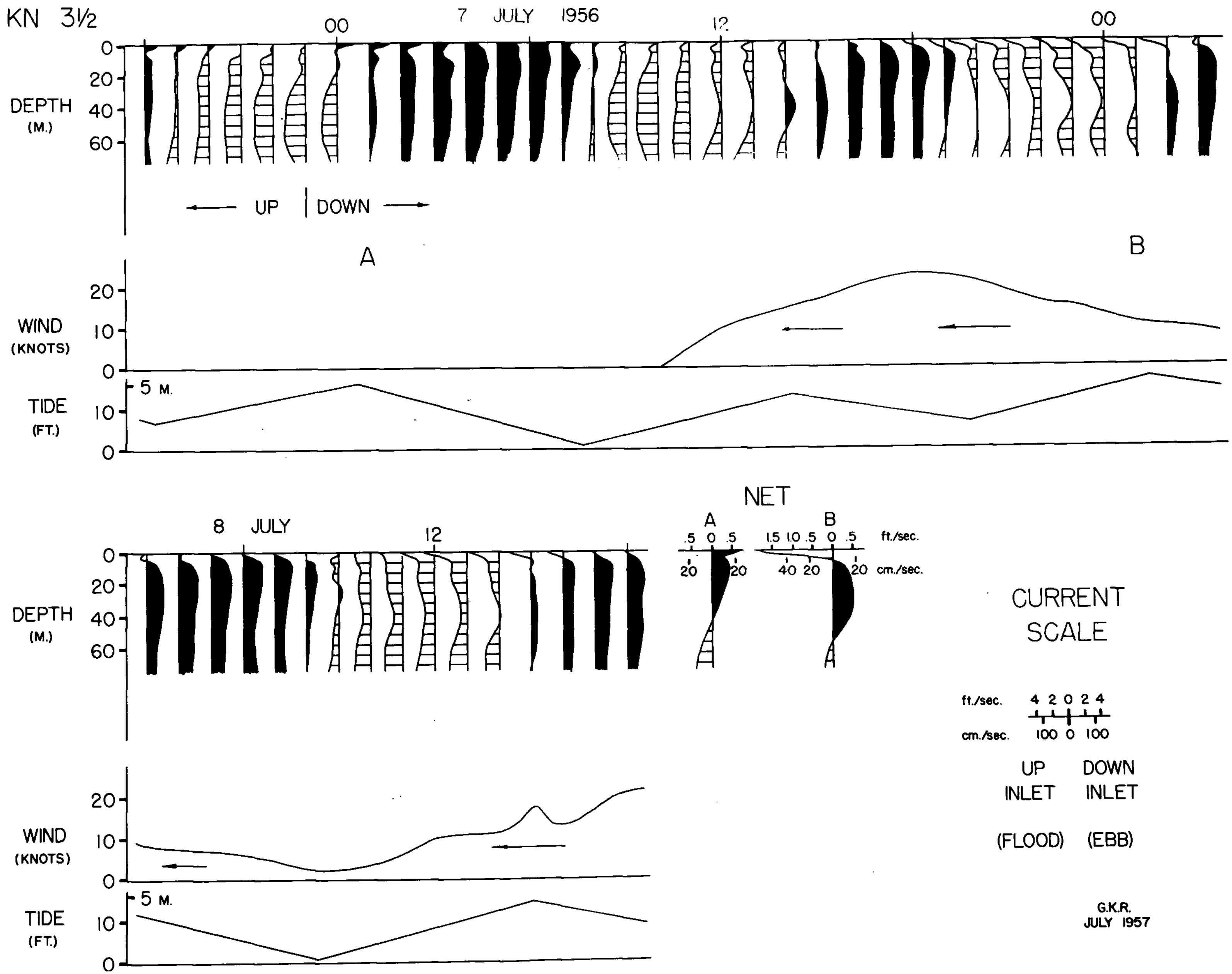

KN 3½
7 JULY 1956
00
12
00
DEPTH (M.)
UP
DOWN
A
B
WIND (KNOTS)
TIDE (FT.)
5 M.
8 JULY
12
NET
A
B
ft./sec.
cm./sec.
CURRENT SCALE
ft./sec. 4 2 0 2 4
cm./sec. 100 0 100
UP INLET
DOWN INLET
(FLOOD)
(EBB)
G.K.R.
JULY 1957

Figure 12

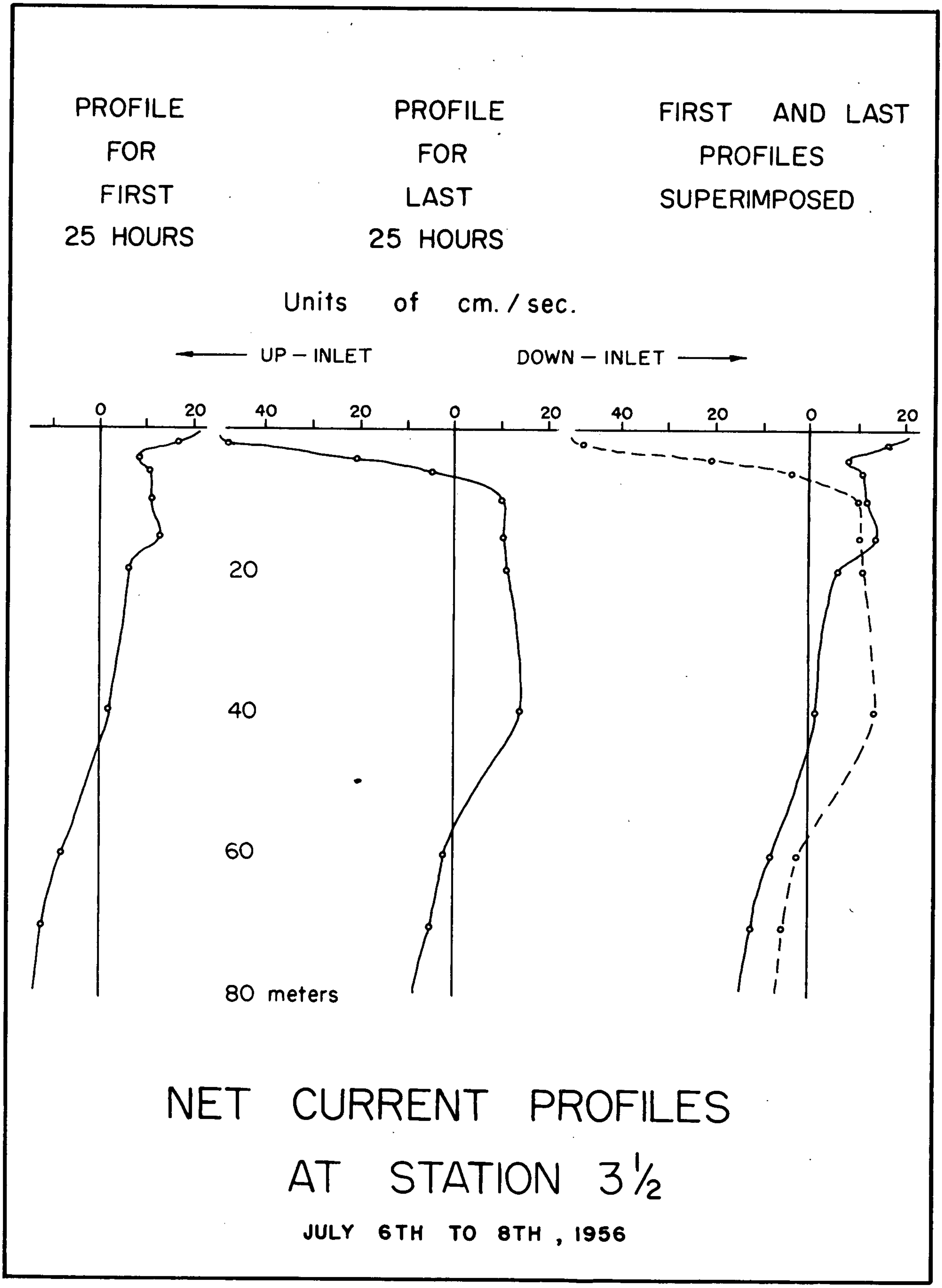

PROFILE
FOR
FIRST
25 HOURS
PROFILE
FOR
LAST
25 HOURS
FIRST AND LAST
PROFILES
SUPERIMPOSED
Units of cm. / sec.
UP – INLET
DOWN – INLET
0
20
40
20
0
20
40
20
0
20
20
40
60
80 meters
NET CURRENT PROFILES
AT STATION 3½
JULY 6TH TO 8TH, 1956

Figure 13

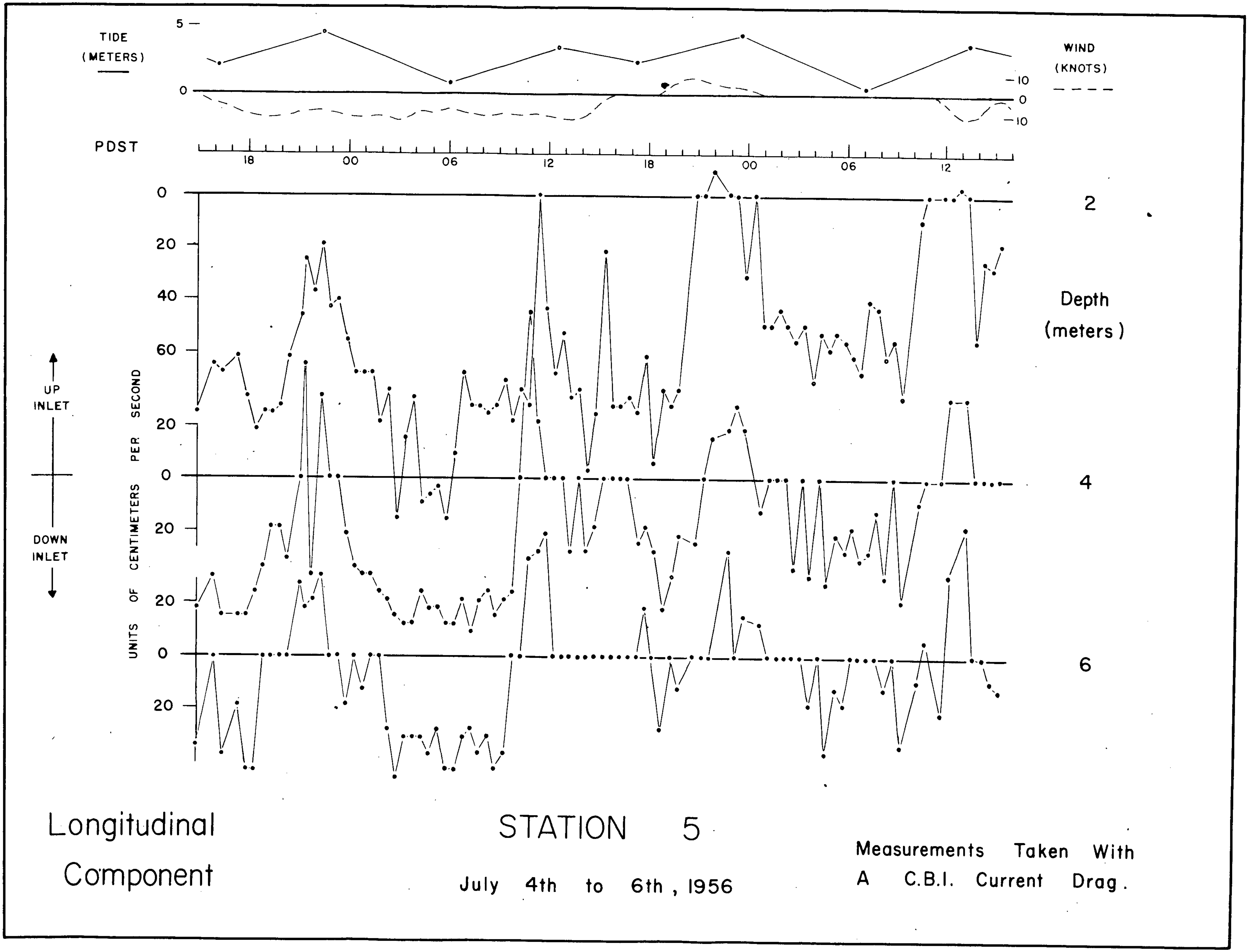
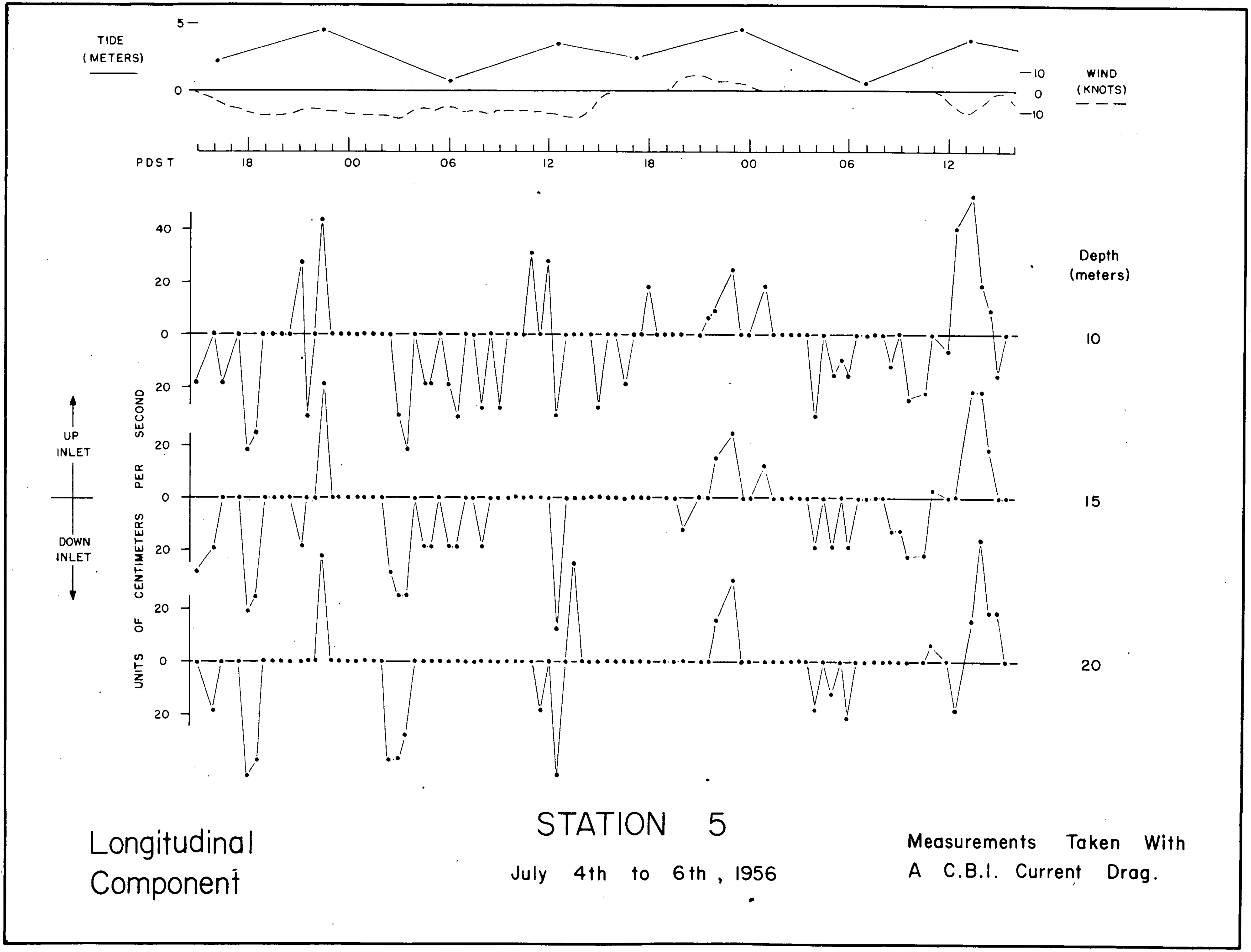
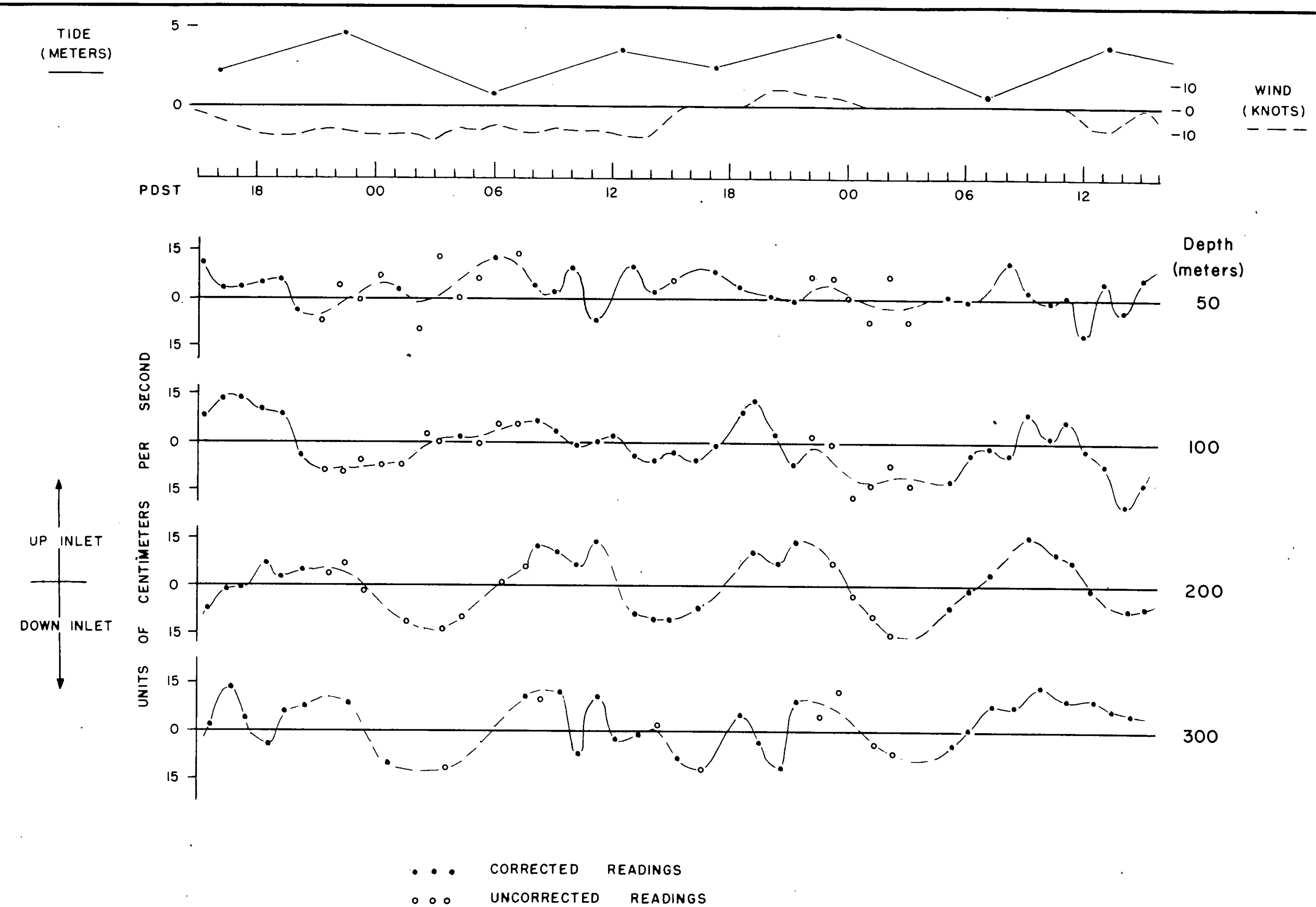

TIDE
(METERS)
WIND
(KNOTS)
PDST
18
00
06
12
18
00
06
12
5
0
10
0
10
0
20
40
60
20
0
20
20
0
20
2
4
6
Depth
(meters)
UP
INLET
DOWN
INLET
UNITS OF CENTIMETERS PER SECOND
Longitudinal
Component
STATION 5
July 4th to 6th, 1956
Measurements Taken With
A C.B.I. Current Drag.

Figure 14 (a)



TIDE
(METERS)
5
0
WIND
(KNOTS)
10
0
10
PDST
18
00
06
12
18
00
06
12
Depth
(meters)
10
15
20
40
20
0
20
UP
INLET
DOWN
INLET
UNITS OF CENTIMETERS PER SECOND
STATION 5
July 4th to 6th, 1956
Longitudinal
Component
Measurements Taken With
A C.B.I. Current Drag.

Figure 14 (b)



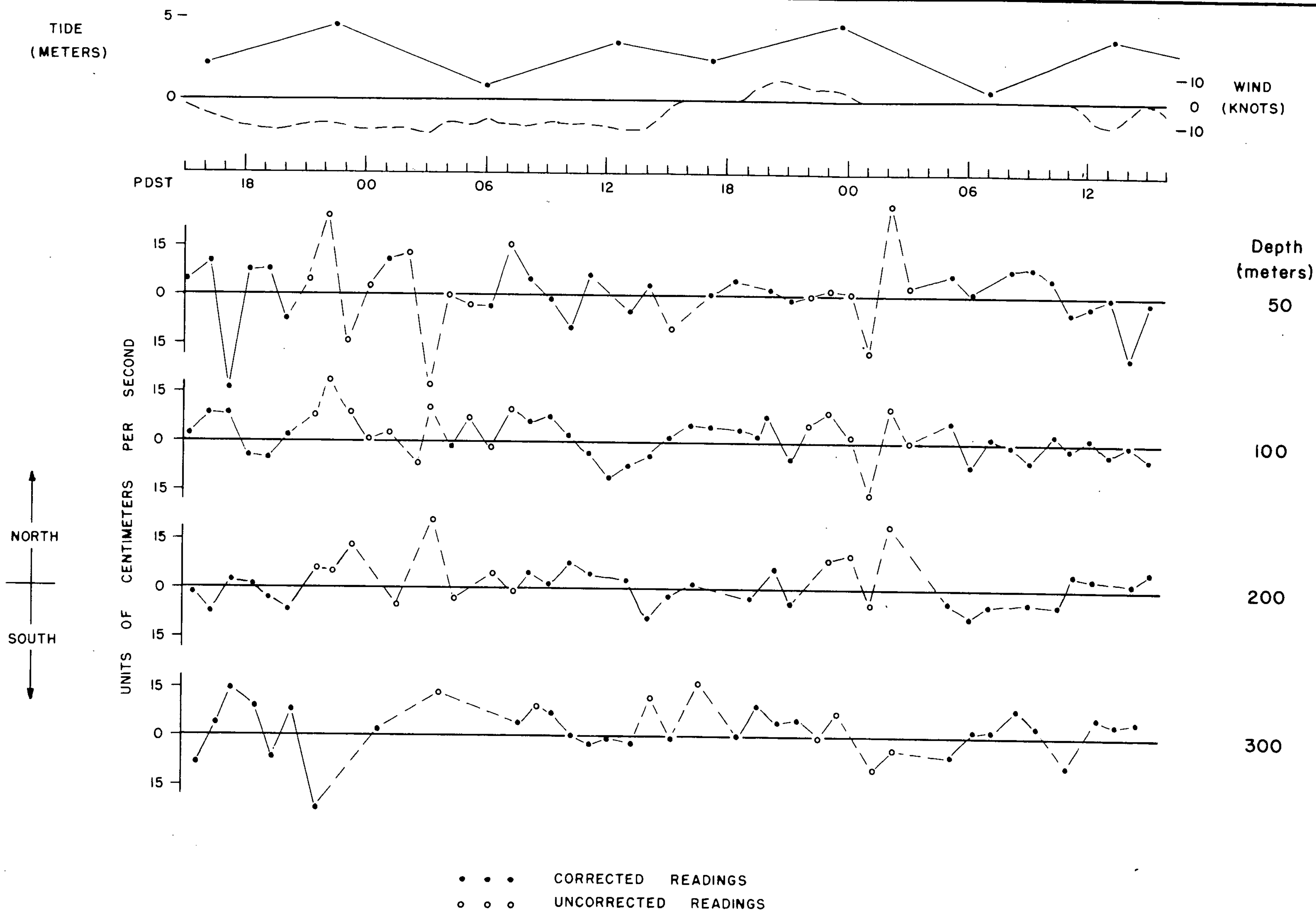
Longitudinal Component

STATION 5

July 4th to 6th, 1956

Measurements Taken With An Ekman Current Meter.

Figure 14 (c)



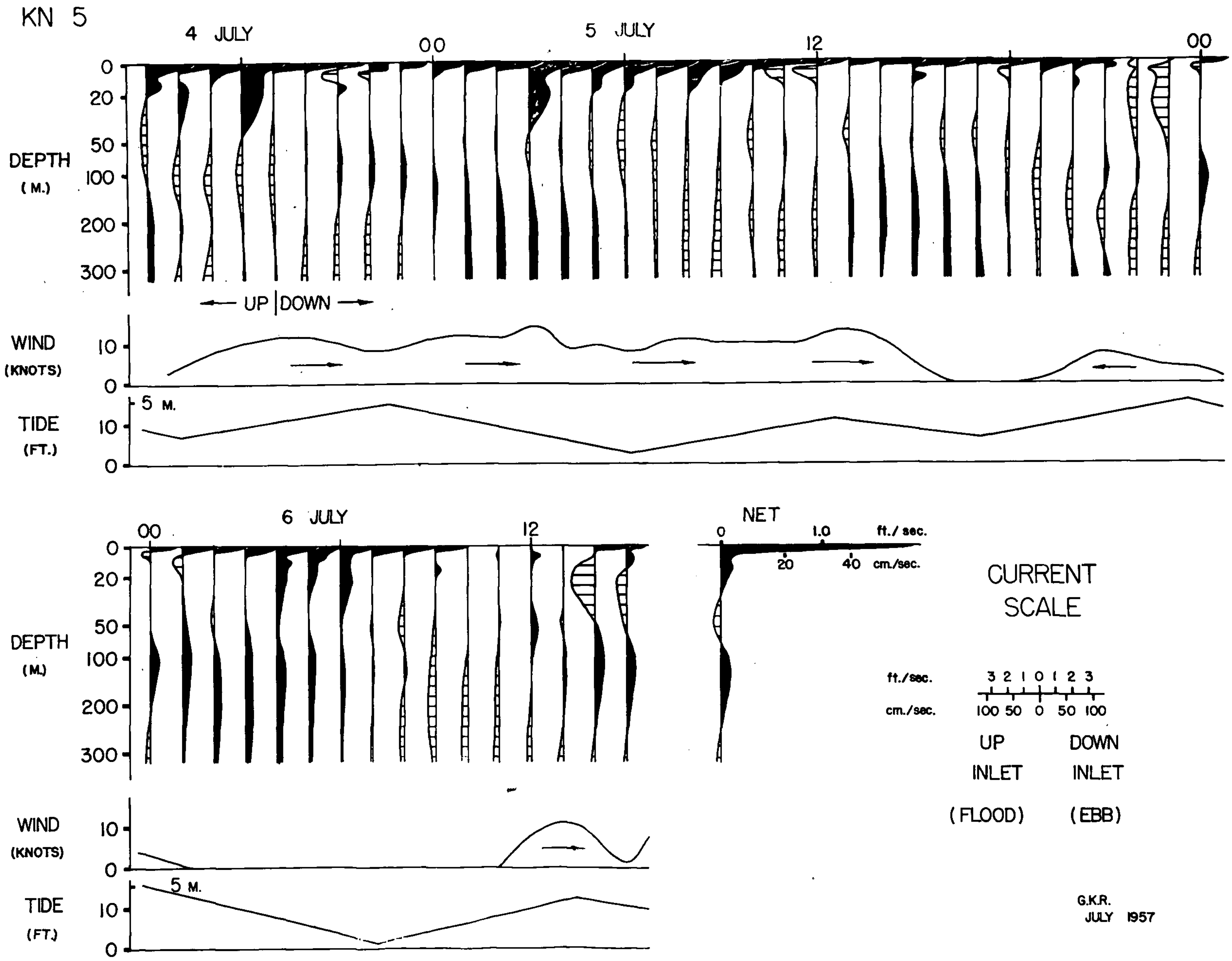
Transverse Component

STATION 5

July 4th to 6th, 1956

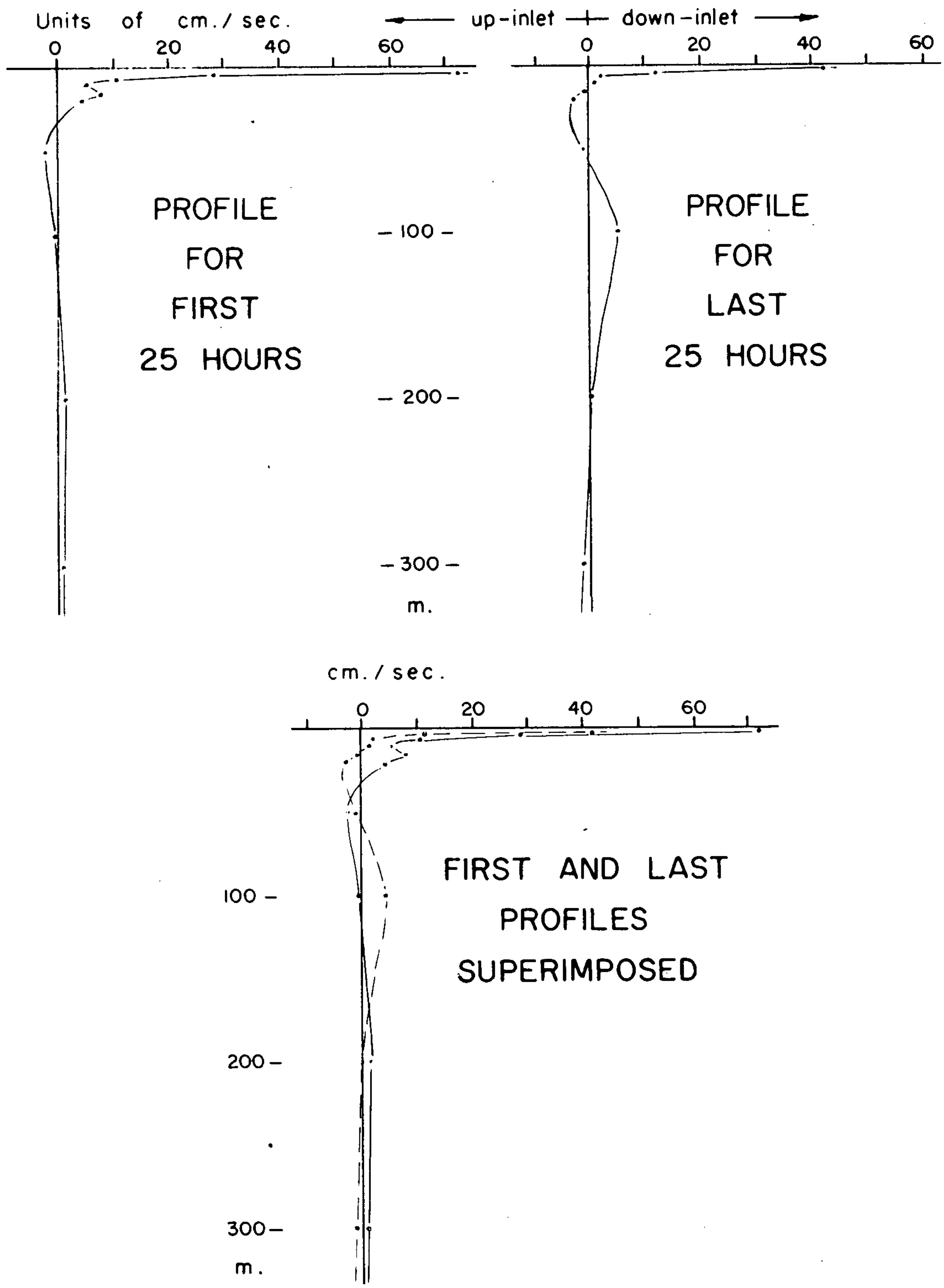
Measurements Taken With An Ekman Current Meter.

Figure 15



KN 5
4 JULY
00
5 JULY
12
00
DEPTH (M.)
0
20
50
100
200
300
← UP | DOWN →
WIND (KNOTS)
10
0
TIDE (FT.)
5 M.
10
0
6 JULY
00
12
NET
0
1.0
ft./sec.
20
40
cm./sec.
CURRENT SCALE
ft./sec.
3 2 1 0 1 2 3
cm./sec.
100 50 0 50 100
UP INLET (FLOOD)
DOWN INLET (EBB)
G.K.R.
JULY 1957

Figure 16



NET CURRENT PROFILES FOR STATION 5

JULY 4 TH TO 6 TH, 1956

Figure 17

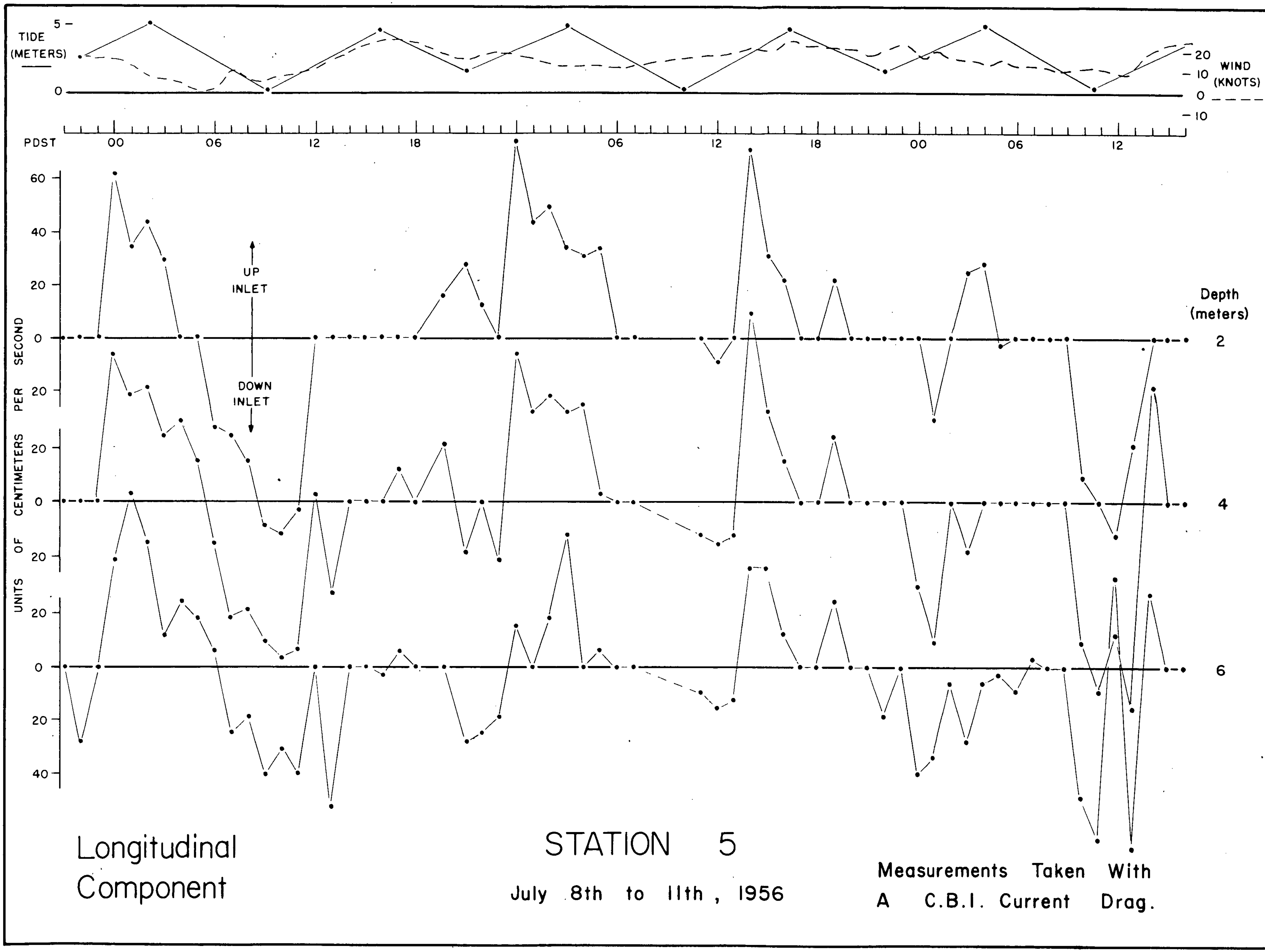
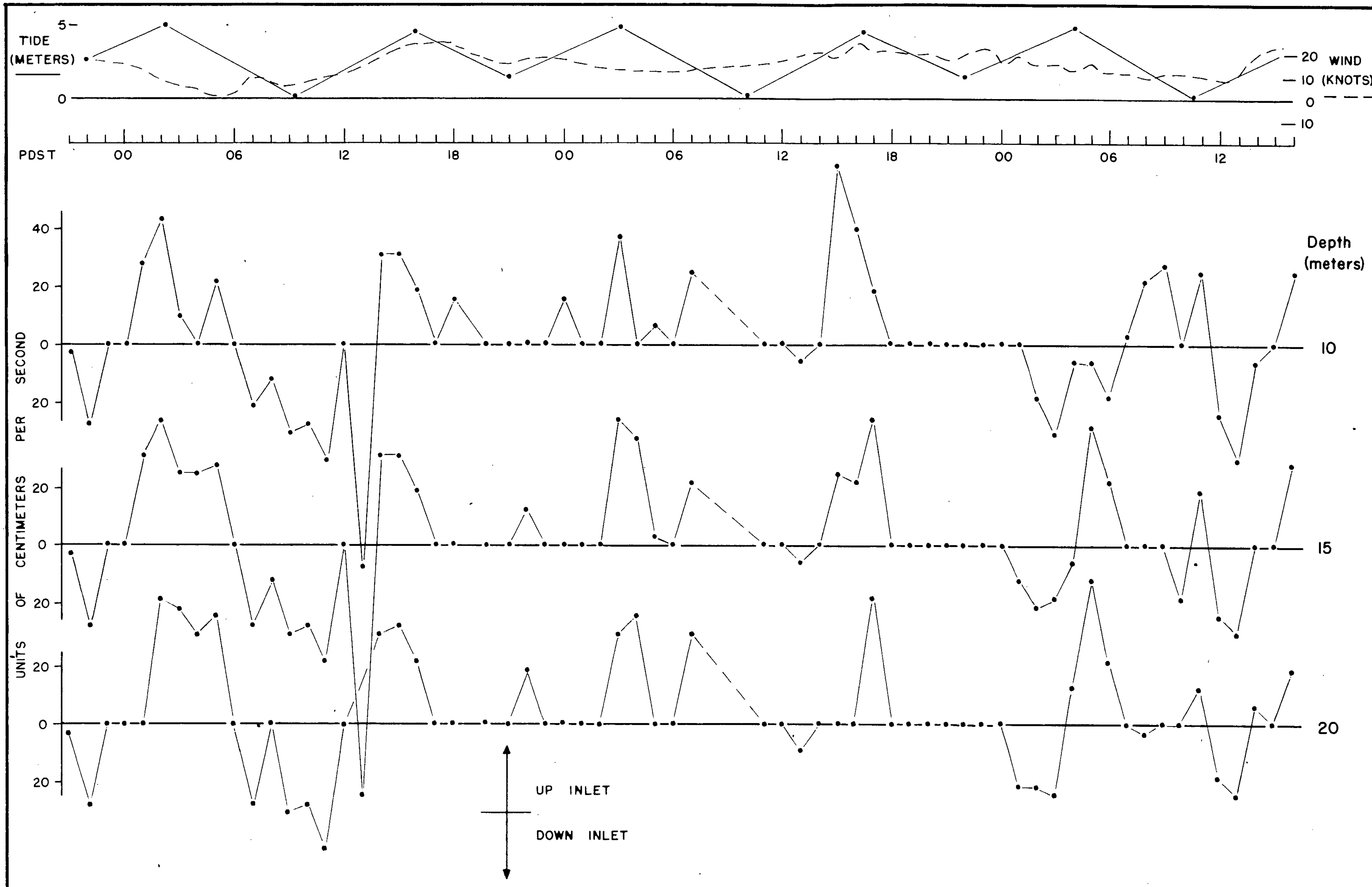

TIDE
(METERS)
WIND
(KNOTS)
PDST
UP
INLET
DOWN
INLET
UNITS OF CENTIMETERS PER SECOND
Depth
(meters)
Longitudinal
Component
STATION 5
July 8th to 11th, 1956
Measurements Taken With
A C.B.I. Current Drag.

Figure 18(a)



Longitudinal Component

STATION 5

July 8th to 11th, 1956

Measurements Taken With A C.B.I. Current Drag.

Figure 18 (b)

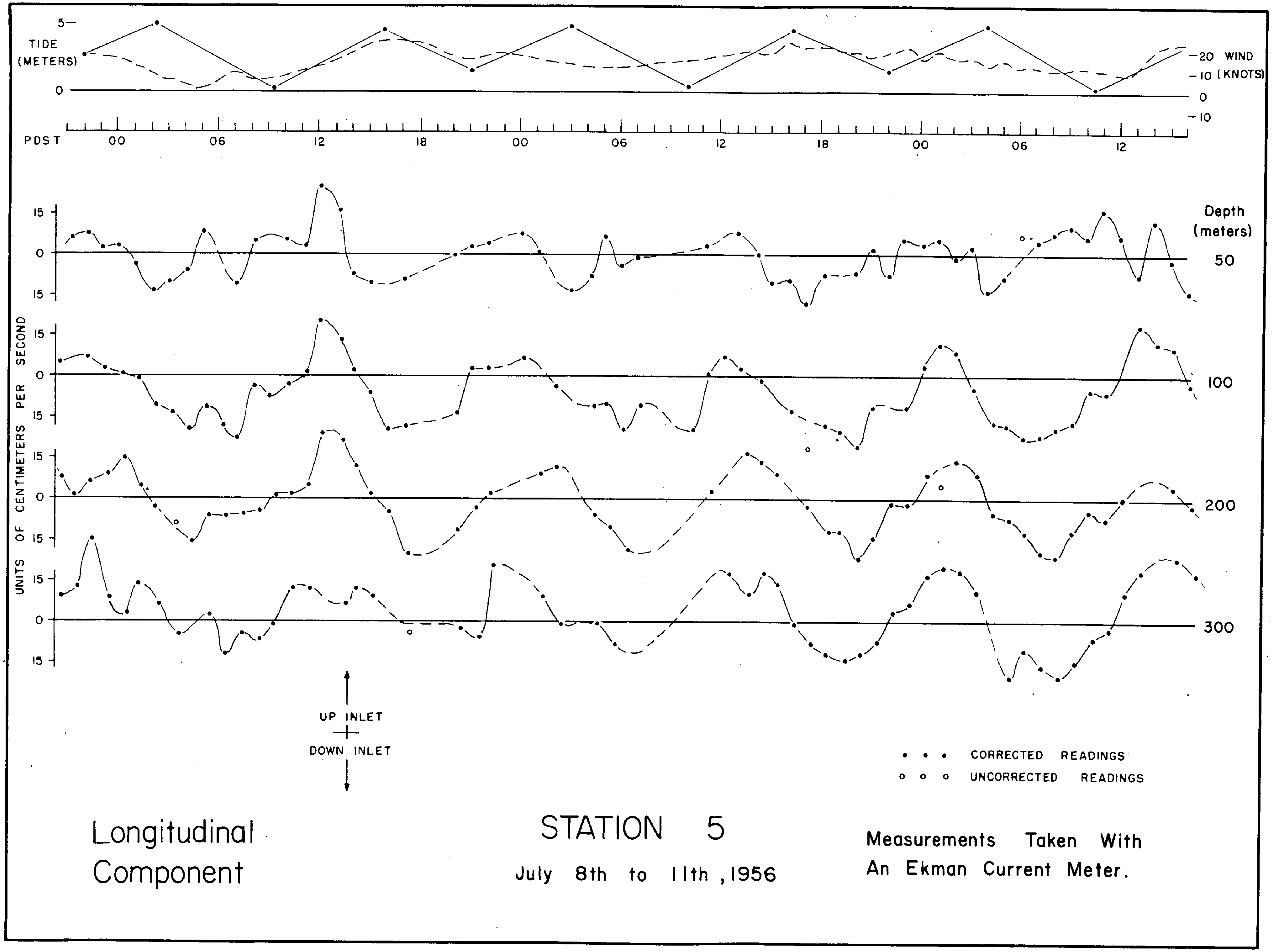
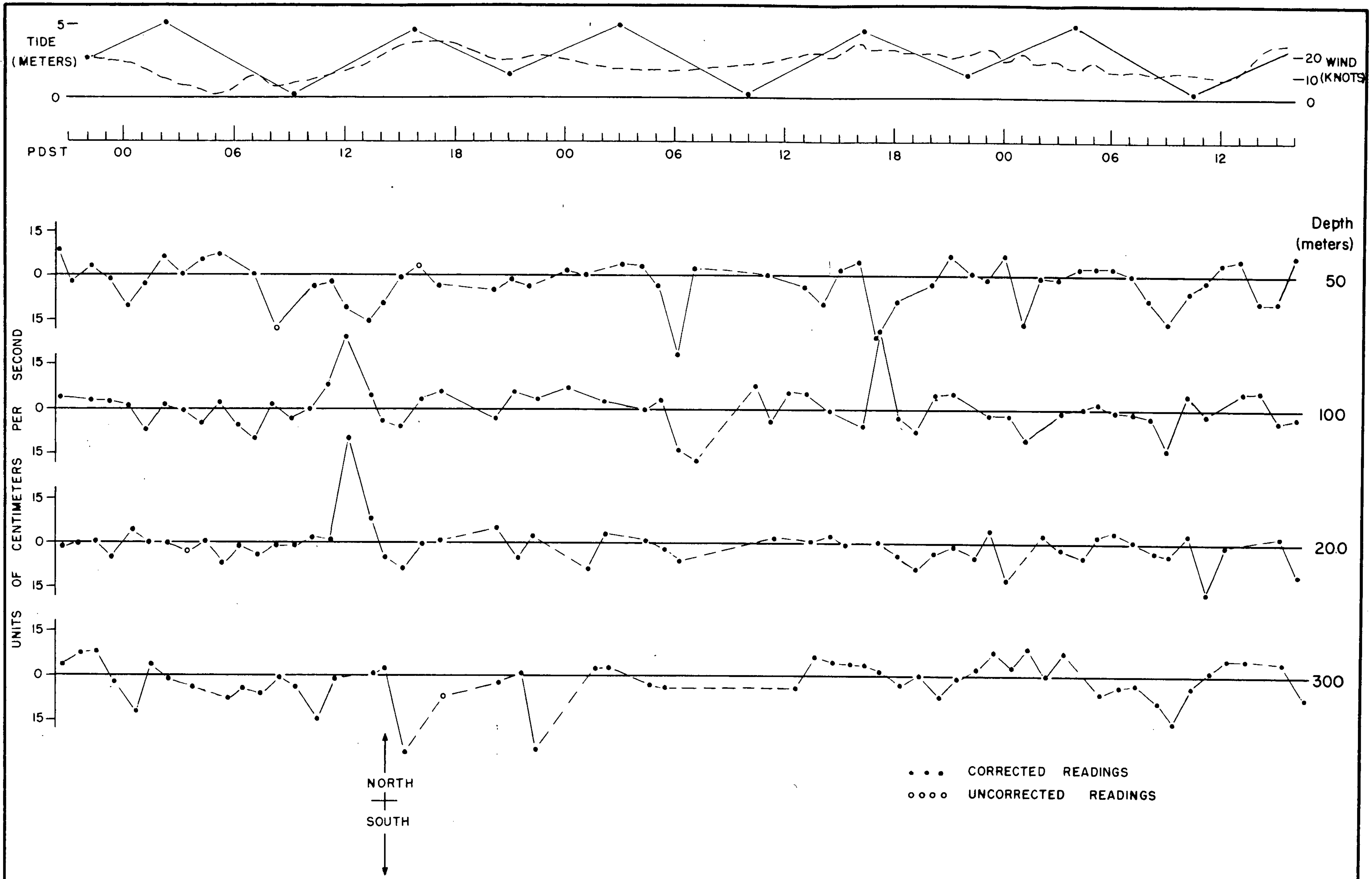

TIDE (METERS)
5
0
20 WIND
10 (KNOTS)
0
-10
PDST
00
06
12
18
00
06
12
18
00
06
12
UNITS OF CENTIMETERS PER SECOND
15
0
15
Depth (meters)
50
100
200
300
UP INLET
DOWN INLET
CORRECTED READINGS
UNCORRECTED READINGS
Longitudinal Component
STATION 5
July 8th to 11th, 1956
Measurements Taken With An Ekman Current Meter.

Figure 18 (c)



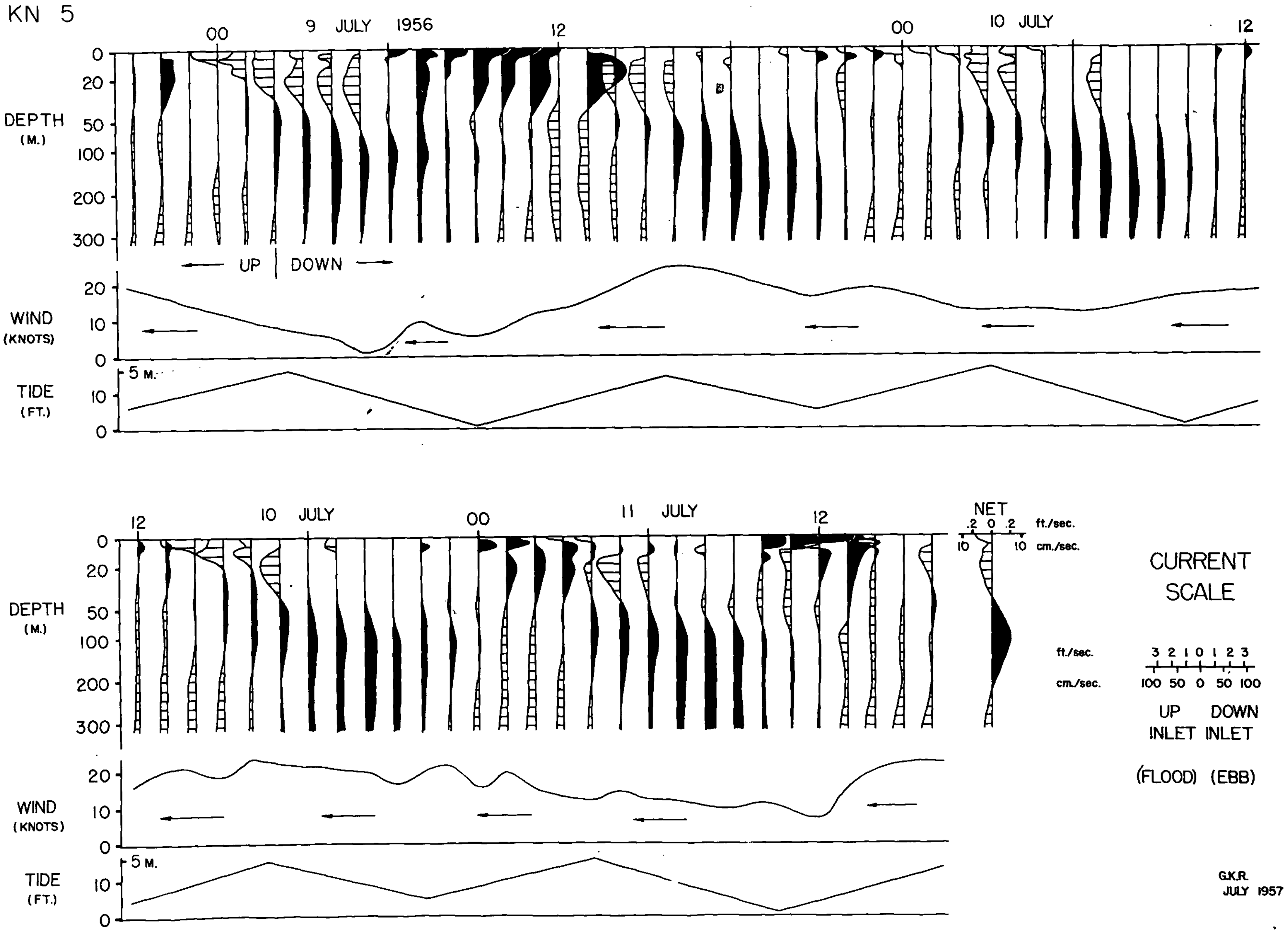
Transverse
Component

STATION 5

July 8th to 11th, 1956

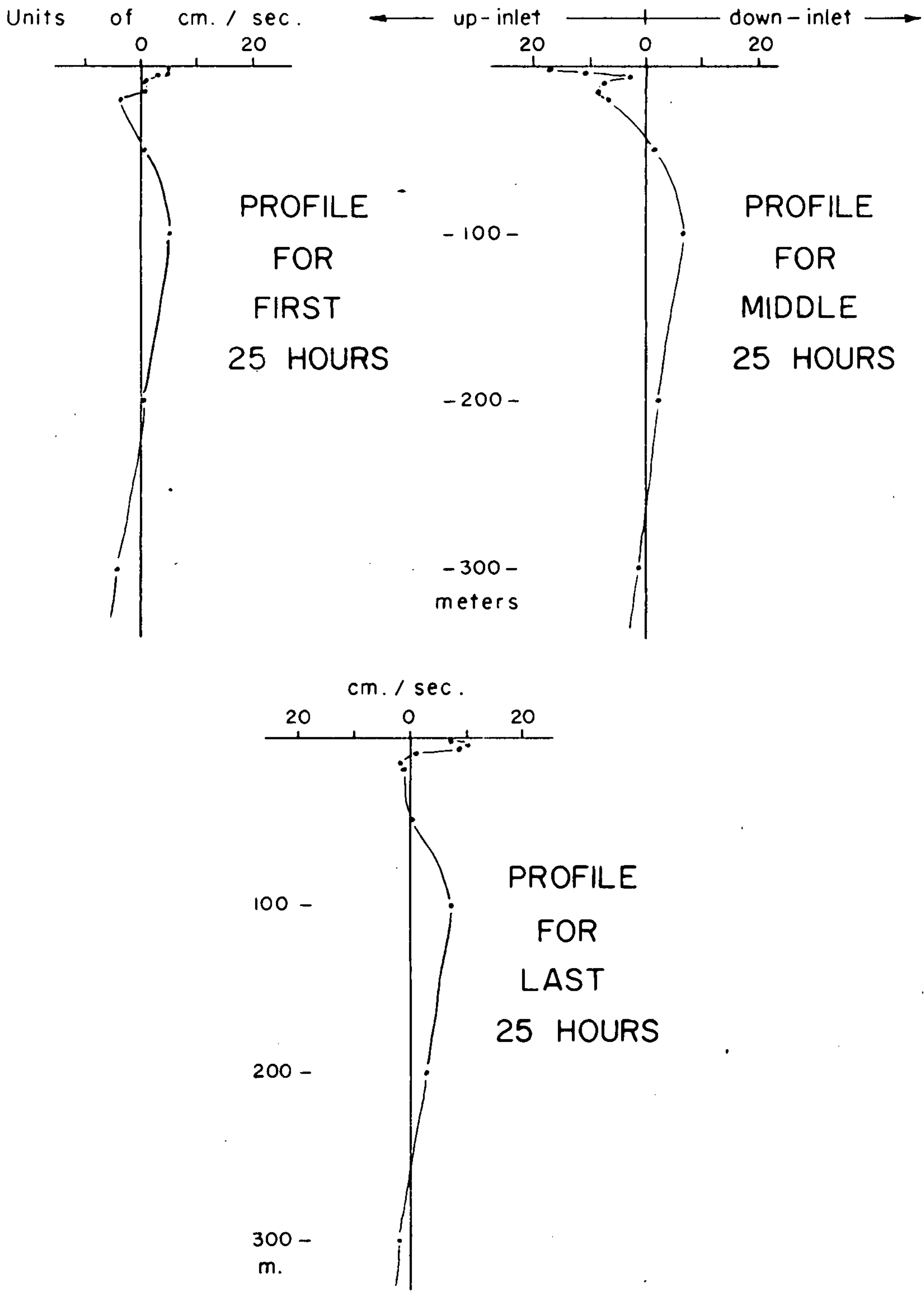
Measurements Taken With
An Ekman Current Meter.

Figure 19



KN 5
00
9 JULY 1956
12
00
10 JULY
12
DEPTH (M.)
0
20
50
100
200
300
UP
DOWN
WIND (KNOTS)
TIDE (FT.)
5 M.
10
0
12
10 JULY
00
11 JULY
12
NET
.2 0 .2 ft./sec.
10 10 cm./sec.
CURRENT SCALE
ft./sec.
3 2 1 0 1 2 3
cm./sec.
100 50 0 50 100
UP INLET
DOWN INLET
(FLOOD) (EBB)
G.K.R.
JULY 1957

Figure 20



NET CURRENT PROFILES FOR STATION 5

JULY 8TH TO 11TH, 1956

Figure 21

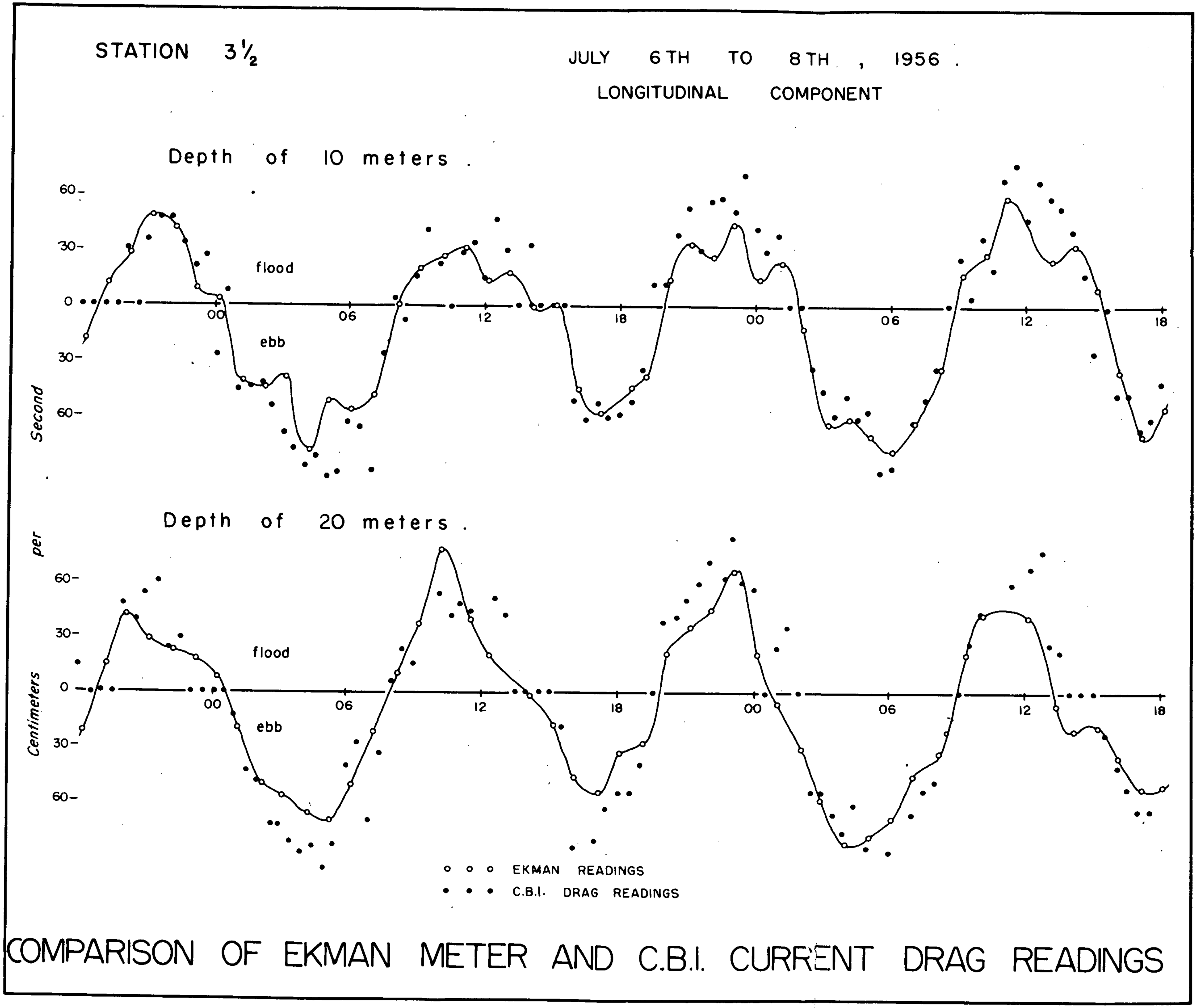
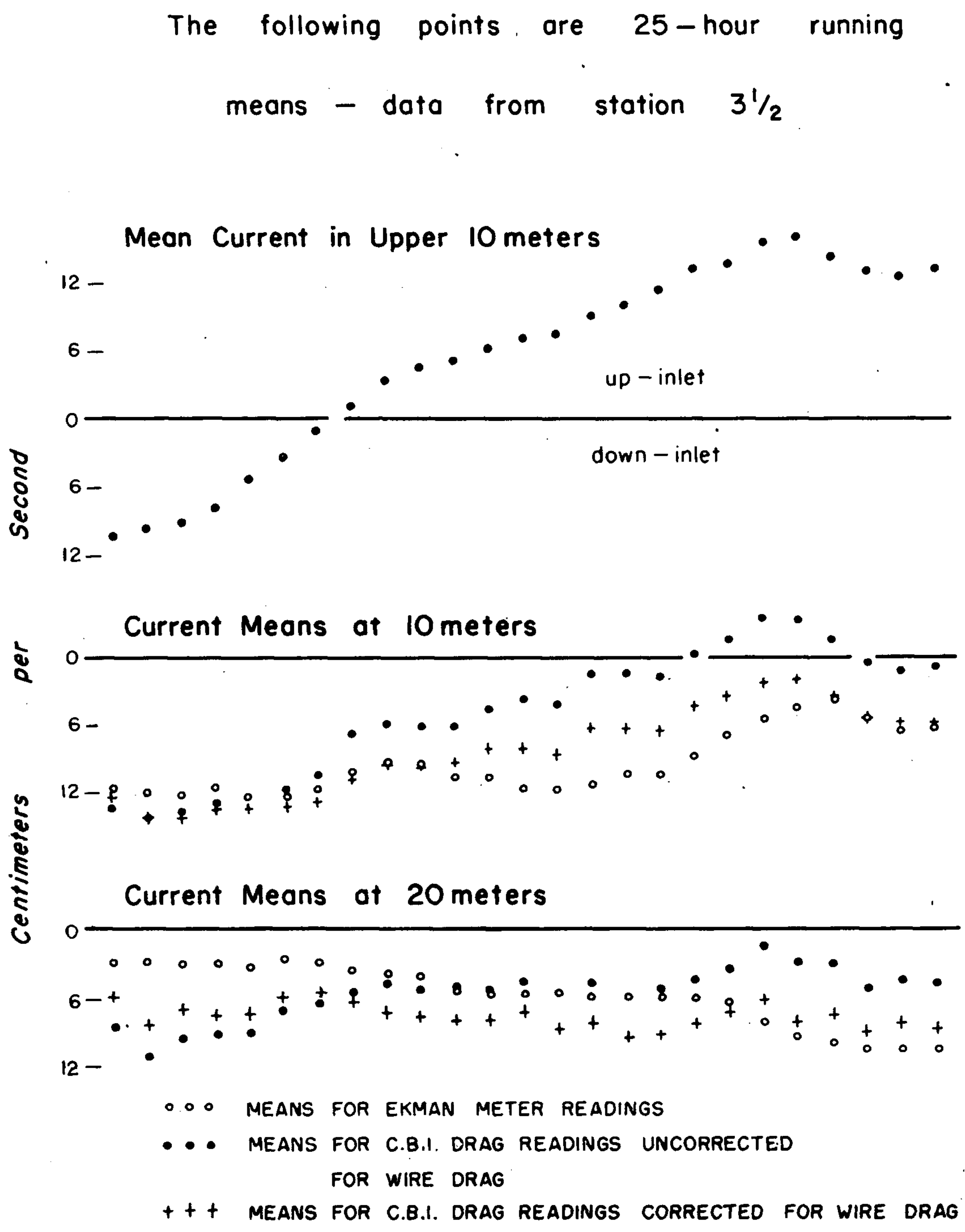

STATION 3½
JULY 6TH TO 8TH, 1956.
LONGITUDINAL COMPONENT
Depth of 10 meters.
Depth of 20 meters.
Centimeters per Second
60
30
0
30
60
flood
ebb
00
06
12
18
00
06
12
18
EKMAN READINGS
C.B.I. DRAG READINGS
COMPARISON OF EKMAN METER AND C.B.I. CURRENT DRAG READINGS

Figure 22



THE EFFECT OF THE WIRE DRAG CORRECTION

Figure 23

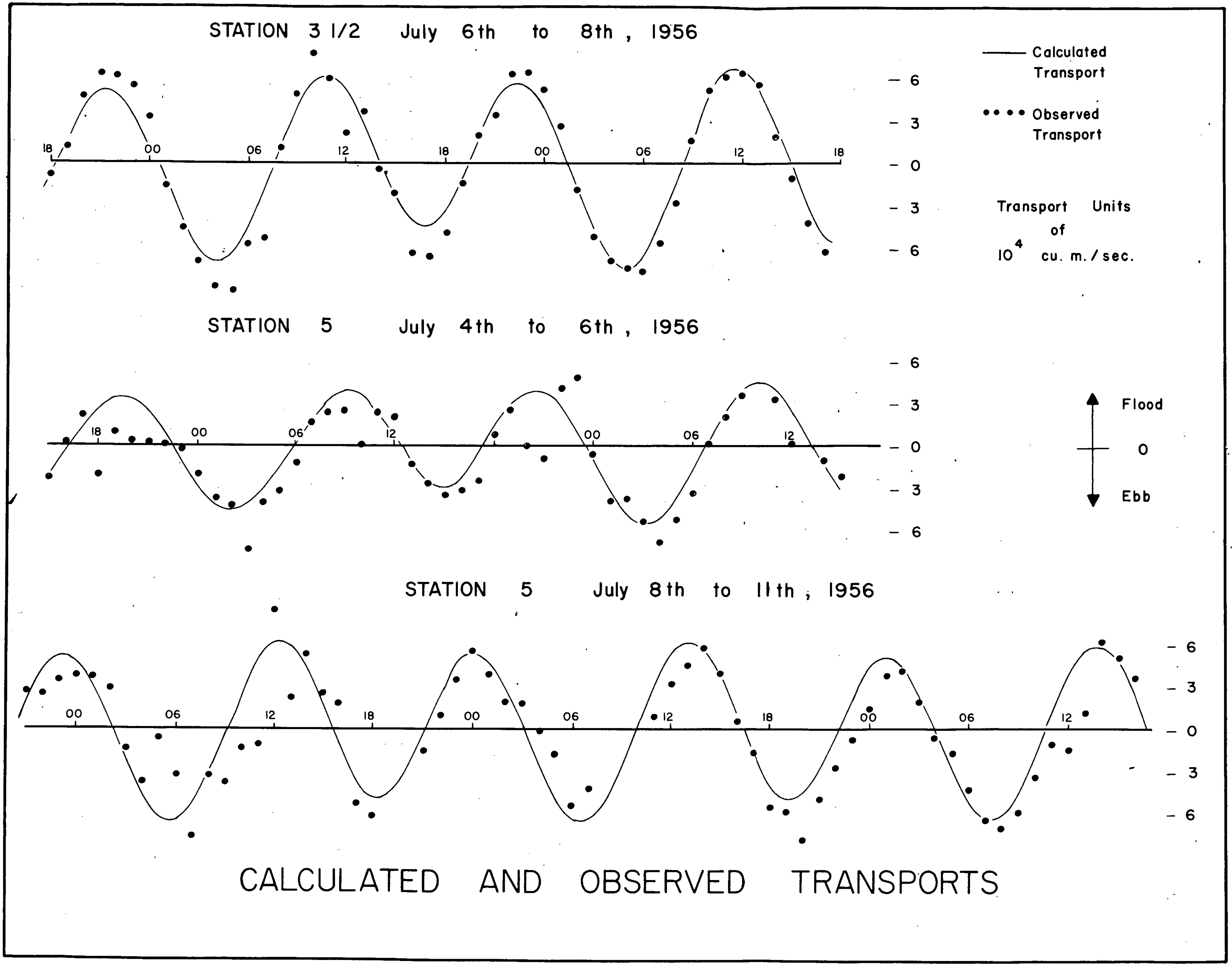

STATION 3 1/2 July 6th to 8th, 1956
STATION 5 July 4th to 6th, 1956
STATION 5 July 8th to 11th, 1956
Calculated Transport
Observed Transport
Transport Units of 10^4 cu. m./sec.
Flood
Ebb
CALCULATED AND OBSERVED TRANSPORTS

Figure 24

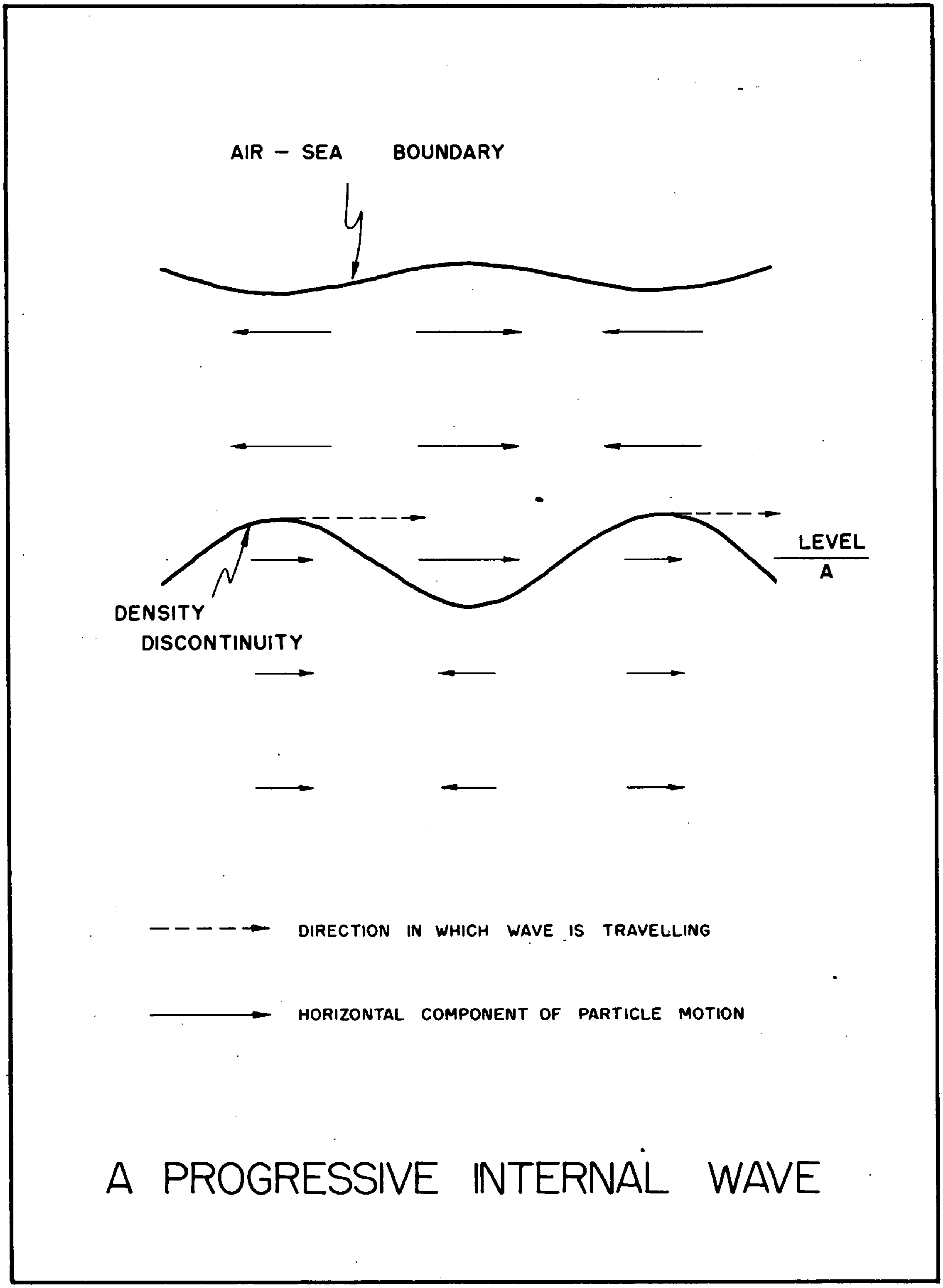

AIR — SEA BOUNDARY
LEVEL
A
DENSITY
DISCONTINUITY
DIRECTION IN WHICH WAVE IS TRAVELLING
HORIZONTAL COMPONENT OF PARTICLE MOTION
A PROGRESSIVE INTERNAL WAVE

Figure 25