BOTTOM AND NEAR-BOTTOM SEDIMENT DYNAMICS IN NORTON SOUND, ALASKA

by

David A. Cacchione and David E. Drake

Pacific-Arctic Branch of Marine Geology
U.S. Geological Survey
345 Middlefield Road
Menlo Park, California 94025

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L SUMMARY

A. Overview

An investigation of sediment dynamics in Norton Sound and other sections of the northern Bering Sea was conducted to define the principal pathways and mechanisms of bottom and suspended materials transport. A major topic of this research is the complicated interrelationships of sediment movement and hydrodynamic stresses that occur in the marine environment. Temporal contrasts like those caused by seasonal cycles and quiescent versus storm conditions are of particular interest. This research is pertinent to two major impact areas of petroleum development in the marine environment: (1) transport of materials including pollutants; and (2) hazardous sea floor conditions caused by wave and current erosion.

B. Results

Distributions of suspended matter in July 1977 and February-March 1978 were essentially the same as those found in September-October 1976. The pattern is dominated by a broad tongue of turbid water trending northwest across the mouth of Norton Sound from the Yukon Delta. Mixed Yukon and Alaska Coastal Water carrying large amounts of suspended silt extends through the entire water column along this transport pathway.

Mud deposits in the eastern part of the area are supplied by weak or intermittent surface currents which transport Yukon River detritus eastward along the southern coast of Norton Sound. The presence of remnant winter water (low temperature, high salinity) in inner Norton Sound probably is important in the accumulation of a blanket of mud in this area. Pollutants entering this “cul-de-sac” maybe retained for relatively long periods owing to the limited water exchange with the outer part of Norton Sound.

The GEOPROBE results demonstrate that storms play a major part in the transport of sediment in Norton Sound. Suspended sediment transport during one 1977 storm exceeded transport during the 2 months of fair weather preceding the storm. Thus, sediments (and potentially pollutants) which have been temporarily deposited on the sea floor can suddenly be remobilized during a short storm.

During relatively quiescent conditions characterized by insignificant surface wave activity, the currents generated by the mixed astronomical tides dominate the bottom stress field. These currents are able to maintain fine silt and clay in suspension, but bedload transport probably occurs only during spring tide cycles or in shallow (<5 m) areas where waves become significant. On balance, the months of June, July, and August are characterized by deposition of very fine sand and silt delivered during the peak discharge of the Yukon River. Late summer storms disrupt the system and cause substantial erosion of the surficial sediment on the Yukon prodelta. Bottom stress measurements show that these high-energy events are responsible for the spread of sand north across the prodelta and we estimate that one 2-3-day storm transports a volume of sediment equal to 4 months of quiescent hydrodynamic conditions.

Although our data suggest that variations in sea floor elevation caused by erosion–deposition "events" are typically less than 2 cm on the Yukon prodelta, such short-term variations (storm-related) should be substantially greater in the shallow areas surrounding the delta. Depressions in the delta front have been discovered by Nelson (1978) and it is possible that these features are produced and maintained by storm currents.

Nelson and Creager (1977) have discussed the relatively low growth rate of the modern Yukon prodelta. In addition to the erosive action of storms, major causes for the low accumulation rates are the absence of large low-energy basins near the Yukon Delta and the lack of any measurable subsidence of the modern delta. Also, the low clay content of the Yukon sediment limits the development of cohesive mud deposits; exceptions to this are the fine-grained deposits in the eastern part of Norton Sound and in Norton Bay.

Conversely, a substantial amount of Yukon silt and sand has been incorporated in the prodelta and the eastern part of Norton Sound during the past several thousand years. Accumulation of this material is directly related to the absence of significant surface wave-generated currents during most of the year. Except for the brief periods of intense wave action during storms, the transport of sediment is controlled by the tides and the mean flow. The latter are capable of sustaining a flux of fine silt and clay but leave the coarser particles behind on the Yukon prodelta, delta front, and sub-ice platform.

II. INTRODUCTION

A. General Nature and Scope

This research unit is designed to investigate the transport of sediments and other materials in the northern Bering Sea, with special attention on Norton Sound. This work is part of a larger program of continental margin sediment dynamics in which the principal investigators have been involved since July, 1975. The overall program is directed at increasing our understanding of the pathways, rates, and mechanics of sediment movement in a variety of geological settings. A major topic of this research is the complicated interrelationships of sediment movement and hydrodynamics stresses that occur in the marine environment. Temporal contrasts like those caused by seasonal cycles and quiescent versus storm conditions are of particular interest.

The northern Bering Sea is characterized by several unique and extreme environmental conditions: (1) sea ice covers the sea surface over 50 percent of the year, (2) late summer to early fall storms that travel along the polar front often bring severe local weather to the area, and (3) the Yukon River effluent, second largest of North American rivers, enters the system at the southwestern side of Norton Sound (Fig. 1).

A comprehensive picture of the geological and geophysical setting for this region has been developed by Nelson (1977, 1978) from several years of data collected under OCSEAP support. His work has provided the in-depth background that is a necessary prerequisite for the more topically focused research in this project. For example, Nelson

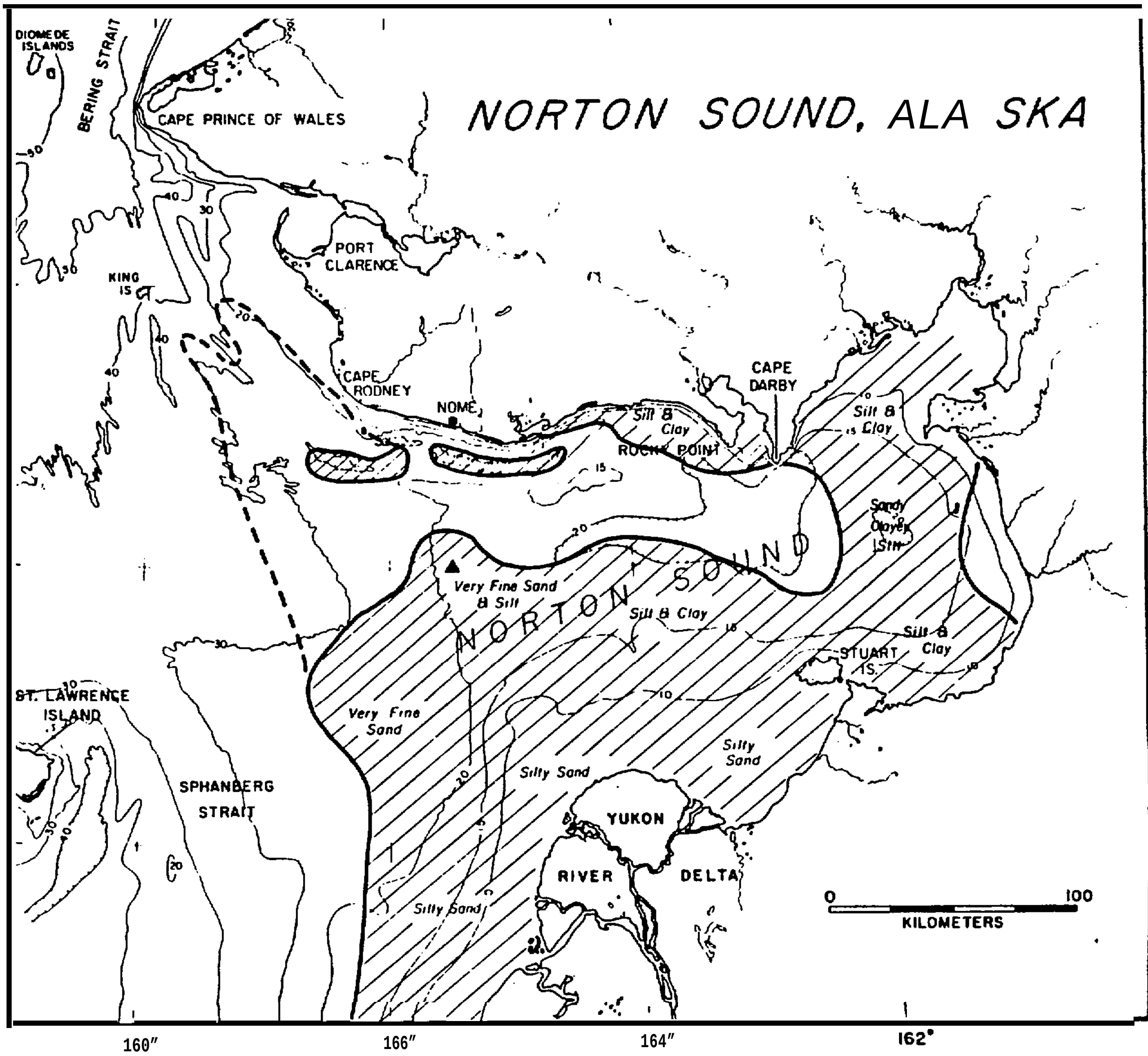

Figure 1.—Bathymetry of Norton Sound and adjacent area in meters. The cross-hatched area defines the area of modern deposition of Yukon River sediment. The triangle 60 km south of Nome is the GEOPROBE site.

and Creager (1977) and others have shown that the enormous flux of sediment introduced at the mouth of Norton Sound annually by the Yukon River has not yielded sediment accumulations commensurate with the rate of supply. The causes and modes of transport for this apparent exit of Yukon River materials from the immediate region of Norton Sound are topics included in this investigation.

The scope of research in this project also includes topics such as (1) patterns and rates of transport of sediments, nutrients, and pollutants as suspended load in the northern Bering Sea; (2) patterns and rates of transport in the sedimentary bedforms located west of the Seward Peninsula; and (3) wintertime suspended sediment concentrations in western Norton Sound.

B. Specific Objectives

The principal objective of this work is to develop an understanding of the relationships between suspended and bottom sediment transport in Norton Sound and the hydrodynamic regime that causes this transport. Specific objectives are:

1. Completion of maps showing the spatial distributions of suspended particulate matter during the summer and winter seasons and interpretation of these data in terms of sources, transport pathways and hydrography.
2. Production of site-specific temporal histories of sediment transport parameters and hydrodynamic values; these data would include analysis of bottom currents, bottom stress, roughness coefficients, flux vectors and the comparison of quiescent versus storm conditions.
3. Development of quantitative relationships between bottom velocity shear and sediment entrainment for specific sites in Norton Sound.

This research unit addresses "Task D" (transport) described in the OCSEAP Technical Development Plan (1978).

C. Relevance to Problems of Petroleum Development

Our research is pertinent to two major impact areas of petroleum development in the marine environment: (1) transport of materials including pollutants; and (2) hazardous sea floor conditions produced by erosion caused by currents and waves.

The data and analyses produced in this work will enable future engineers, scientists, and other personnel to make better estimates of transport pathways for oil that is spilled in Norton Sound and the northwestern Bering Sea. The transport patterns of suspended fine materials (Iike Yukon River silts and clays) are indicators of the paths oil will take in the average or mean sense (long times >1 month); the transport vectors produced at specific sites will better define the temporal variability of the oil and sediment transport.

This information is immediately useful to chemists and biologists who are assessing the impact that oil and trace metals might have on the local Norton Sound and Bering Sea environment. Oil that is absorbed by the fine suspended organic and inorganic material and is mixed into the bottom sediments will be transported by the regional mean currents. The higher frequency currents such as tidal flow and surface wave-induced currents add local complications to the transport effects. For example, a tidal current average of about 10 cm/s during the ebb stage in Norton Sound (typical for the data) will produce transport over about 4.5 km during the 1.2 hour half-cycle. Biota over this distance would be affected by the local transport of pollutants and nutrients.

The ability to predict accurately the movements of pollutants in the sea is strongly dependent on our knowledge of local transport processes. The mechanisms which control the paths and amounts of material that is moved will have unique aspects in specific geographic regions, like Norton Sound. This study attempts to identify and elaborate upon the most important transport-producing mechanisms in this region, and to relate these mechanisms to entrainment and movement of near-bottom materials.

The eventual understanding which this study has as its goal will hopefully permit an accurate description of bottom transport of sediments, pollutants, nutrients, and other particulate matter in Norton Sound.

III. CURRENT STATE OF KNOWLEDGE

The suspended sediments found in Norton Sound are nearly all derived from the Yukon River, which discharges 70-100 million tons of material per year into the southwestern corner of this area (Fig. 1). Despite this enormous sediment source, Nelson and Creager (1977) and McManus et al. (1977) show that in recent times (< 5,000 years B.P.) modern Yukon fine sands and silts have been accumulating on the Yukon subdelta in southern Norton Sound at a surprisingly low rate. The thin accumulation of sediments has been attributed to the erosive action of storms that occur in the early fall prior to the formation of ice cover (Nelson and Creager 1977). The fine-grained fraction of Yukon-derived materials is presumably transported through the northern Bering Sea with the Alaska Coastal Water and deposited in the southern Chukchi Sea (McManus et al. 1974; Nelson and Creager 1977).

Modern Yukon very fine sands and silts do not forma continuous blanket in Norton Sound. Despite the proximity of this large sediment supply, the modern muds tend to deposit along the southern border of the sound, leaving substantial areas in the north-central area with little or no recent cover (<20 cm). The explanation for the slow rates of accumulation in the northern half of the sound was not known prior to our work. We now believe this situation is the result of strong tidal and storm currents along with an advective transport pattern that diverts the bulk of the Yukon silt to other areas.

Investigations of the large-scale current patterns in the northern Bering and Chukchi Seas have been summarized by Coachman et al. (1975). When viewed in a regional sense, the mean circulation is relatively simple. Bering Sea shelf water flows toward the Arctic Ocean and the magnitude of this transport is modulated primarily by atmospheric pressure changes. Owing to topography, the current speed increases toward the north; the effect of flow constriction is particularly apparent north of 64°30'N latitude. Bottom sediments in the approaches to Bering Strait are predominantly sands which have been molded into a progression of bedform types that are characteristic of progressively stronger bottom currents. There is little chance for permanent deposition of fine-grained sediments in this area (north of 64° 30') and suspended material moves rapidly through Bering Strait and into the Chukchi Sea (Drake et al., in press).

Whereas the gross aspects of the regional flow field are reasonably well known, the physical oceanography of Norton Sound has only recently been examined. As is typical of most investigations of' 'unknown" areas the initial gains in knowledge tend to come easily but the detail needed to achieve a quantitative understanding comes only after several years of intensive research.

Studies in 1976 by Muench, Charnell, and Coachman (1977) and Cacchione and Drake (1977) were the first adequate investigations of the physical oceanography of Norton Sound. Among many results the following should be noted:

1. Muench et al. (1977) suggested that the circulation in the outer part of Norton Sound is characterized by a cyclonic gyre.
2. Exchange of water between the outer Sound and the eastern "cul-de-sac" is limited. In fact, the bottom water in the cul-de-sac late in the summer of 1976 was probably remnant from the previous winter (Muench et al. 197'7).
3. GEOPROBE data for September-October 1976 showed that tidal currents were surprisingly strong in 18 m of water (60 km south of Nome). Sediment transport calculations suggested that the tidal currents plus the mean flow should produce bed shear stresses close to those needed to initiate sand motion (Cacchione and Drake 1977).
4. The regional sampling by Cacchione and Drake revealed a pronounced tongue of turbid water originating near the Yukon Delta and extending across the mouth of Norton Sound toward the Nome coast.

Geologic studies by Nelson (1978) have revealed the presence of a number of circular depressions on the Yukon delta front. The origin of these features is presently unknown but it is possible that they are related to intense currents during storms. The delta front is an area of rapid sand and silt deposition in the summer and these materials should be readily eroded during the late summer storms.

IV. STUDY AREA

Norton Sound *is a* shallow arm of the northern Bering Sea, located on the western margin of Alaska, south of the Seward Peninsula (Fig. 1). It is approximately rectangular in shape, 250 km long east to west, and 130 km long north to south. Water depth everywhere is less than 24 m; average depth is 18 m. Nome, population 2,400, is situated along the northwest coast.

The geologic history of Norton Basin and the Yukon delta complex have been discussed by Nelson et al. (1974) and Dupré (1978). A complete description of the bottom sediments in the northern Bering Sea is presented by McManus et al. (1977). Seasonal climatic variations are briefly discussed in Appendix B.

Although we have concentrated our work within Norton Sound we have also collected data in Bering Strait and in the region of sand waves west of Port Clarence. In addition, Nelson (USGS, pers. commun.) collected water samples for suspended sediment analysis in previously unsampled areas north of Saint Lawrence Island.

V. DATA COLLECTION

We employed two complementary methods of data collection in our Norton Sound work. The first method involved regional sampling of hydrographic parameters and suspended particulate matter in order to examine the spatial variation in sediment transport. Sampling cruises were conducted in September-October 1976, July 1977, and February–March 1978. The second method focused on temporal variation in transport and employed an instrumented, bottom tripod system (GEOPROBE). The GEOPROBE system is designed to measure bottom currents and pressure, temperature, and light transmission and scattering for periods of about 3 months. In addition, bottom photographs are taken at a fixed time-interval and also at times when the bottom current exceeds preselected speeds. GEOPROBE operation and data analysis are described in Appendix A.

Specific methods of sample collection and analysis have been discussed in detail in Cacchione and Drake (1977) and Appendixes A-D.

VI. RESULTS

A. Suspended Particulate Matter

Distributions of total suspended matter (TSM) during September-October 1976, July 1977, and February-March 1978 are shown in Appendixes B and C. In each case the distribution reflects the dominance of the Yukon River sediment supply in Norton Sound and the advective transport of this material across the mouth of the sound. Combustion analysis of the suspended matter shows that inorganic components compose the bulk of the material during both summer and winter seasons. The TSM during fair weather conditions (negligible surface wave action) is principally finer than 16 pm, although coarser material was in suspension near the delta in July 1977 and February 1978.

Subsurface distribution of TSM in the summer reveals a two-layer stratification which corresponds closely to the water density stratification (Appendix B). The bulk of the suspended matter is located in the lower layer within a few meters of the sea floor and the concentrations and texture of this material reflect the balance between turbulent energy and particle settling. In the winter the discharge of fresh water is negligible, and vertical mixing due to surface water cooling and ice formation leads to the destruction of the two-layer system and formation of a single, nearly homogeneous layer in western Norton Sound (Appendix C). Vertical mixing of suspended matter is not restricted in the winter, and the TSM concentrations show only slight increases at depth. When the winter TSM values are integrated over the entire water column and compared to the depth-averaged suspended load in summer, it is evident that seasonal variation in “wash load” is negligible on the pro delta (Appendix C). The suspended matter in winter is dominated by fine silt and clay and is essentially the same as the suspended matter in summer (quiescent conditions).

B. Temporal Variations—GEOPROBE Results

GEOPROBE tripods were deployed in 1976 and 1977 at a site 60 km south of Nome (64°06’N latitude, 165°30’ W longitude) near the northern margin of Yukon pro delta deposits (Fig. 1). Both deployments resulted in successful measurements of bottom currents, pressure, temperature and the optical parameters, transmission and scattering. The 1977 record covered an 80-day period, July 8-September 26, and this data set provides an excellent comparison between fair weather and storm conditions. The 1977 GEOPROBE data are discussed in Appendixes B and D. In addition, a complete presentation of these data was included in our annual report for 1978 (Cacchione and Drake 1978). The significant aspects of the GEOPROBE results which were presented in the 1978 report are reproduced here.

Hourly Average Current Measurements

Currents are measured at five positions on each GEOPROBE tripod as shown in Figure 2. As discussed in Section V, the rotor/vane values represent average currents for each 1-hr interval; each e-m current sensor produces "burst" measurements taken one per second for 60 seconds during each l-hr interval. The hourly averages for each current sensor over the entire 80-day period are shown in Appendix E. Also shown for each sensor are the statistics and histograms of speed and direction for the entire record (July 8-September 26, 1977).

Several significant results are obvious in the current data and are pointed out here. Refer to Appendix E for the figures.

(1) The speed and direction records are dominated by a tidal periodicity for the first 57 days (to about September 5). The tidal current has a mixed periodicity with a dominant diurnal component prevalent in the more intense E-W motion. A distinct spring-neap fortnightly cycle is evident, with relatively low currents with confused direction occurring during the neap stage. For example, CM 4 has weak, neap tidal current-speeds during the period around July 10 and again 2 weeks later on July 24, August 8, and so on. The strongest tidal currents occur during peak springs, achieving speeds of about 25 cm/s at CM 1 to about 35 cm/s at CM 4. The E-W tidal currents are very energetic; these records compare favorably with the current meter record taken by PMEL near site G1 (not shown).

(2) The current records show events that are longer in duration than the daily tidal cycle. For example, on July 24-25, September 4-7, and especially during September 13-16 and subsequently the current speed records show prolonged periods (>1 day) of increased, non-tidal flows. As will be discussed below, these events are correlated with increased wind speeds and wind direction shifts.

(3) The dominant low frequency non-tidal flow (daily-averaged) is generally northward, with added eastward component at CM 1 and CM 4 (Appendix E—' 'stick" diagrams). The small magnitudes of the daily averages, denoted by the short' 'sticks" in the daily vector records are statistically insignificant. However, the large northward daily component during September is significant and occurs during strong southerly winds. The progressive vector plots essentially estimate the daily drift over the 80-day record at each sensor, and show the north-northeastward motion (about 2.5 km/day or 3 cm/s at CM 4).

(4) The storm-intensified bottom flow during September 13-15 has hourly average values (i.e., burst-averaged) of nearly 25 cm/sat 20 cm above the bed (CM 1) and greater

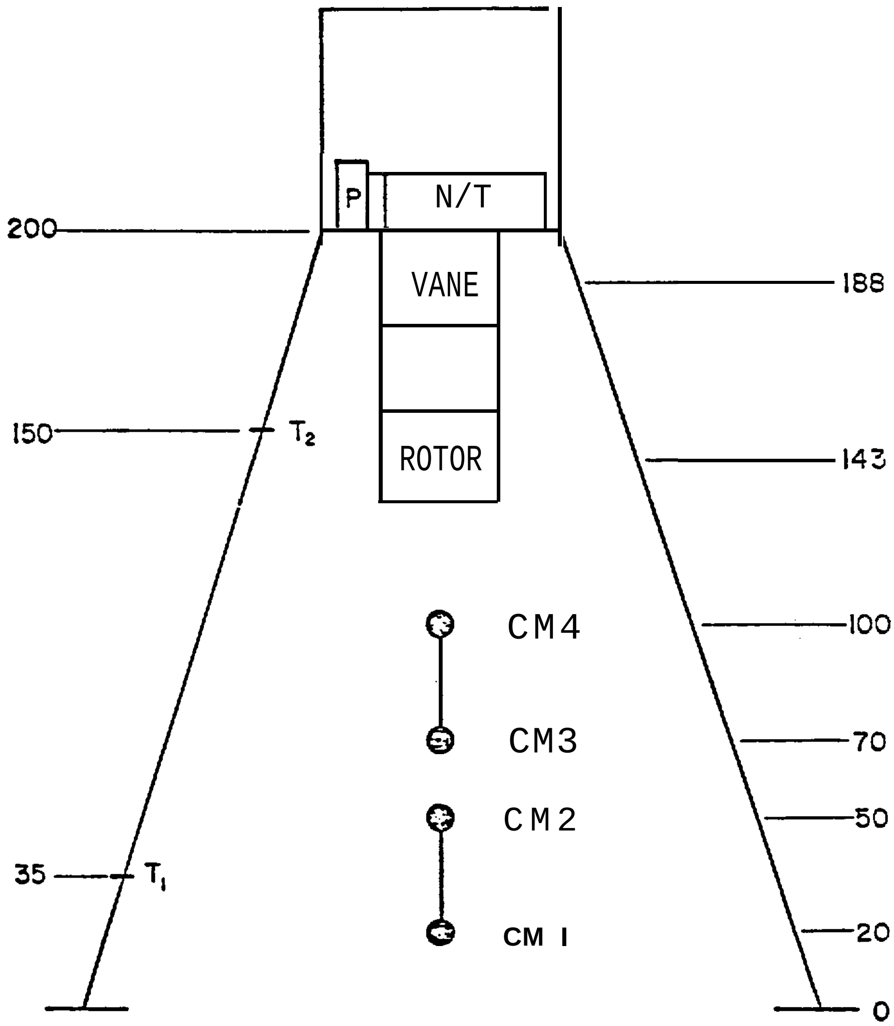

Figure 2.–Schematic of GEOPROBE tripod.
AU distances are given in centimeters from the base of the foot pads.

than 40 cm/s at 100 cm above the bed (CM 4).

(5) Strong non-tidal flows subsequent to the September 13-15 storm event are evident. The N-S component has a marked northward component of about 10 cm/s at CM 4 throughout the period September 21–22 and the diurnal overtones. The other sensors show a similar northward polarization during the post-storm period.

Graphs of the power spectra for each time-series record of burst-averaged currents are given in Appendix E. The kinetic energy spectrum for each sensor shows that the diurnal and semi-diurnal components dominate the motion field; however, a lower frequency peak (not significant at 95% confidence interval) is present at a period of about 140 hr (5.8 days). The spectral plots for E-W and N-S components generally show largest power at the diurnal period.

Burst Data

The e-m current sensors were sampled each second over a single 60-s burst to obtain measurements of the surface wave-induced currents. The data are too numerous to present as time series plots for the entire 1,900 burst sequences. The total number of burst data points for each e–m current sensor is about 1.2x 10^5.

The most significant finding is that the large surface waves and swell (l-2 m) during September 13-14 occurred during strong southwesterly winds (-20 knots) that persisted for over 24 hr. Additionally, this was a period of high spring tides. The combined wind-driven, wave-induced, and tidal currents produced near-bottom currents of 60-'70 cm/s at the times of measurements.

The maximum periods of the wave motion derived from the pressure data were 5 s, 7 s, and 11 s. The relatively long periods during the strong winds of September 13-14 are particularly significant because of the shallow water depth of 20 m at site G1. These waves probably were swell that had propagated into the areas from the southwest.

Other Current Data

Figure 3 contains GE OPROBE sensor data for the first 30 days (July 8-August 7) of the 1977 experiment. The uppermost graph shows hourly averages of current speed obtained with the rotor/vane sensors. Semi-diurnal tidal motion and two fortnightly tidal cycles are quite obvious in this record. Spring tidal current speeds have daily maxima of 25-32 cm/s; neap tidal current maxima are 10-15 cm/s.

The plots of light transmission (TRANS) and light scattering (NEPHEL) in Figure 3 are presented as relative units of measurement taken once each hour (basic interval). The relatively persistent, low levels of scattering, about 0.24 relative, correspond to about 3-5 mg/liter as derived from calibration data (not shown here). These levels are representative of the quiescent conditions in the region of measurement as determined by independent shipboard sampling (about 4.4 mg/liter).

Light transmission is more sensitive to turbidity fluctuations than scattering at relatively low levels of suspended concentrations. Therefore, the diurnal fluctuations in light transmission, not apparent in the scattering record (July 8-July 21), correspond to real changes in the turbidity levels (about 1-2 mg/liter peak-to-peak). These tidal fluctuations in turbidity are correlated with similar diurnal oscillations in the temperature data. A more detailed examination of these results shows several significant features:

1. The oscillations are distantly diurnal, not semi-diurnal.
2. Periods of low temperatures (' 'cold") are correlated with values of low turbidity ("clear").
3. During times of neap tide (July 8, July 23, August 6), both turbidity and temperature are relatively steady.

The above features suggest that tidal advection, specifically the E-W diurnal motion evident in the current speed (E-W) values transports water into and out of Norton Sound, sweeping past site G1. This mechanism is a more plausible explanation for the

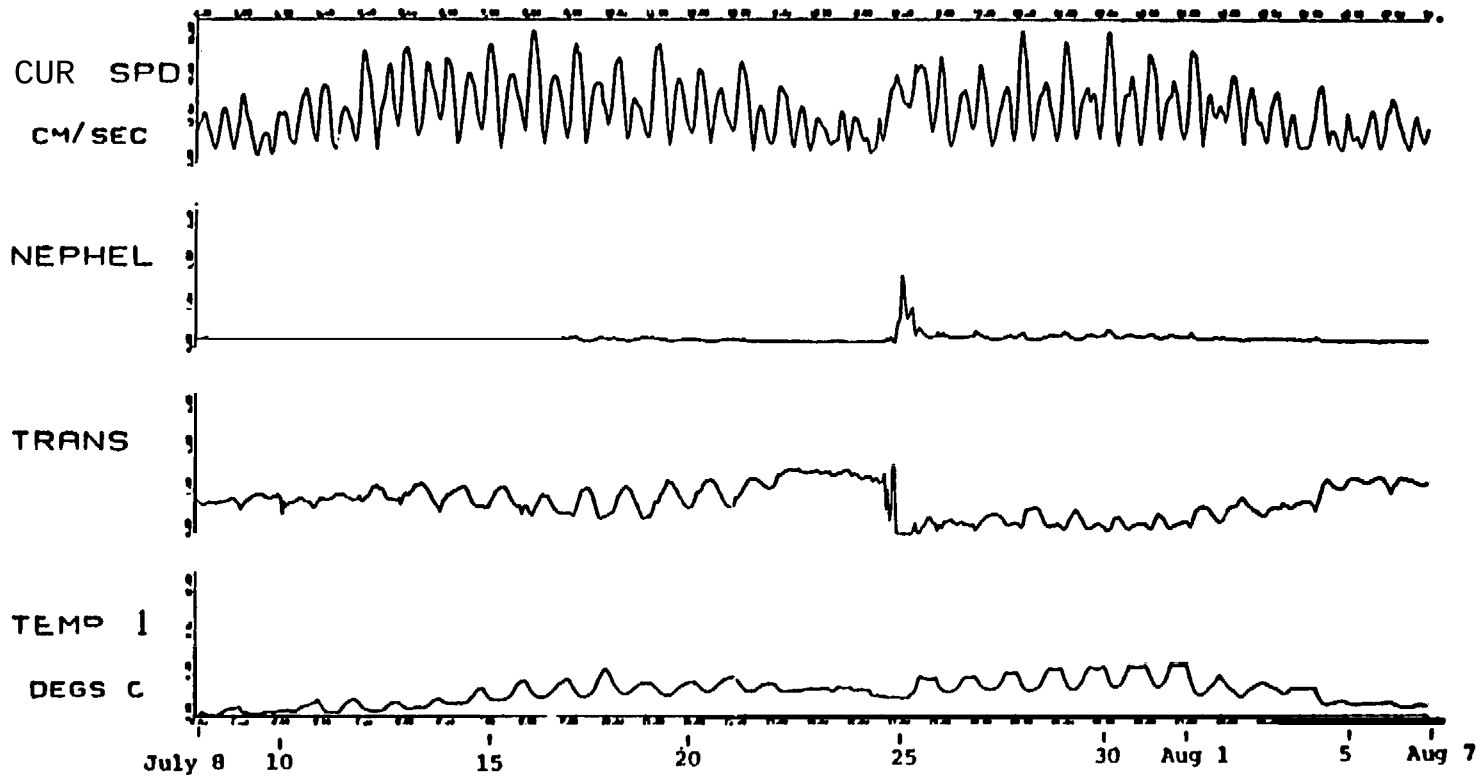

Figure 3.–Hourly GEOPROBE data taken over the 30-day period from 0000, July 8, to 0000, August 7, 1977. Current speeds (CUR SPD) at top are hourly averages obtained with the Savonius rotor. Light scattering (NEPHEL) and light transmission (TRANS) are in relative units; value for these and for temperature (TEMP 1) were taken once each hour. Horizontal axis is in days.

observed values than vertical advection or mixing caused by the internal tide because of the correlation of "cold" with "clear" water. Since the bottom water is colder and more turbid than the surface layer, a vertical mixing or advection process would presumably cause a correlation of "cold" with "turbid" values. The horizontal tidal advection implies, then, that with a rms diurnal tidal speed of about 10 cm/s, reversing lateral E-W transport of about 4.5 km will occur every 1.2 hr.

Even more noteworthy in Figure 3 is the unusual "event" that occurs on July 25, characterized by a sudden increase in scattering speed increase due to a non-tidal current. The peak NEPHEL value of 2.0 relative corresponds to about 50 mg/liter in sediment concentrations, an order of magnitude increase over the "normal" levels.

Figure 4 shows the weather data recorded at the National Weather Service station at Nome (about 30 miles to the north) during the period of this unusual event. Hourly values of wind speed, wind direction, and air pressure are plotted in this figure. The wind data show a regular diurnal cycle, with wind speeds generally lower during the late evening-early morning hours. During July 24, wind speeds increased to 9-10 m/s (about 20 knots) and became persistent, about 12 knots, over the next several days. Wind direction also became steadier from the southeast during this period. Air pressure dropped off, suggesting the passage of a low pressure center through the region. The larger surface waves caused by the increased wind stress produced maximum oscillatory bottom currents as high as 35 cm/s (Fig. 5). The increased, sustained wind stress, occurring at the end of a neap stage in the tidal regime, apparently also caused an increase in magnitude and duration of the mean bottom current speed. The combined effect of higher wave-induced and wind-driven currents produced a bottom stress competent enough to cause the relatively large increase in concentrations of suspended materials (-50 mg/liter). The sudden onset and equally sudden decrease in the concentration values are probably a result of initial resuspension of fine-materials that had settled out locally during the preceding time of neap tide, and to increased upward turbulent mixing of the higher near-bottom suspended load by vigorous wave activity.

The effects on sediment movement at site G1 caused by the passage of a moderate storm were even more vividly demonstrated in September 1977. A detailed analysis of this storm is presented in Appendix D.

VII. DISCUSSION

A. Transport Pathways of Suspended Matter

Three transport pathways are important in the dispersal of terrigenous silt and clay delivered by the Yukon River (see Appendix B for detailed discussion):

1. Initial transport (during the summer months at least) is characterized by westerly and southerly flow within 20 km of the Yukon Delta. Turbid water commonly extends south to Cape Romanzof and on June 29, 1977, a NOAA satellite image suggests transport as far south as Hazen Bay. This transport pattern, evident on satellite images, is rather surprising because one would expect that the density

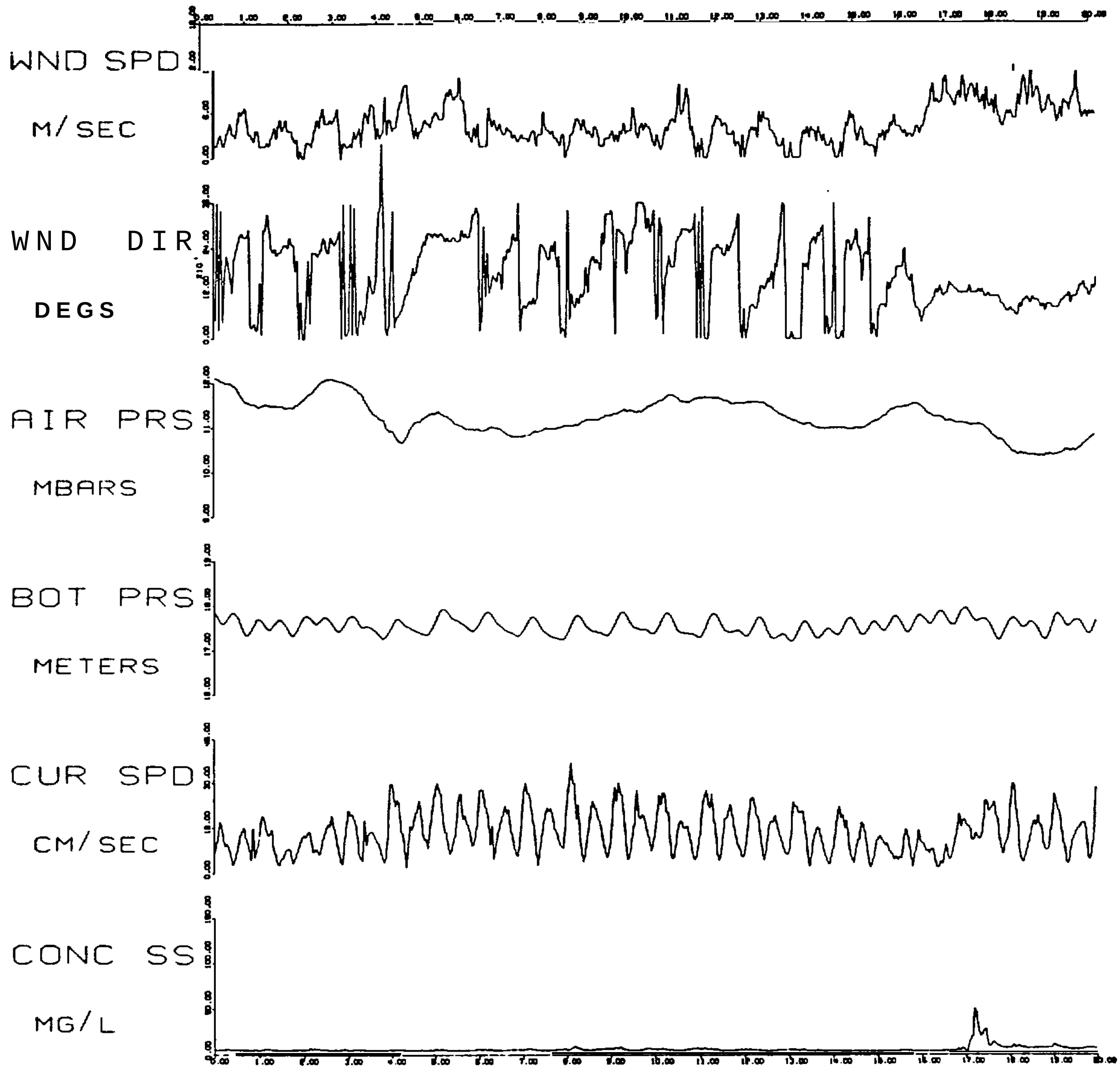

Figure 4.—GEOPROBE data obtained during July 8–28, 1977, and meteorological data recorded at Nome, Alaska (National Weather Service). The data show an increase in wind speed on July 24 which was followed by a sudden increase in suspended matter concentration. The current speed data are hourly averages obtained with the Savonius rotor. See Figure 5 for wave-generated currents on July 25.

distribution would generate currents to the north and east around the delta front (owing to Coriolis effect). We suspect that the observed current is the result of entrainment of nearshore water by the Alaska Coastal Water as it flows northward past Cape Romanzof. Dupré (RU 208) has found that embayments to the south of the major Yukon River distribution contain large amounts of modern Yukon silt. This finding provides independent evidence to support the importance of southward nearshore flow.

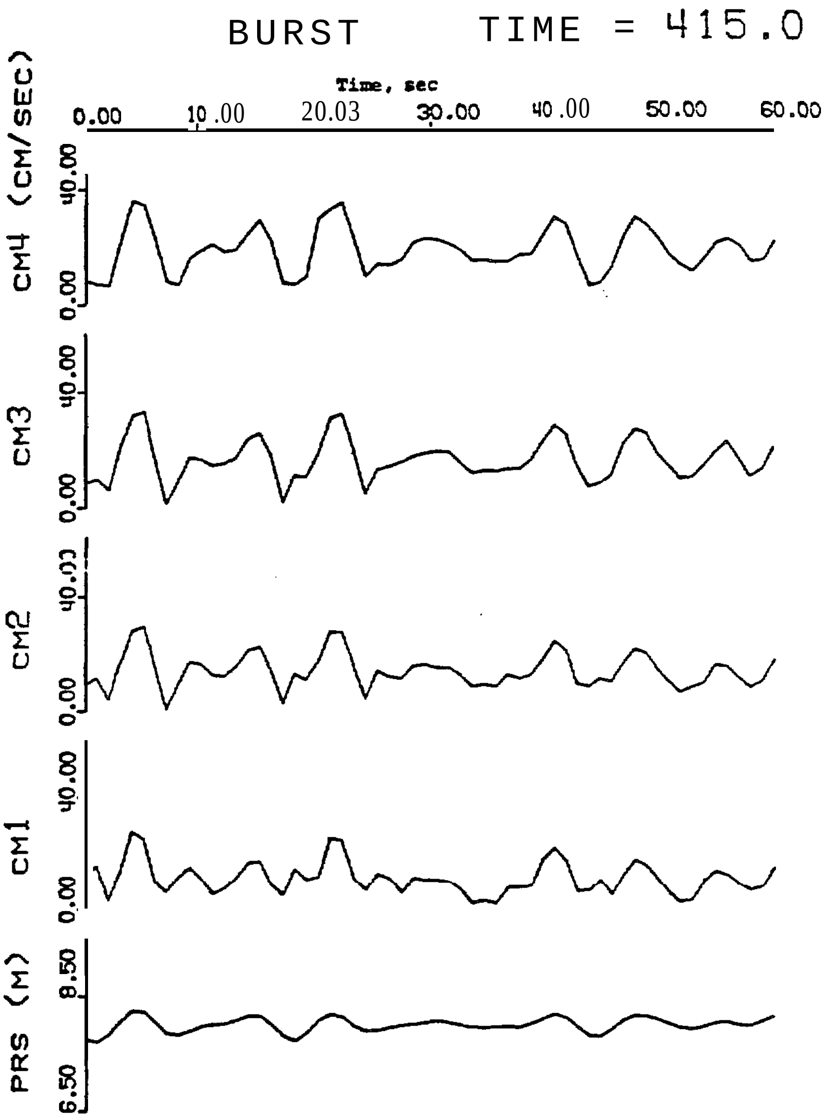

Figure 5.—"Burst" current (CM) and pressure (PRS) data taken on July 25, 3.977.

2. The suspended matter that is moved southward along the west shore of the delta either accumulates in "low energy" lagoons and bays or returns with the Alaska Coastal Water. Our studies, the studies of Muench et al. (1977), and a large body of data collected over the years by L. Coachman and his associates (University of Washington) demonstrates a nearly' 'unidirectional" flow of shelf water northward between the mainland and St. Lawrence Island. This flow is driven by the difference in sea level between the Bering Sea and the Arctic Ocean and the need to replace water lost from the Arctic Ocean to the Atlantic Ocean.

As this shelf current flows past Norton Sound it tends to mix with turbid Yukon water in the vicinity of the delta. This mixed water then extends across the mouth of the sound toward the coast at Nome. There is no question that the currents immediately north and northwest of the delta are complex. Nevertheless, the distributions of both surface and near bottom suspended matter demonstrate the existence of this important northward transport pathway. Muench et al. (1977) have postulated a mean circulation system that includes a cyclonic gyre centered in the outer part of the sound north of the delta. In order to obtain agreement between our results and this circulation pattern, it is necessary to postulate a split in the northward flow near the Yukon Delta with part of the water moving directly across the sound and another part moving into the sound to feed the cyclonic gyre. Obviously, more long-term current measurements are needed to fully describe the flow field over the Yukon prodelta.

3. Bottom sediments in the inner part of Norton Sound are derived from the modern Yukon River (Nelson and Creager 1977). In fact, accumulation rates of mud in this area (east of Cape Darby and Stuart Island) are among the highest on the northern Bering Sea shelf. Suspended matter distributions in 1977 and in 1976 (Cacchione and Drake 1977) suggest transport of Yukon silt and clay eastward past Stuart Island. However, the available data do not support a strong interchange of water between the inner and outer parts of Norton Sound (Drake et al. 1977; Muench et al. 1977. Satellite images tend to show a steep gradient decrease in TSM at the surface near Stuart Island such that the bulk of the suspended matter is confined to Pastel Bay (west of Stuart Island).

The effects of wind stress on the circulation in Norton Sound are not well understood but it seems likely that periods of westerly winds would drive surface water eastward along the southern coast and into the inner sound. West and southwest winds exceeding 15 knots occur on about 3-4 days during each of the summer months (based on weather records at Nome); winds come from the southwest quadrant approximately 40% of the time. It is possible that flow into the inner sound occurs whenever the wind stress is sufficient to overcome the effects of other forcing mechanisms.

The volume transport of suspended matter eastward from the delta is not as important as other transport pathways. However, the sediment that is carried into the inner part of Norton Sound tends to remain there. We believe that key factors in this sediment retention are the low energy of bottom currents in this area and the limited exchange of bottom water with the outer sound (as shown by the presence of remnant, winter bottom water well into the ice-free season). Of these two factors we suspect that the latter is the more significant because TSM concentrations in the remnant water are relatively high, indicating that this water, although isolated, is not motionless. For example, current data collected by R. Muench within the postulated remnant water body southwest of Cape Darby (Fig. 1) show tidal currents of up to 30–40 cm/s but essentially no net motion. It seems likely that a similar but less vigorous current regime also would characterize the bottom water within the inner sound. Additional data are needed.

B. Comparison of 1976 and 1977 Results

Suspended sediment distributions on many continental shelves exhibit a large degree of spatial and temporal variability. It is probable that much of the variability is caused by wind-driven transport combined with variable rates of fine sediment resuspension by wave action.

The data for Norton Sound in late summer of 1976 and early summer of 1977 reveal strikingly similar suspended sediment patterns (Cacchione and Drake 1977). In both cases the distributions at the surface and near the bottom are dominated by a broad tongue of turbid water that originates along the western side of the Yukon Delta and extends across the mouth of Norton Sound. Temperature and salinity values show that this water is a mixture of Alaska Coastal and Yukon River water.

These results along with the GEOPROBE measurements indicate that current patterns and speeds in the outer part of Norton Sound are caused principally by the tides and the regional transport of Bering Sea shelf water toward the Chukchi Sea. In particular, it appears that the regional flow establishes, to a large degree, the mean circulation pattern in the sound whereas the tidal currents (primarily constrained to flow E-W) serve to maintain particles in suspension and to resuspend materials at times of spring tides. Tidal excursions are approximately 4-5 km with only a small net motion. Consequently, they act as a diffusing element. The' 'clarity" of the observed suspended matter distributions (i.e., the sharpness of boundaries between clear and turbid waters) suggests the importance and consistency of the advective flow regime in Norton Sound.

The situation is different in the inner part of Norton Sound (east of Cape Darby and Stuart Island). Here the suspended matter distribution tends toward greater horizontal uniformity, particularly in September 1976. This suggests that tidal and wind-driven currents are more significant compared to advection. As discussed above, the inner part of Norton Sound is strongly two-layered and the lower layer is water, formed during the winter months. Substantial advective motion must be restricted to the low density surface layer and mixing across the pycnocline must be minimal (Muench et al. 1977).

The results of our winter sample collections (February-March 1978) confirm our conclusion that the bottom currents generated by the astronomical tides are sufficient to maintain the transport of fine silt and clay through Norton Sound; i.e., the continuous sediment flux which we term" wash load." More significantly, the concentration levels observed in the winter demonstrate that a reservoir of Yukon River silt must exist near the delta. Furthermore, the currents near the delta (below the shorefast ice) must be strong enough to resuspend silt and feed particulate matter to the advective flow across the prodelta (Appendix C).

C. Temporal Variability

The GEOPROBE tripod data provide a valuable time history of near-bottom measurements of fluid and sediment parameters at site G1 (Appendix D) for the 80-day deployment period. A complete listing and plot of all data is not included here because of the large volume of numbers that are generated by one GEOPROBE station tape. Only the most pertinent information is given in Section VI.

One of the most significant results is the contrast in dynamic conditions that occurs during "normal" and stormy periods. The normal near-bottom flow field at G1 is characterized by the data shown in Figures 3 and 4 for July 8-24. During this time, tidal forcing dominates the hourly mean values of pressure, bottom current, temperature, and turbidity. Small perturbations in the tidally dominated normal regime occur, principally due to short periods of increased wind-driven currents and waves.

The tidal bottom currents are most intense during spring tides, commonly achieving values of greater than 30 cm/s at 1 m above the sea floor. During neap, the daily maximum currents at 1 m are much reduced, typically less than 15 cm/s during the smallest tides. As Figure 4 shows, the bottom pressure has a definite change in pattern during the fortnightly cycle. The spring tides are strongly mixed, with two unequal highs during each daily cycle; the neaps are more nearly a diurnal type.

Figures 6 and 7 point out the extreme importance of storm conditions in affecting the sediment transport pattern in this area. The relatively high, sustained values of hourly averaged bottom current speed and the persistent northward directions are indicative of active, large transport of materials. These wind-generated events appear to overwhelm the rhythmic pattern that is the "normal" condition.

In terms of evaluating the fluid motion at the seafloor for its effect in the transport of sediments, two of the most critical parameters are shear velocity, u_*, and bed roughness, z_o, where

$$u_* = (\tau_o/\rho)^{1/2}; \qquad (1)$$

τ_o is the bottom shear stress, ρ is fluid density, and z_o is the roughness length in the Karman-Prandtl turbulent boundary layer equation

$$u/u_* = \frac{1}{k} \ln \left(\frac{z + z_o}{z_o} \right) \qquad (2)$$

u is the velocity at a distance z above the bed; k -0.4 is von Karman's constant.

To compute u_* and z_o from equation (2), u can be measured at several levels (z) above the bed. If more than two levels are used then the validity of equation (2) can also be estimated. Since the four GEOPROBE e-m current sensors are operated within the bottom tidal boundary layer, these measurements afford a unique data set to derive u_* and z_o values. Figure 8 shows examples of the hourly current speed profiles obtained during neap, spring, and storm conditions. The maximum values of u_* and the maximum speed at 1 m are highest during the storm; spring tide values are significantly greater than during neap.

The threshold values of u_* to initiate movement on non-cohesive sediment can be estimated from the modified Shields Diagram (Madsen and Grant 1976), even when

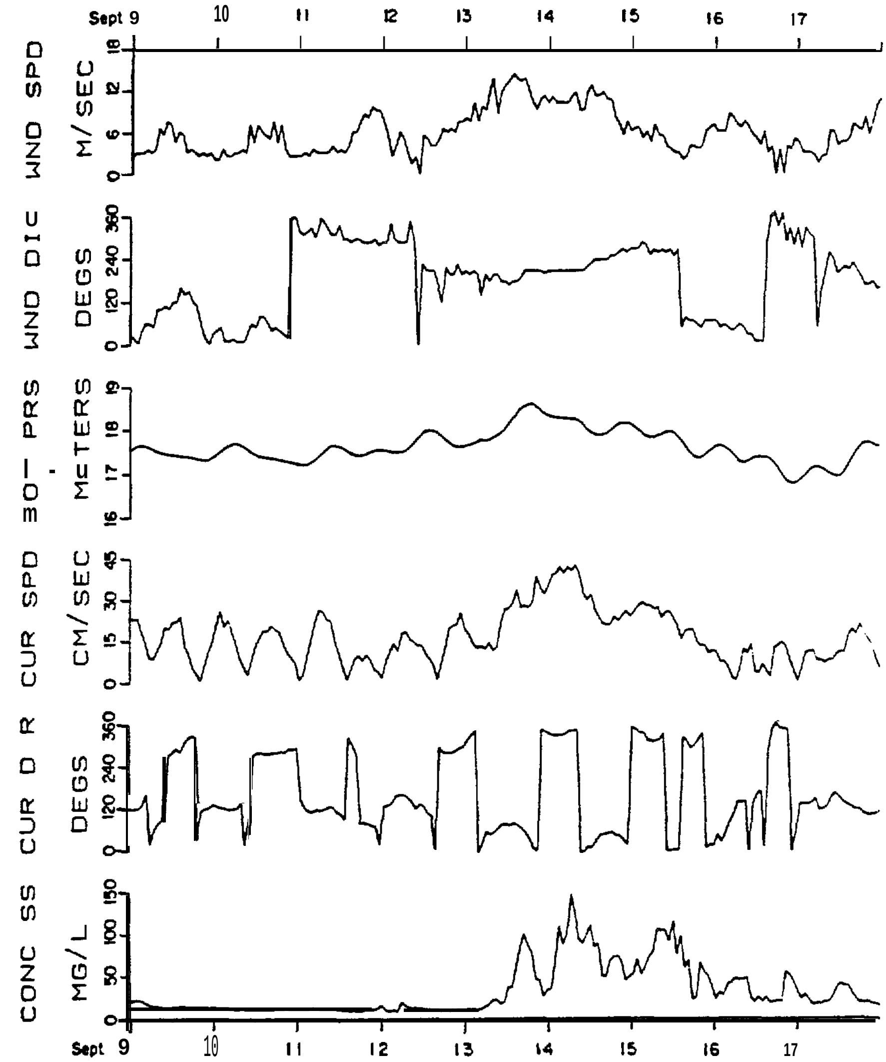

Figure 6.—GEOPROBE and meteorological data during September 9-18, 1977, in Norton Sound. Current speed and bottom pressure are hourly averages and the suspended matter concentrations at 2 m above the sea floor are derived from light scattering values using calibration data. See Figure 7 for examples of the wave-generated currents on September 15.

the flow is unsteady. The critical, or threshold, value of u. for the mean particle size of 0.07 mm at site G1 is 1.3 cm/s. This value, together with u * values in Figure 8, suggests that incipient sediment motion in the vicinity of site G1 occurs during storms and spring tides. The added effects of organic materials (cohesive) and finer-grained sediments (< 62 μ) are not well understood; Jumars (1977) and Southard (1977) have discussed these problems with regard to sediment transport and pointed out the poor state of knowledge in this area. Possibly the binding caused by mucoid surface materials explains the patchiness of the sediment ripples throughout the central western Norton Sound area. Also, the high silt content would tend to inhibit ripple formation and bedload transport. The clay fraction at G1 is less than 5% of the sediment.

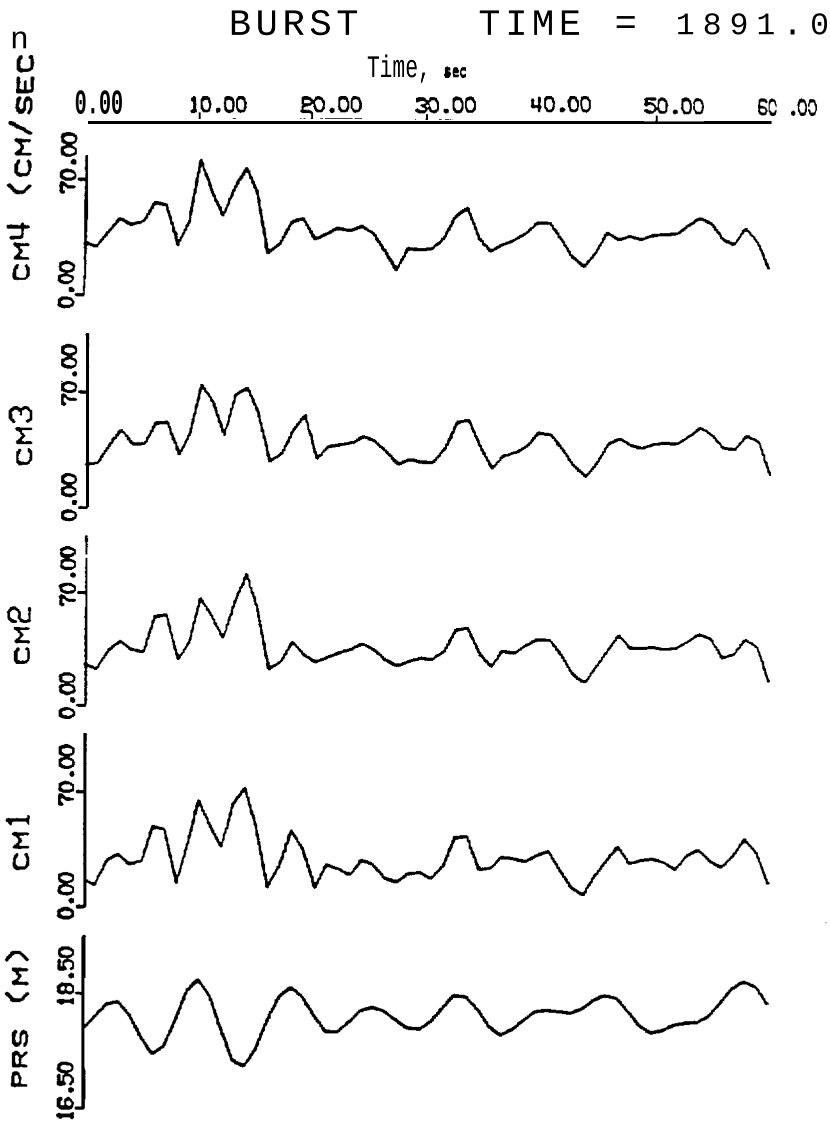

Figure 7.—"Burst" current (CM) and pressure (PRS) data taken on September 15, 1977.

Another important part of the overall transport pattern in this region is demonstrated by Figure 9. Daily average values of u. and z_0 were computed by first taking averages of u at each level over consecutive 24-hr periods. These new daily-averaged values of u, called <u>, were then used in equation (2) to derive daily averaged values of u* and Z., which are shown in Figure 9. Throughout the 80-day period, all vertical profiles of < u > fit a logarithmic curve to within 270. The maximum standard error of estimate of any single value of <u> that derives from using the logarithmic profile is 0.03 cm/s.

Figure 9 clearly shows the effect of the fortnightly tidal cycle on shear velocity, The dashed line is the estimated critical value of u_* of 1.3 cm/s. During times of peak

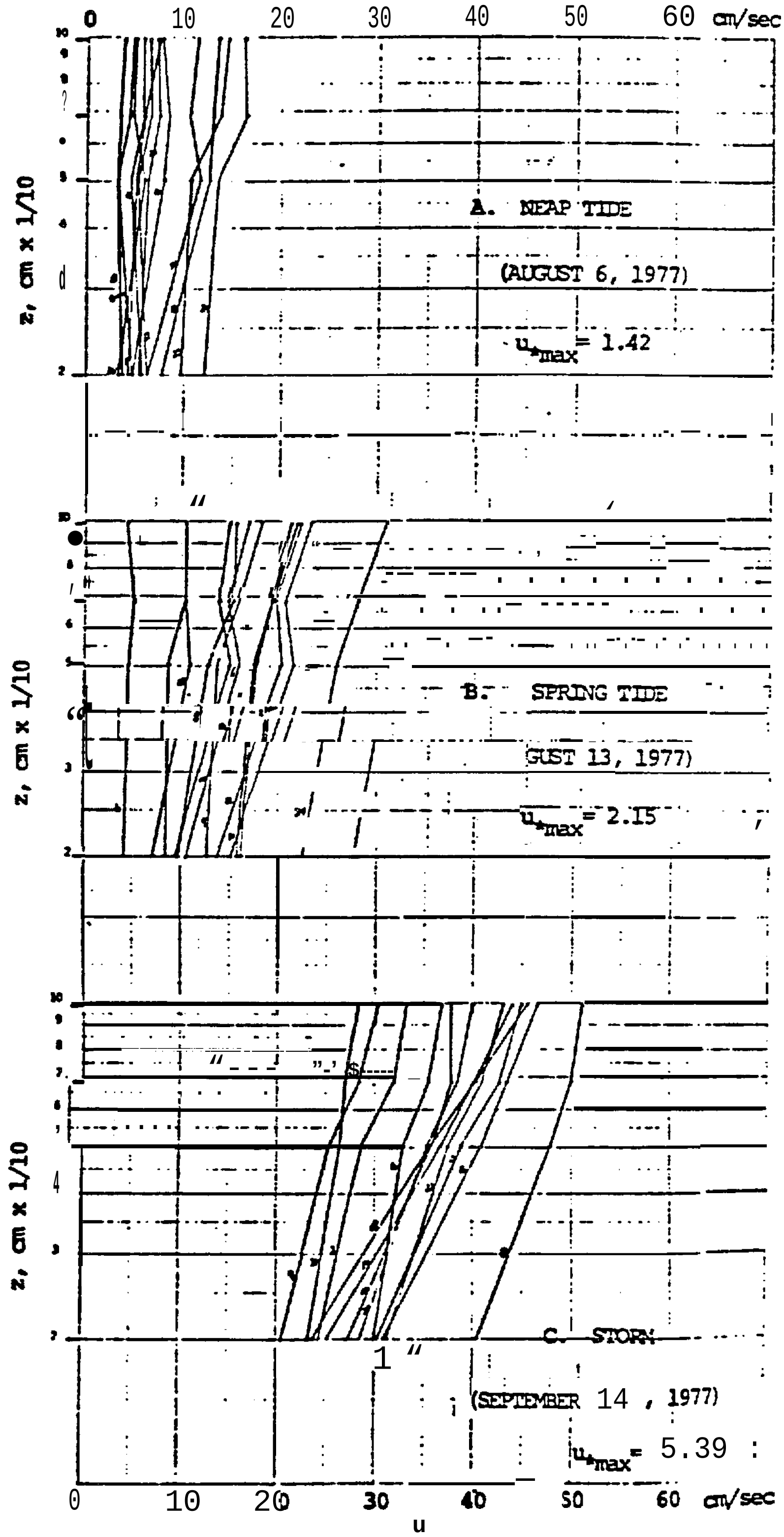

Figure 8.–Current speed, u, in cm/s measured at 4 levels with the electromagnetic current sensors plotted against the natural logarithm of distance above the sea floor (in z) at different times during the 80-day period, July 8-September 27, 1977, in Norton Sound, Alaska. Maximum values of shear velocity, u_*, are shown.

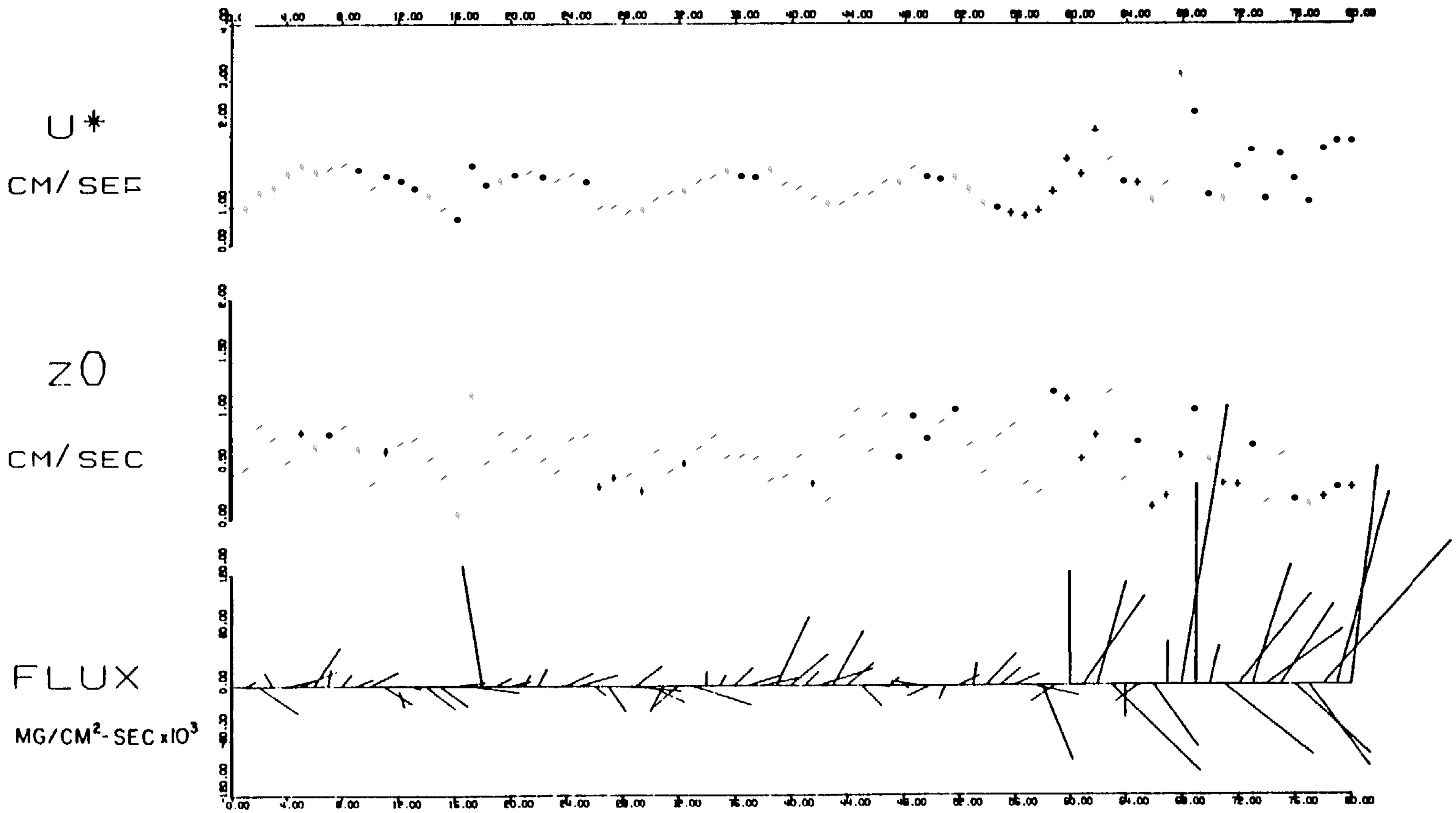

Figure 9.—Daily average values of u_* and z_0 are shown in top two panels. Suspended matter flux is shown in lower panel and was computed using the mean current at 1 m above the bottom and the suspended matter concentrations determined from the nephelometer values.

spring tides, u_* exceeds or equals the critical value. Storm periods during September generate the highest shears. The relatively small change in z_0, even during the storm period is interesting and somewhat surprising (see Appendix D for more complete discussion).

The above discussion did not directly assess the effects of surface waves. Obviously, during times of high winds, the larger waves would be expected to contribute a substantial increase to the instantaneous bed shear stress. In Section VI and Appendix D, examples of the wave-induced currents are shown. The added stress from these waves will produce local resuspension when the combined wave-induced and lower frequency components cause u_* to exceed the critical value. In a water depth of about 20 m, waves of 0.5 m in height with periods of 6s, typical of this area over normal conditions, produce maximum wave-induced bottom currents of about 7-8 cm/s. The bottom stresses contributed by these normal wave conditions, when combined with spring tidal currents, certainly would produce initial motion and resuspension of bottom sediment. Yet when compared to the shear velocities and transport during storms, the quiescent period is not characterized by important bed load transport on the Yukon prodelta.

VIII. CONCLUSIONS

The transport of sediment in Norton Sound can be conveniently described in terms of the distinctly different quiescent and storm regimes. The quiescent or fair weather regime is characterized by generally low levels of sediment transport caused principally by the tides and mean flow augmented by surface waves during spring tide cycles. The quiescent regime is characterized by surface winds of <8-10 m/s, short period surface waves (<6 s), and a predominance of fine silt and clay moving as "wash load." Bedload transport is negligible except in shallow areas where the surface waves become important (for example, on the "2 m bank" which surrounds the Yukon Delta). Although calm weather conditions appear to occur for about 90% of the year in the northern Bering Sea, our GEOPROBE data suggest that less than 50% of the sediment transport occurs under these conditions (see Appendix B). In fact, the GEOPROBE measurements show that critical shear stresses on the prodelta are reached only briefly during spring tides during quiescent periods. This implies that much of the fine-grained suspended matter present over the prodelta is material that was resuspended at shallow depths near the delta and moved northward with the mean current.

During about 30-40 days of each year the surface wind approaches or exceeds 10 m/s, although National Weather Service records for Nome, Alaska, show that sustained winds >15 m/s recur with less than annual frequency. The 2-day storm in September 1977 appears to be representative of the more energetic late summer atmospheric events in Norton Sound. In September, October, and November the polar front migrates south and tends to steer low pressure weather systems from the southwest to the northeast across the northern Bering Sea (see Appendix D). Norton Sound is commonly exposed to strong southerly and southwesterly winds generated by the low pressure cells. Winds from this quadrant can generate 1-3-m waves with periods of 8-n seconds because of the essentially infinite fetch southwest of Norton Sound. It is waves like these which cause severe damage along the northern coast of the sound (Fathauer 1975).

The instantaneous shear velocity (u.) at the GEOPROBE during the September storm reached >6 cm/s and the light scattering data demonstrate a 20-field increase in TSM at 2 m above the bottom. As shown in Appendix B the amount of sediment transported during this brief event was approximately equal to the transport that would occur during 4 months of quiescent conditions.

Although the amount of sediment eroded during storms does not represent a foundation hazard at depths of 15 m or greater, the impact of storms (particularly the surface wave scour) could be highly significant at depths less than 10 m. Indeed, the morphology of the Yukon Delta shows that wave and current energy is concentrated on the western margin of the delta, which is exposed to the open Bering Sea and the full impact of southwesterly storm winds and waves.

IX. NEEDS FOR FURTHER STUDY

Our understanding of sediment transport vectors is largely dependent on our knowledge of the physical oceanography of a region. The circulation on any segment of the shelf cannot be understood without a sufficient number of long-term current meter records. In Norton Sound this requirement is even more acute because of the complexities introduced by the Yukon discharge (which must produce important density effects) and the topography (which must introduce significant frictional effects). The following points need clarification through additional research.

(1) Dynamic considerations suggest that the Yukon “fresh” water surface plume should produce important baroclinic flow around Stuart Island and into the head of the sound. The nature of the sediments show that this is the case. Because the flushing of the inner part of Norton Sound may depend largely on this advection, a more complete knowledge of flow into and out of the area is needed.

(2) There are strong indications in the temperature and salinity data that ‘‘east-west” components of advection (in addition to the reversing tidal currents) are significant in the western half of Norton Sound. A denser array of current meter moorings extending across the sound along several meridians would substantially improve our understanding of the mean circulation and the effects of wind (which presently are largely unknown).

(3) The characteristics of the flow field in the winter in Norton Sound remain unknown. However, indirect evidence (see Appendix C) from suspended sediment measurements and bottom sediment properties suggests that the currents near the Yukon Delta below the shorefast ice are strong and important to the fate of particulate materials. Current measurements in the winter would be most useful.

(4) Wind-driven currents are not discussed in detail in this report because of the nearly total lack of data on this mechanism. The GEOPROBE data show that these currents are important during storms, but we know very little about the wind stress

and wind-generated currents during less energetic times. This data gap is significant and will require further collection of current meter and meteorologic data.

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APPENDIX A.

A New Instrument System to Investigate Sediment Dynamics on Continental Shelves

D. A. Cacchione and D. E, Drake

ABSTRACT*

A new instrumented tripod, the GEOPROBE system, has been constructed and used to collect time-series data on physical and geological parameters that are important in bottom sediment dynamics on continental shelves. Simultaneous in situ digital recording of pressure, temperature, light scattering, and light transmission, in combination with current velocity profiles measured with a near-bottom vertical array of electromagnetic current meters, is used to correlate bottom shear generated by a variety of oceanic processes (waves, tides, mean flow, and others) with incipient movement and resuspension of bottom sediment. A bottom camera system that is activated when current speeds exceed preset threshold values provides a unique method to identify initial sediment motion and bedform development.

Data from a 20-day deployment of the GEOPROBE system in Norton Sound, Alaska, during the period September 24–October 14, 1976, show that threshold conditions for sediment movement are commonly exceeded, even in calm weather periods, due to the additive effects of tidal currents, mean circulation, and surface waves.

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*The full text of Appendix A is available as: Cacchione, D. A., and D. E. Drake. 19’79. A new instrument system to investigate sediment dynamics on continental shelves. Mar. Geol. 30: 299-312.

APPENDIX B.

Sediment Transport in Norton Sound, Alaska

D. E. Drake, D. A. Cacchione, R. D. Muench, and C. H. Nelson

ABSTRACT*

The Yukon River, the largest single source of Bering Sea sediment, delivers more than 95% of its sediment load at the southwest corner of Norton Sound during the ice-free months of late May through October. During this period, surface winds in the northern Bering Sea area are generally light from the south and southwest, and surface waves are not significant. Although wind stress may cause some transport of low-density turbid surface water into the head of Norton Sound, the most significant transport of Yukon River suspended matter occurs within advective currents flowing north across the outer part of the sound. The thickest accumulations of modern Yukon silt and very fine sand occur beneath this persistent current.

We monitored temporal variations in bottom currents, pressure, and suspended-matter concentrations within this major transport pathway for 80 days in the summer of 1977 using a Geological Processes Bottom Environmental (GEOPROBE) tripod system. The record reveals two distinctive periods of bottom flow and sediment transport: an initial 59 days (July 8-September 5) of fair-weather conditions, characterized by tidally dominated currents and relatively low, stable suspended-matter concentrations; and a 21-day period (September 5-26) during which several storms traversed the northern Bering Sea, mean suspended-matter concentrations near the bottom increased by a factor of 5, and the earlier tidal dominance was overshadowed by wind-driven and oscillatory wave-generated currents.

Friction velocities (u_*) at the GEOPROBE site were generally subcritical during the initial fair-weather period. In contrast, the 21-day stormy period was characterized by u_* values that exceeded the critical level of 1.3 cm/s more than 60% of the time. The GEOPROBE data suggest that the very fine sand constituting about 50% of the sediment on the outer part of the Yukon prodelta is transported during a few late-summer and fall storms each year. A conservative estimate shows that suspended-matter transport during the storms in September 1977 was equal to 4 months of fair-weather transport.

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*The full text of Appendix B is available as: Drake, D. E., D. A. Cacchione, R. D. Muench, and C. H. Nelson. 1.980. Sediment transport in Norton Sound, Alaska. Mar. Geol. 36:97-126.

APPENDIX C.

Sediment Transport During the Winter on the Yukon Prodelta, Norton Sound, Alaska

D. E. Drake, C. E. Totman, and P. L. Wiberg

ABSTRACT*

Winter in the northern Bering Sea brings a drastic reduction in terrestrial runoff and a substantial decrease in air-sea momentum transfer (wind and waves) owing to the formation of shorefast and pack ice. Despite these changes, quantities of suspended silt and clay over the Yukon prodelta in the winter of 1978 were essentially the same as those observed during fair weather summer periods, when the sediment discharge of the Yukon River is at its maximum and there is no ice layer to inhibit surface waves. Furthermore, the regional transport pattern involving northward mean flow across the prodelta in Norton Sound remains unchanged in the winter.

Bottom current and light scattering measurements obtained during the summer of 1977 showed that spring tides are capable of resuspending fine sediment at depths of about 18 m on the pro delta in the absence of significant surface wave action. We conclude that during the winter the suspended matter transport system is driven by tidal current reworking of sediments which were introduced by the Yukon River during the previous summer.

*The full text of Appendix C is available as: Drake, D. E., C. E. Totman, and P. L. Wiberg. 19'79. Sediment transport during the winter on the Yukon prodelta, Norton Sound, Alaska. J. Seal. Petrol. 49:1171-1180.

APPENDIX D.

Storm-Generated Sediment Transport on the Bering Sea Shelf, Alaska

D. A. Cacchione and D. E. Drake

ABSTRACT *

GEOPROBE measurements of bottom stress on the outer margin of the Yukon prodelta in Norton Sound show periods of intensified bottom sediment transport during the passage of a subarctic storm. Wave-induced bottom currents significantly increase the local bed shear stress, exceed the threshold conditions for entrainment of bottom sediments, and effectively increase the local mean roughness scale (go). Although maximum tidal stresses during spring tides have values above threshold, average conditions for sediment entrainment are subcritical during spring tides and fair weather. Storm conditions generate mean stresses of about 10 dynes/cm^2, with instantaneous maximum wave stresses of about 10 dynes/cm^2, and cause considerable resuspension and northward transport of Yukon-derived materials.

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*The full text of Appendix D is available as: Cacchione, R. D., and D. E. Drake. 1980. Storm-generated sediment transport on the Bering Sea shelf, Alaska. Geophys. Res. Lett.

APPENDIX E.

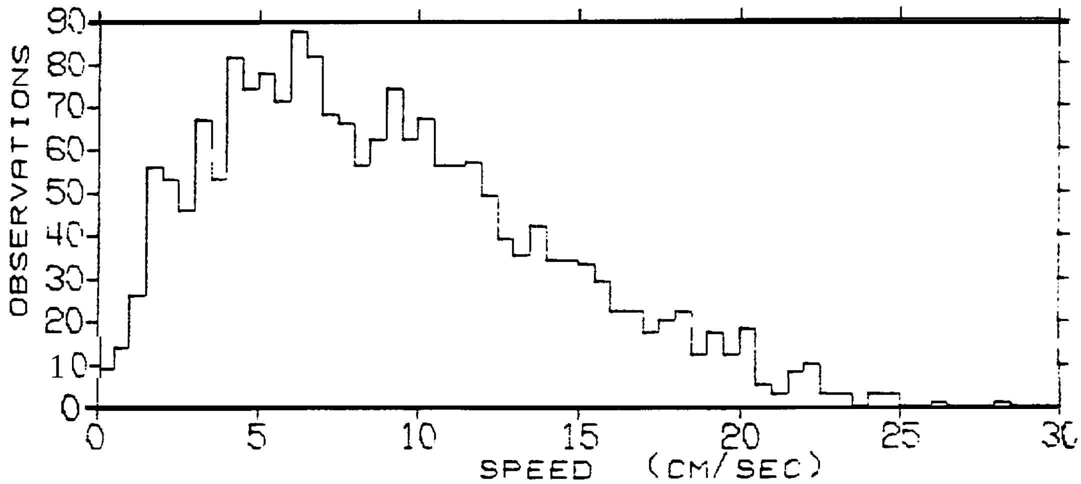
Bottom Currents on the Yukon Prodelta, July 8-September 25, 1977

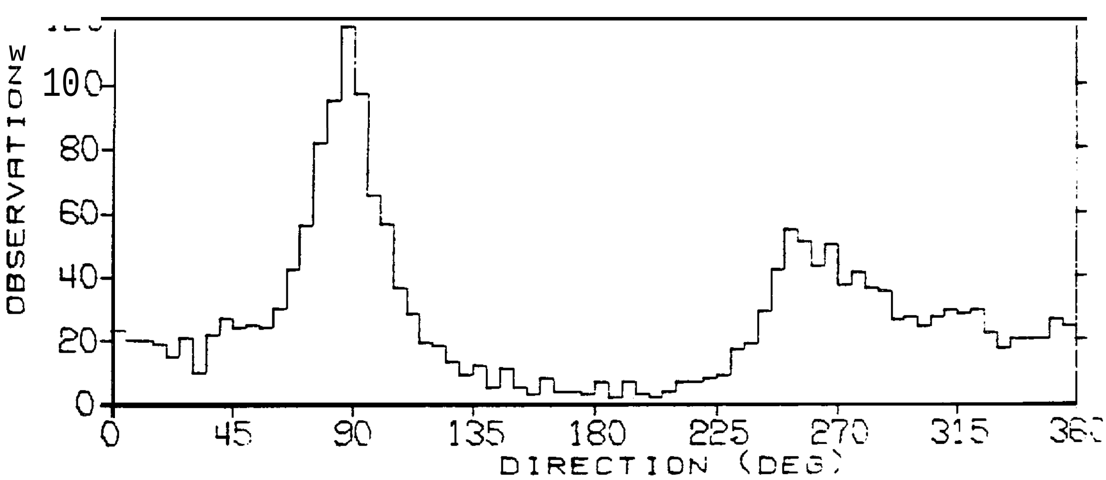
The data were obtained by the electromagnetic current sensors on the GEOPROBE tripod. The raw data consist of' 'burst" measurements of horizontal current speeds taken once per second for 60 consecutive seconds each hour.

STATISTICS AND HISTOGRAMS OF CURRENTS AT CM1 GEOPROBE, NS77
LOCATION = LRT 64 00N, LONG 165 00W, DEPTH 17.5 METERS
OBSERVATION PERIOD = 0000 8 JUL 77 TO 2300 25 SEP 77 (80.0 DAYS)
N = 1920 DT = 1.00 HOURS, UNITS = (CM/SEC)

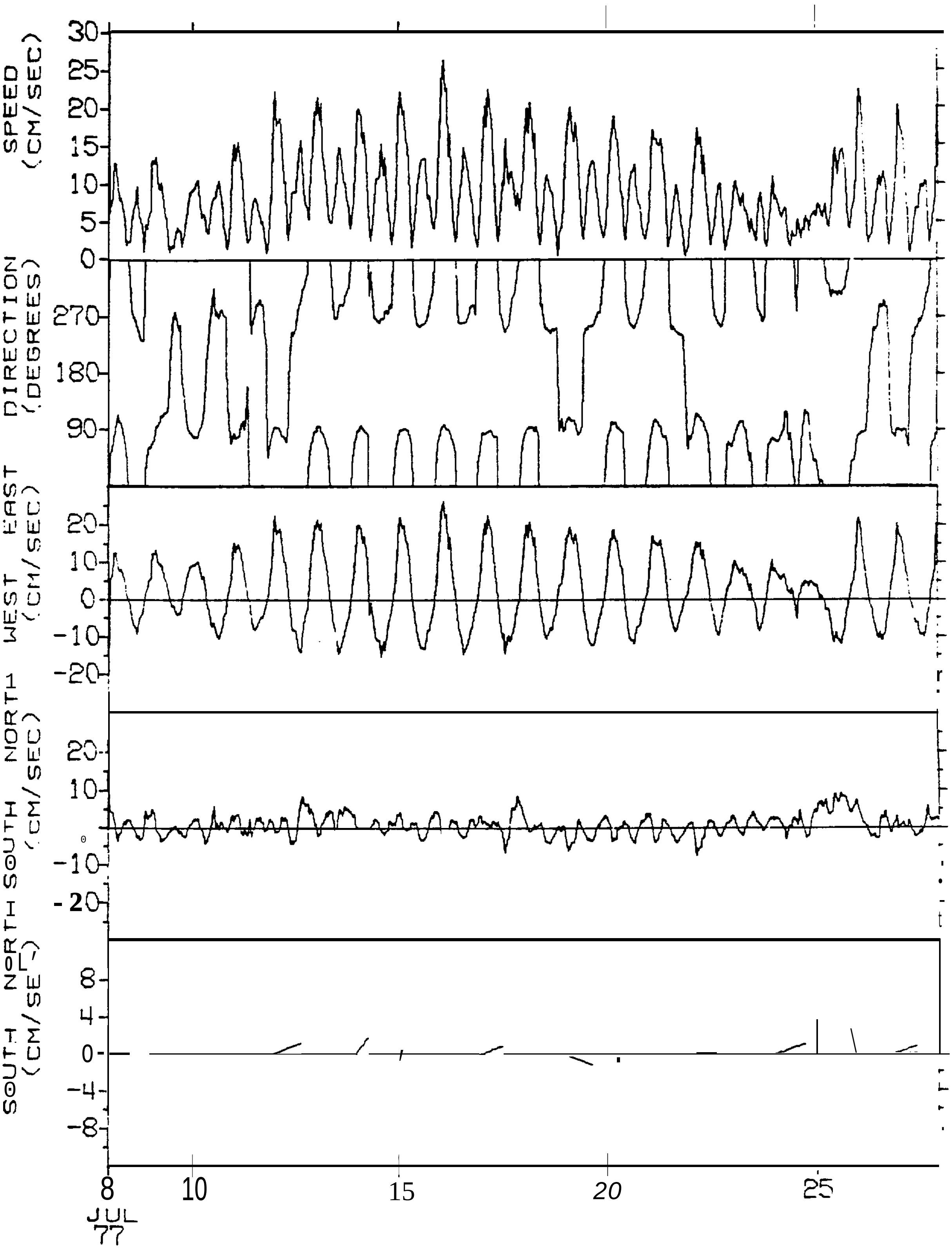
	MEAN	VARIANCE	ST-DEV	SKEW	KURT	MAX	MIN
S	8.93	25.96	5.10	0.622	2.862	28.18	0.03
U	2.14	78.95	8.89	0.279	2.281	28.01	-18.94
V	1.60	19.53	4.42	.0.920	4.804	21.92	-16.12

S = SPEED
U = EAST-WEST COMPONENT OF VELOCITY, EAST = POSITIVE U
V = NORTH-SOUTH COMPONENT OF VELOCITY, NORTH = POSITIVE V





TIME SERIES OF VECTOR AVERAGED CURRENTS AT CM1 GEOPROBE-NS77
LOCATION = LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 8 JUL 77 TO 2300 27 JUL 77 (20.0 DAYS)
AVERAGING INTERVAL = 1.0 HOURS (1 POINTS)



TIME SERIES OF VECTOR AVERAGED CURRENTS AT CM1 GEOPROBE, NS77
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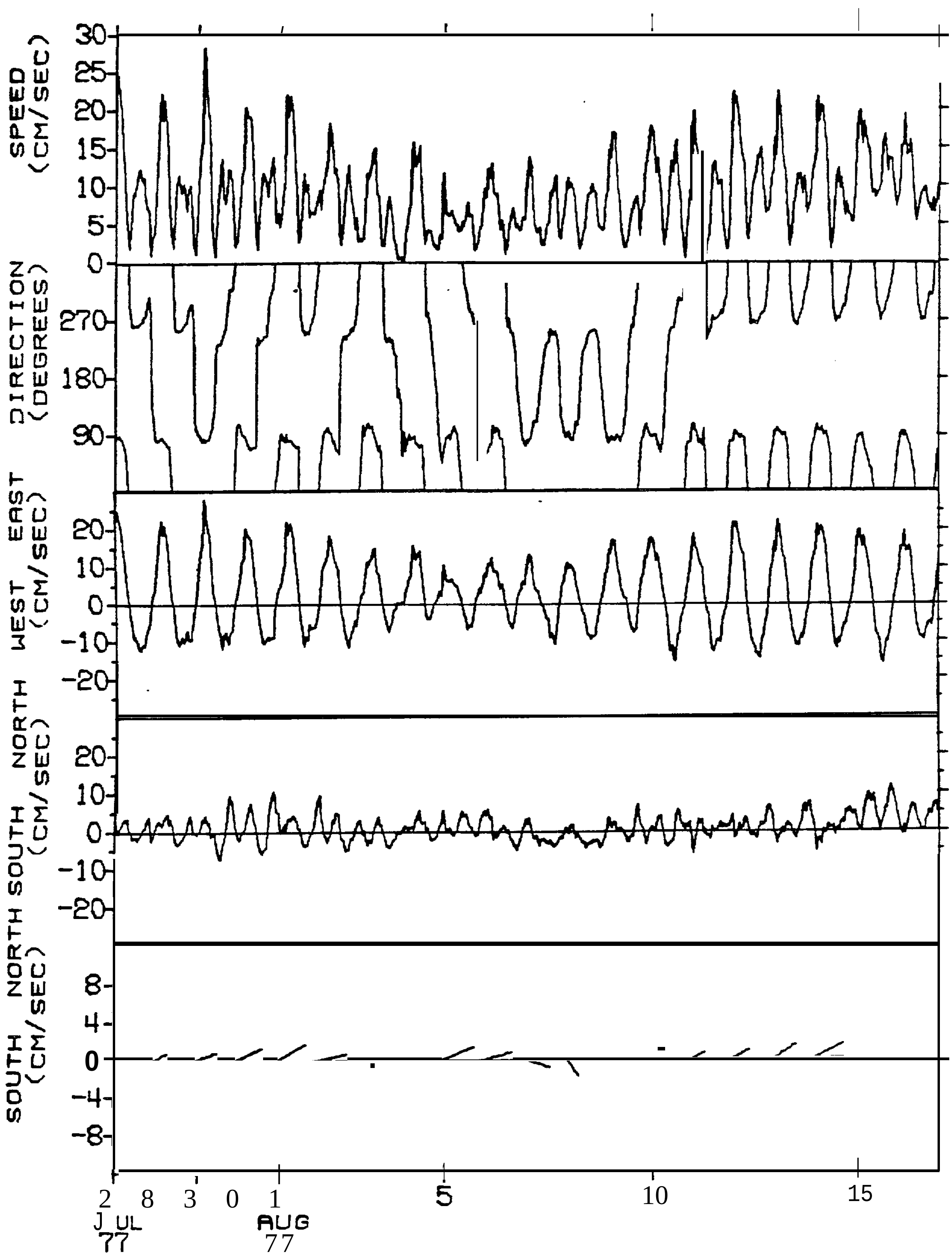

TIME SERIES OF VECTOR AVERAGED CURRENTS AT CM1 GEOPROBE, NS77
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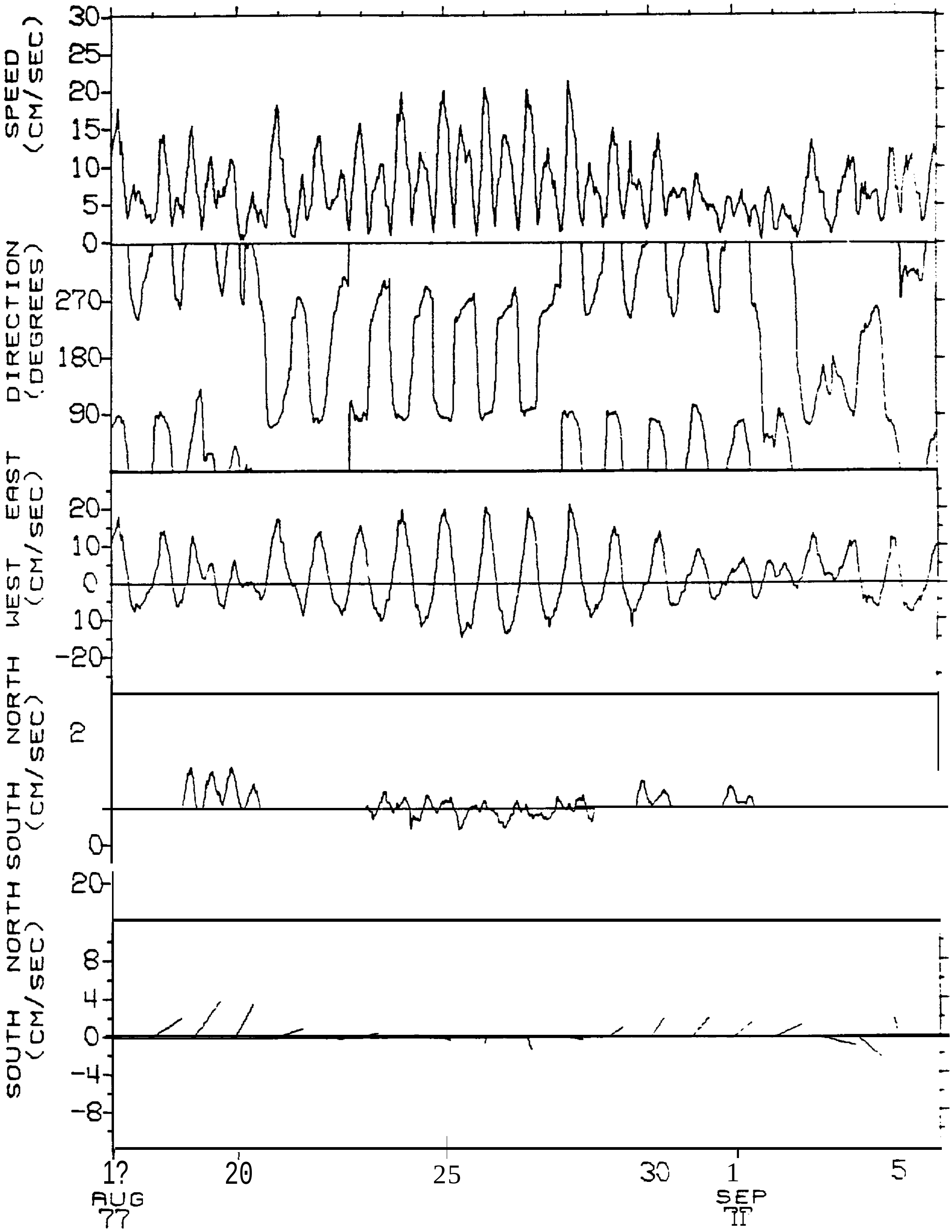
AVERAGING INTERVAL = 1.0 HOURS (1 POINTS)



TIME SERIES OF VECTOR AVERAGED CURRENTS AT CM1 GEOPROBE, NS77
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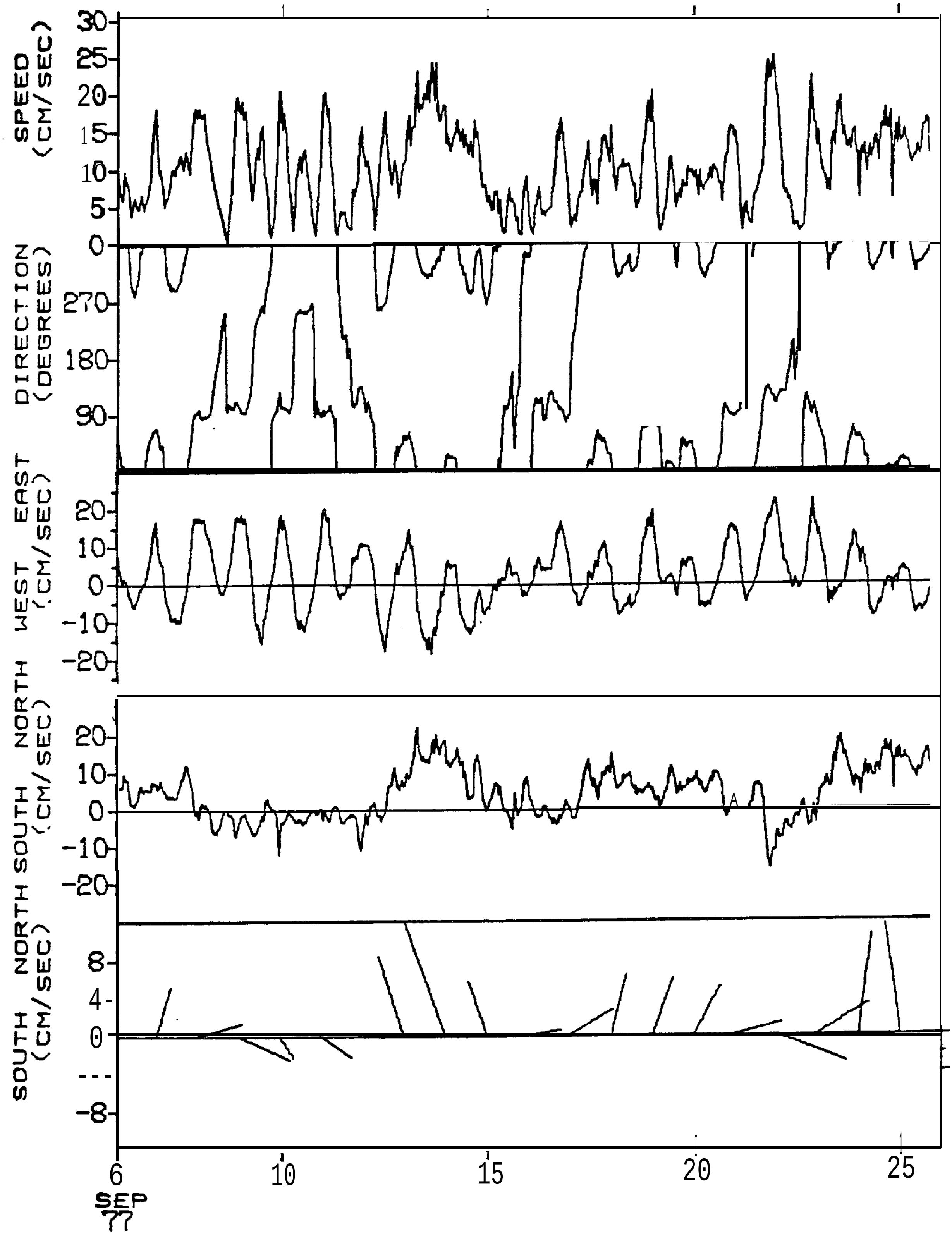
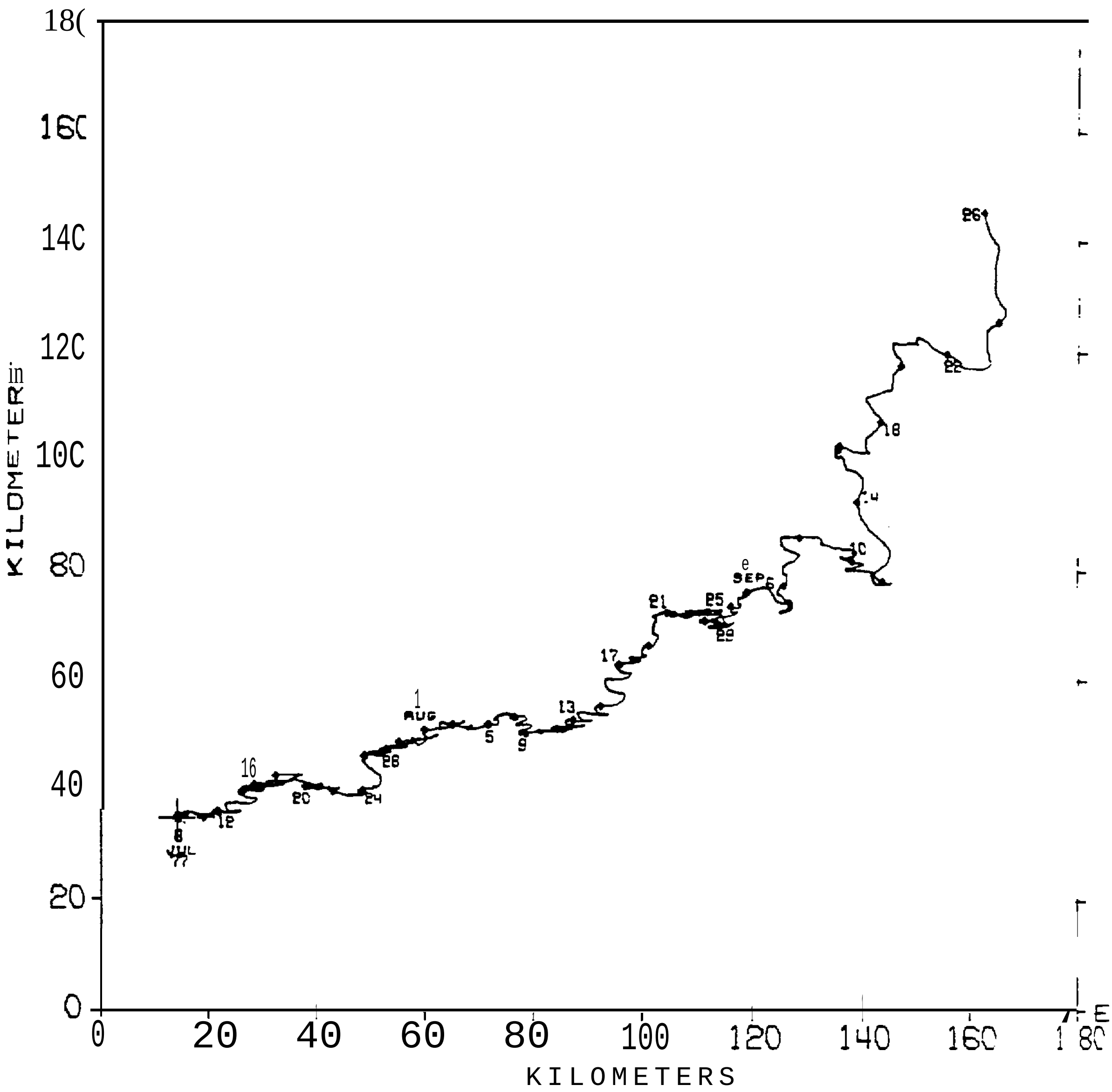
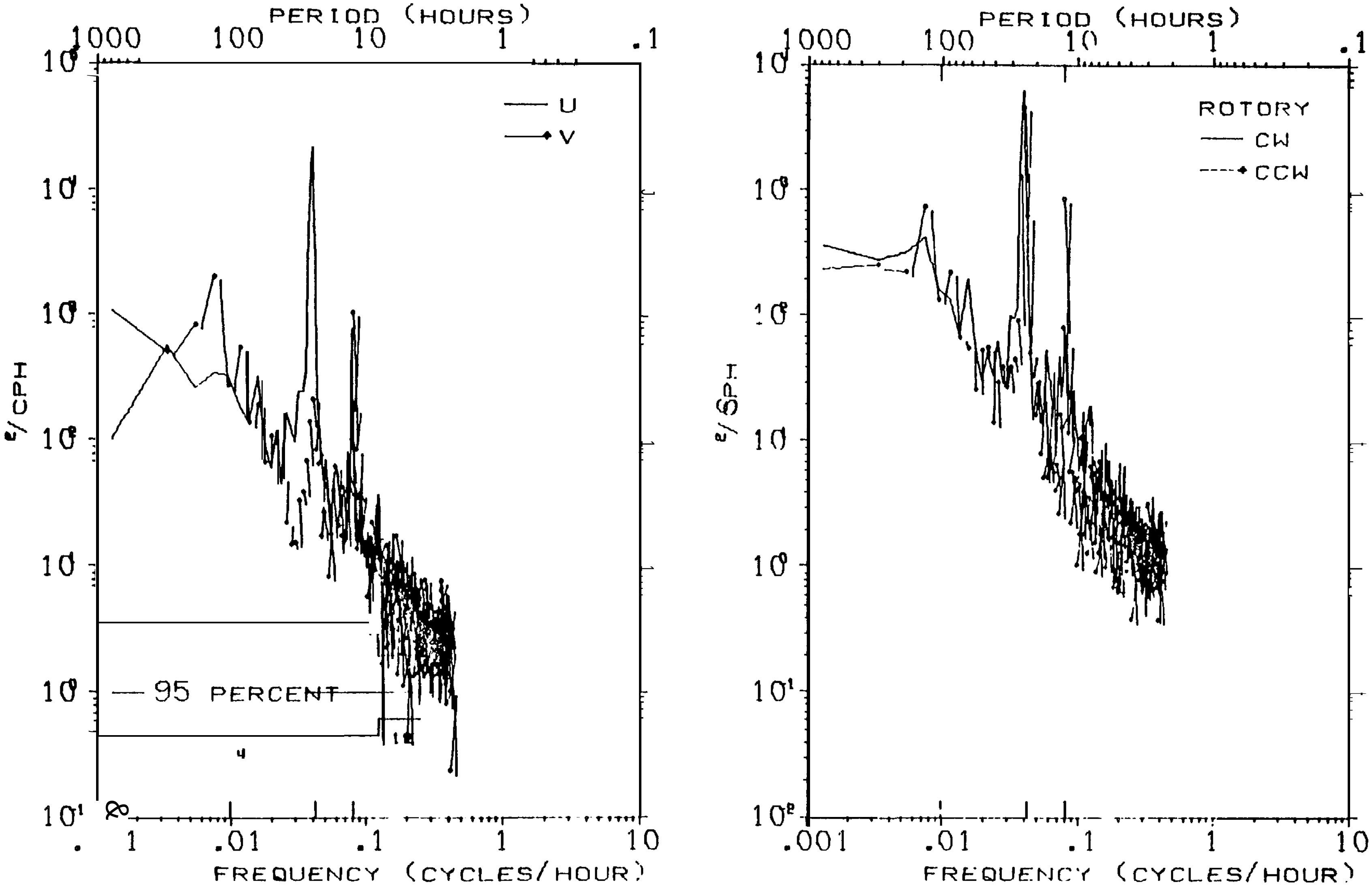
AVERAGING INTERVAL = 1.0 HOURS (1 POINTS)



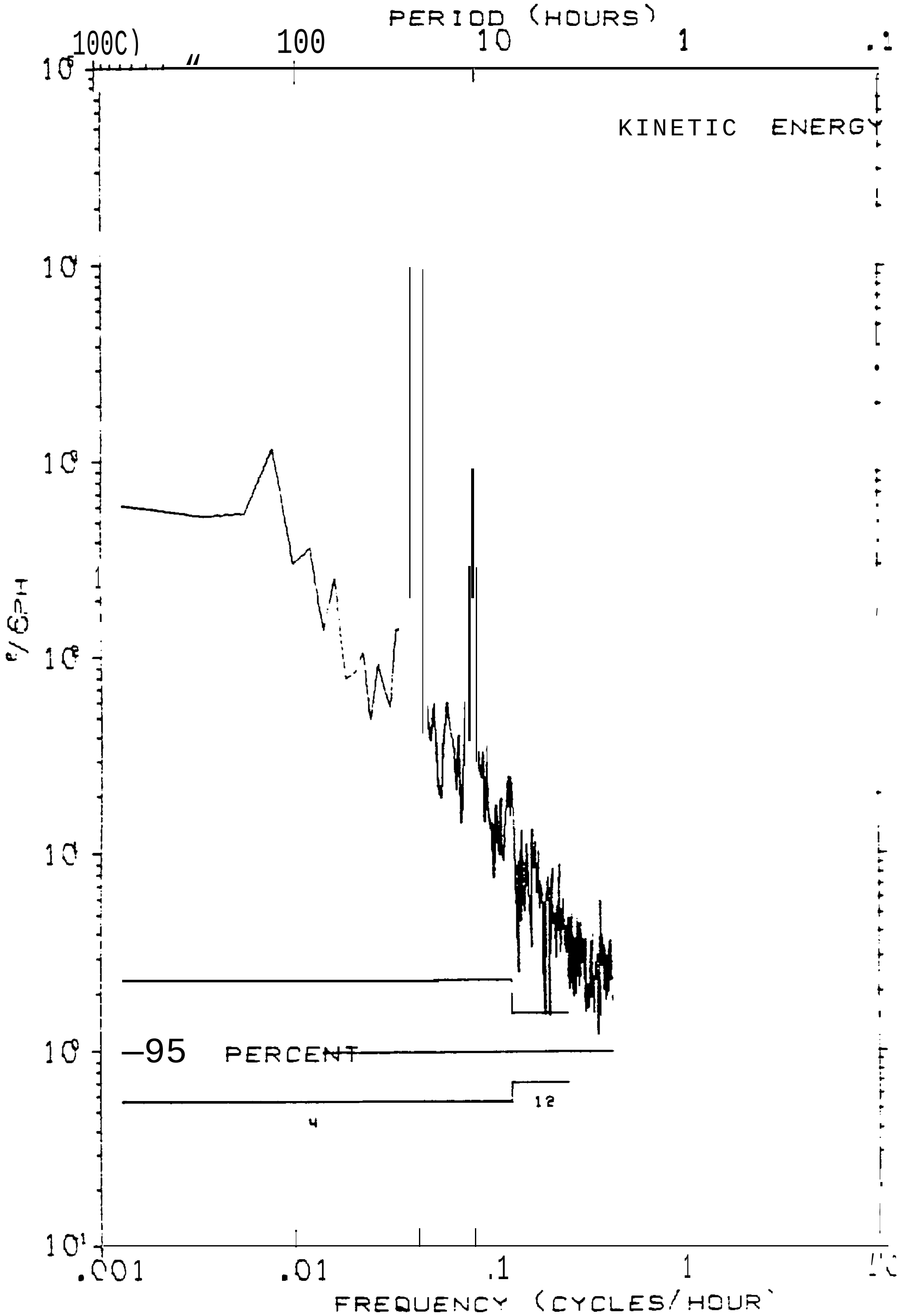


PROGRESSIVE VECTOR DIAGRAM OF CURRENTS AT CM1 GEOPROBE, NS77
LOCATION = LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 8 JUL 77 TO 2300 25 SEP 77 (80.0 DAYS)
•EVERY 2.0 DAYS BEGINNING AT 0000 8 JUL 77



U, V AND ROTORY SPECTRA OF CURRENTS AT CM1 - GEOPROBE, NS77
LOCATION = LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 8 JUL 77 TO 2300 25 SEP 77 (80.0 DAYS)
N = 1920, DT = 1.0 HOURS, SMOOTHING - DANIELL WINDOW

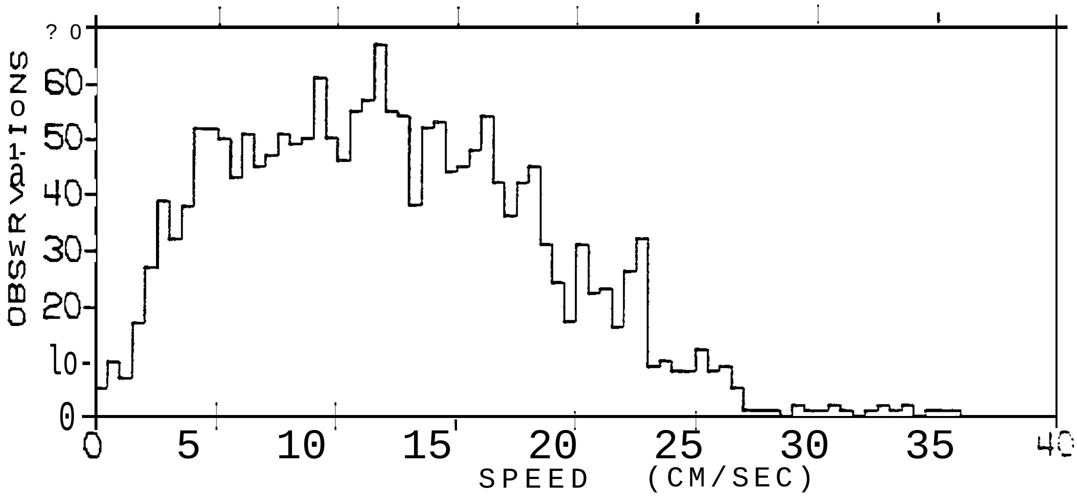
KINETIC ENERGY SPECTRUM OF CURRENTS AT CM1 GEOPROBE NS77
LOCATION LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 8 JUL 77 TO 2300 25 SEP 77 (80.0 DAYS)
N = 1920, DT = 1.0 HOURS, SMOOTHING DANIELL WINDOW

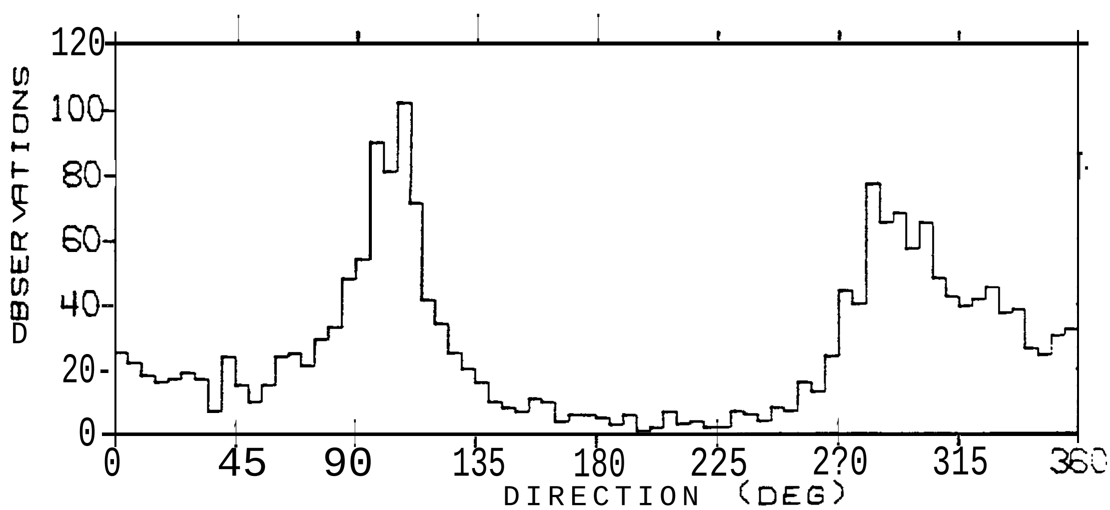


Statistics AND HISTOGRAMS OF CURRENTS AT CM2 GEOPROBE, NS77
LOCATION = LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 8 JUL 77 TO 2300 25 SEP 77 (80.0 DAYS)
N = 1920 DT = 1.00 HOURS, UNITS = (CM/SEC)

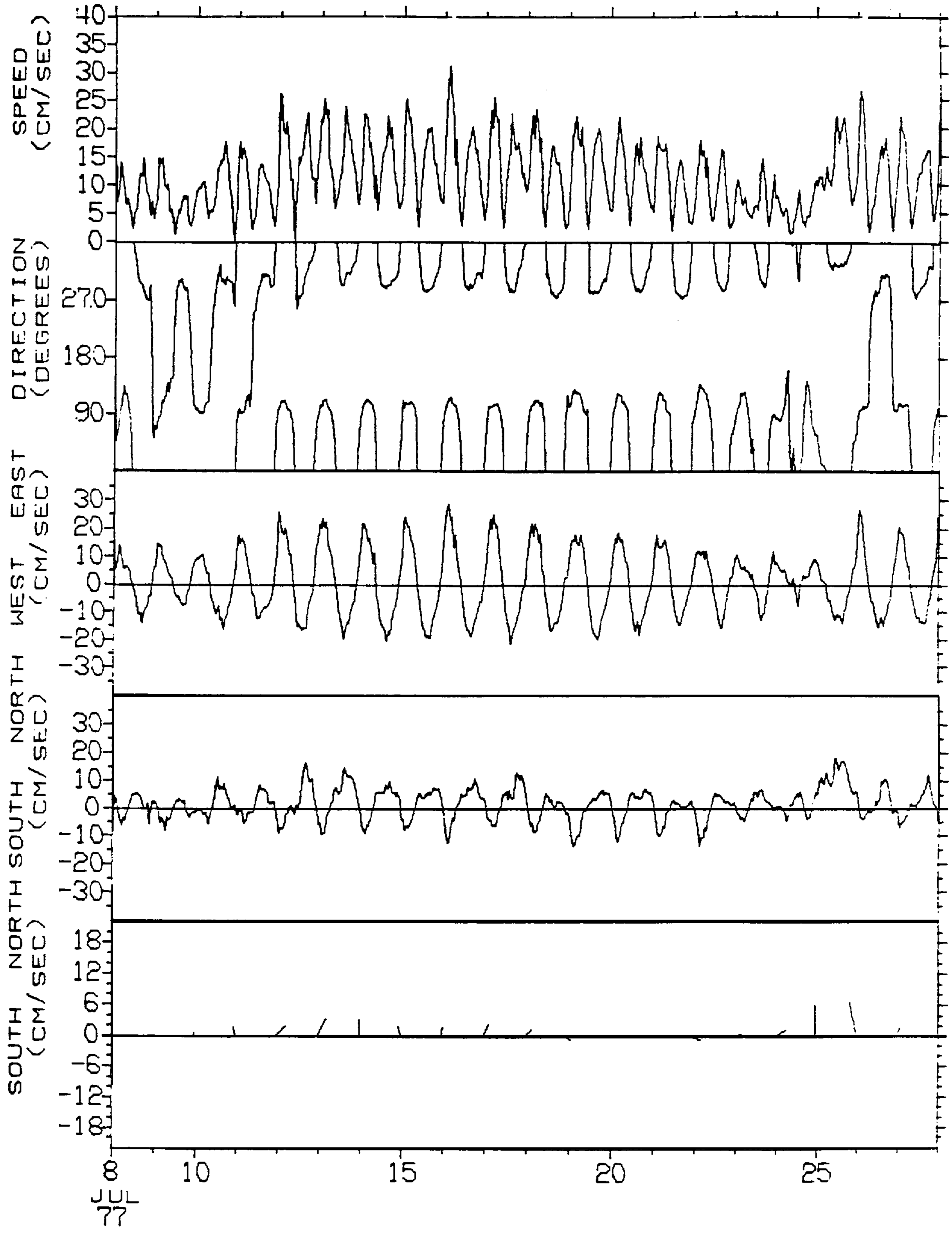
	MEAN	VARIANCE	ST-DEV	SKEW	KURT	MAX	MIN
S	12.11	40.29	6.35	0.465	2.896	36.99	0.23
U	0.96	122.97	11.09	0.173	2.144	32.11	-23.48
V	2.81	55.16	7.43	0.684	4.509	35.84	-27.62

S = SPEED
U = EAST-WEST COMPONENT OF VELOCITY, EAST POSITIVE U
V = NORTH-SOUTH COMPONENT OF VELOCITY, NORTH POSITIVE V

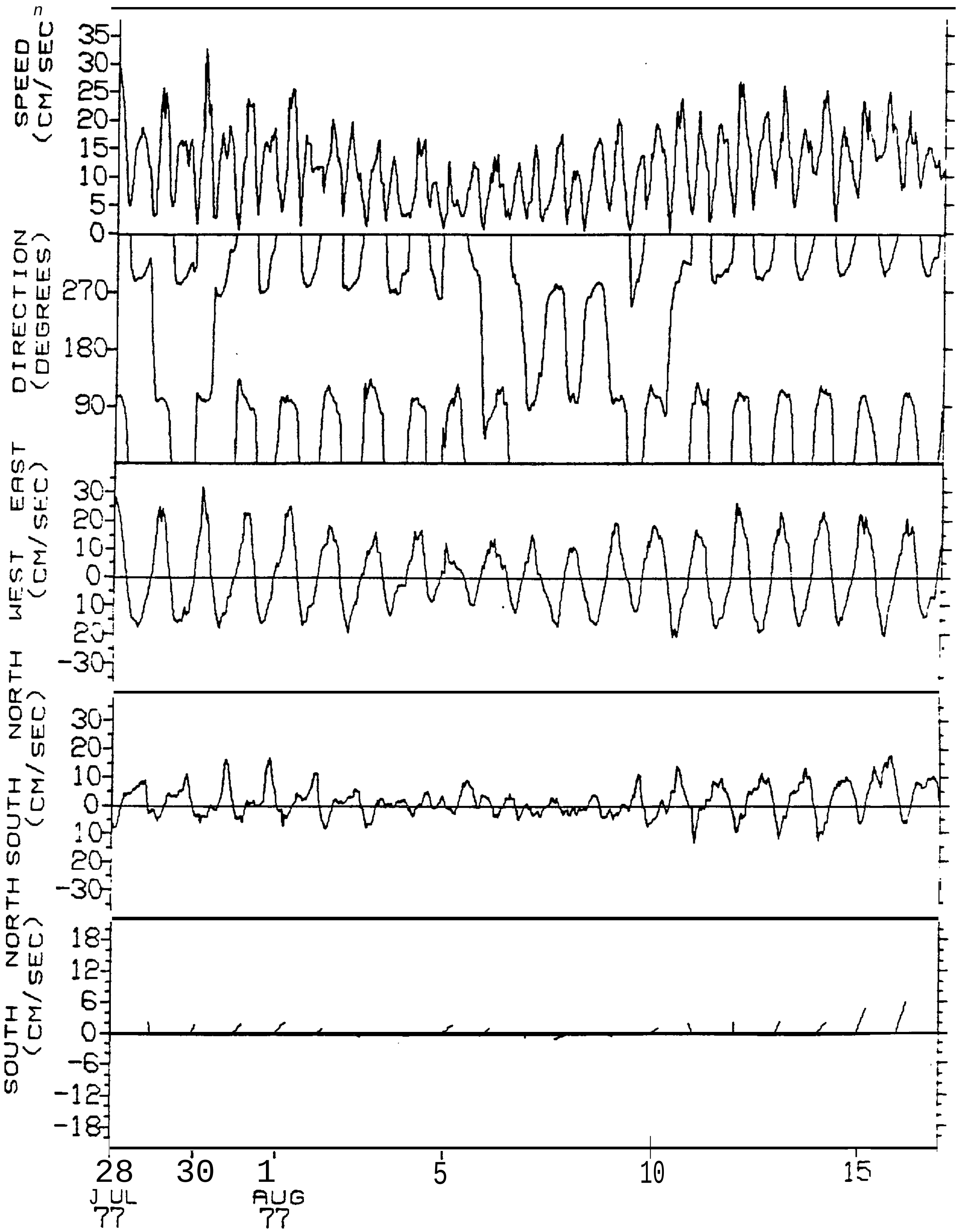




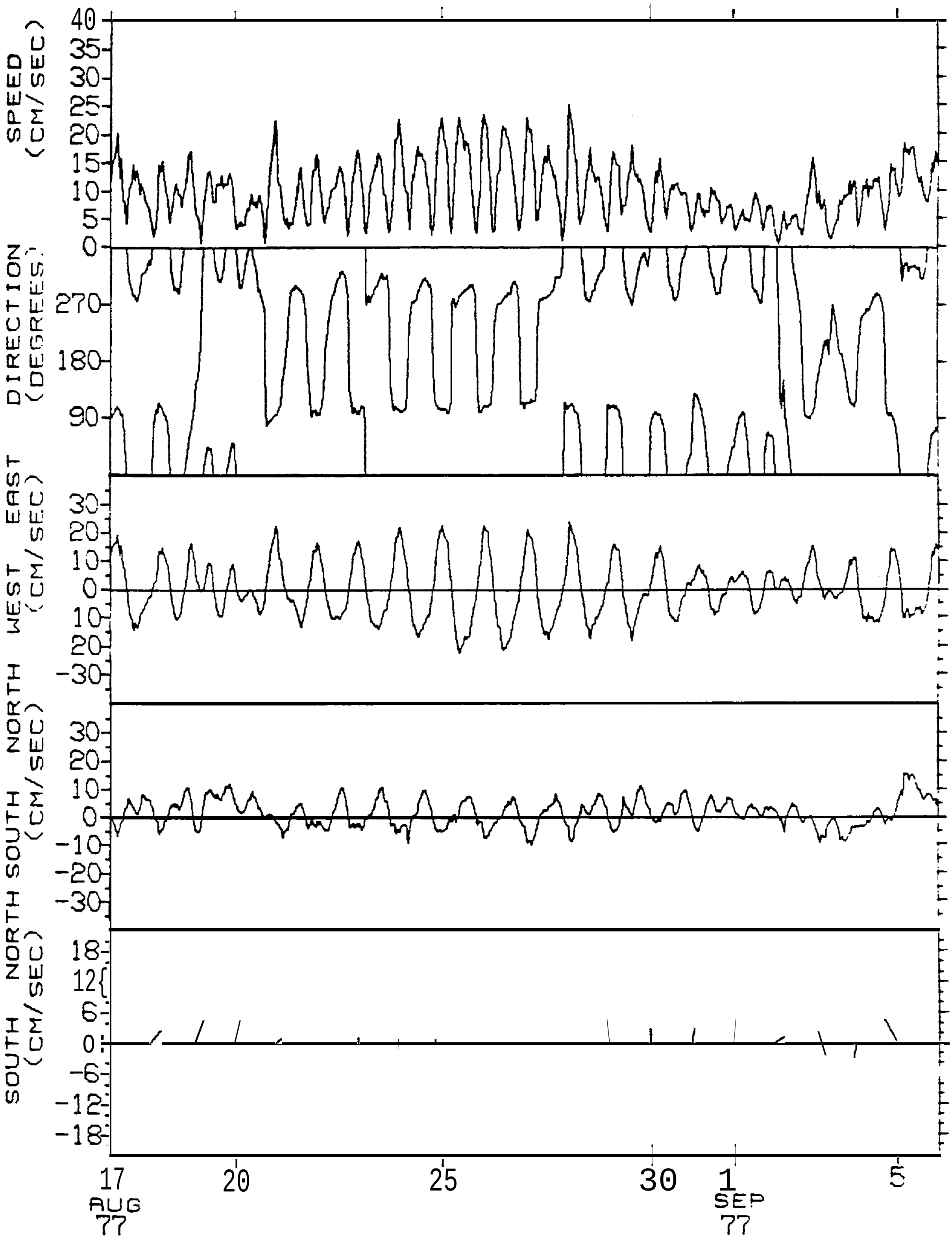
TIME SERIES OF VECTOR AVERAGED CURRENTS AT CM2 GEOPROBE, NS77
LOCATION = LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 8 JUL 77 TO 2300 27 JUL 77 (20.0 DAYS)
AVERAGING INTERVAL = 1.0 HOURS (1 POINTS)



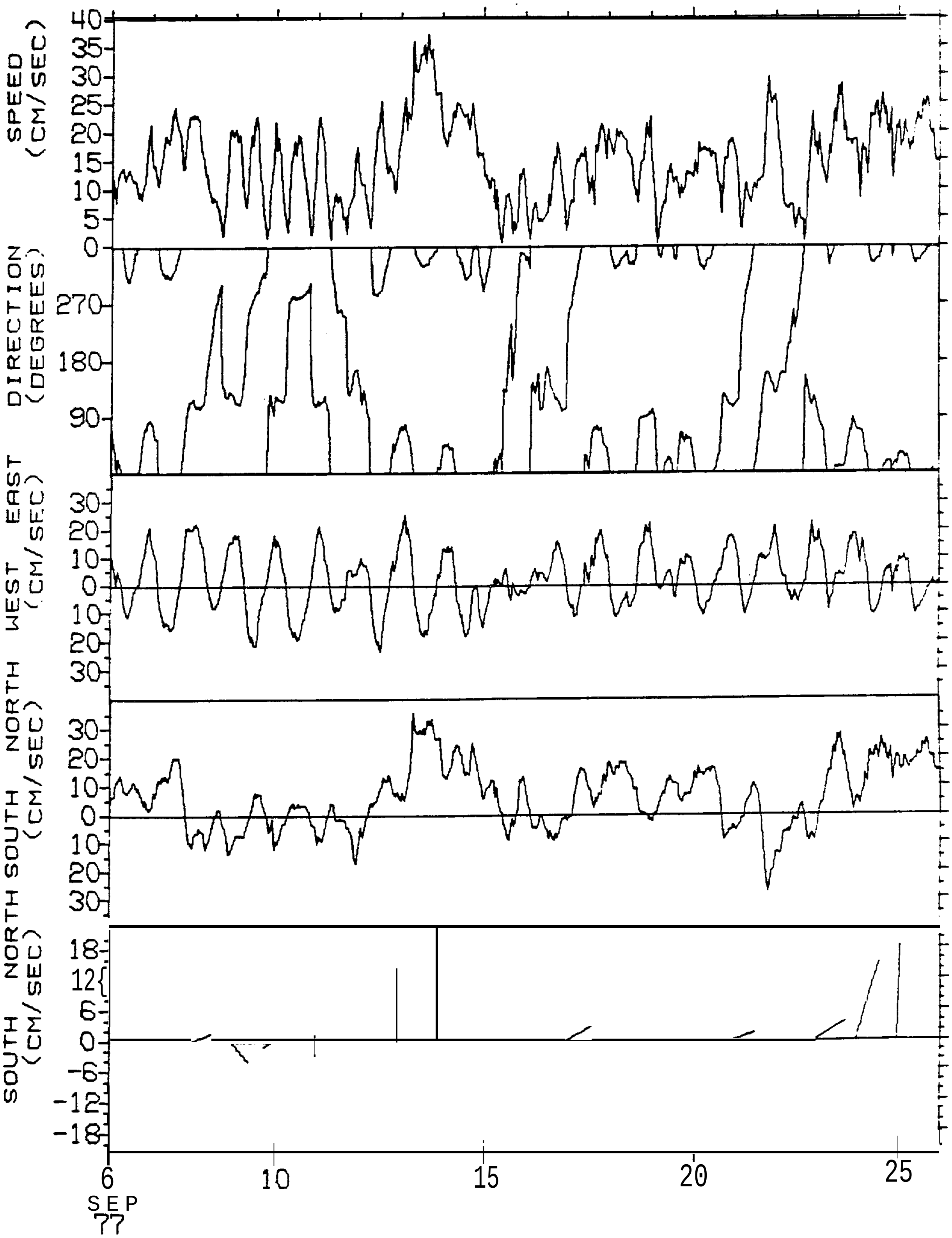
TIME SERIES OF VECTOR AVERAGED CURRENTS AT CM2 GEOPROBE, NS77
LOCATION LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 28 JUL 77 TO 2300 16 AUG 77 (20.0 DAYS)
AVERAGING INTERVAL = 1.0 HOURS (1 POINTS)



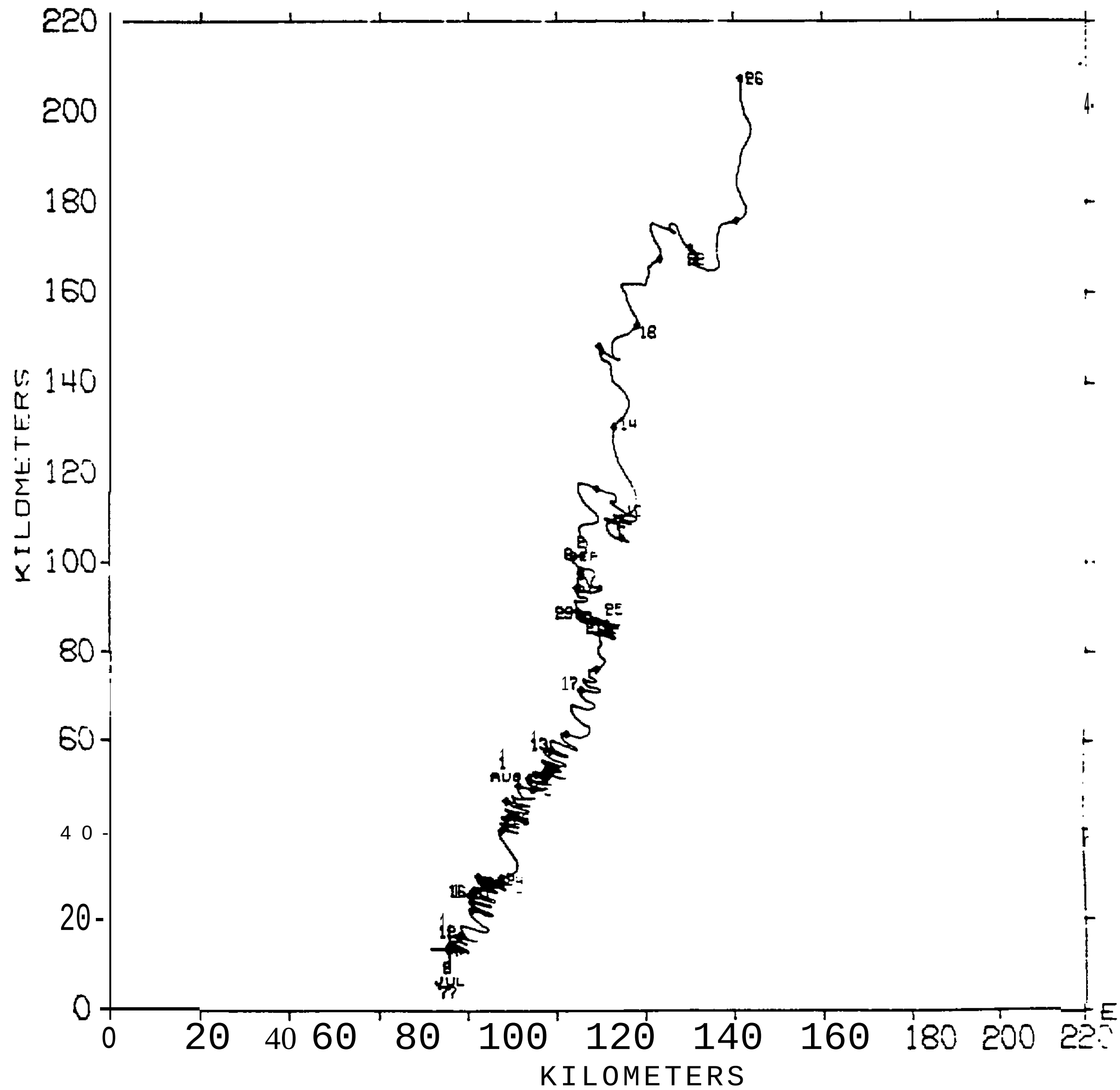
TIME SERIES OF VECTOR AVERAGED CURRENTS AT CM2 GEOPROBE, NS77
LOCATION = LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 17 AUG 77 TO 2300 5 SEP 77 (20.0 DAYS)
AVERAGING INTERVAL = 1.0 HOURS(1 POINTS)

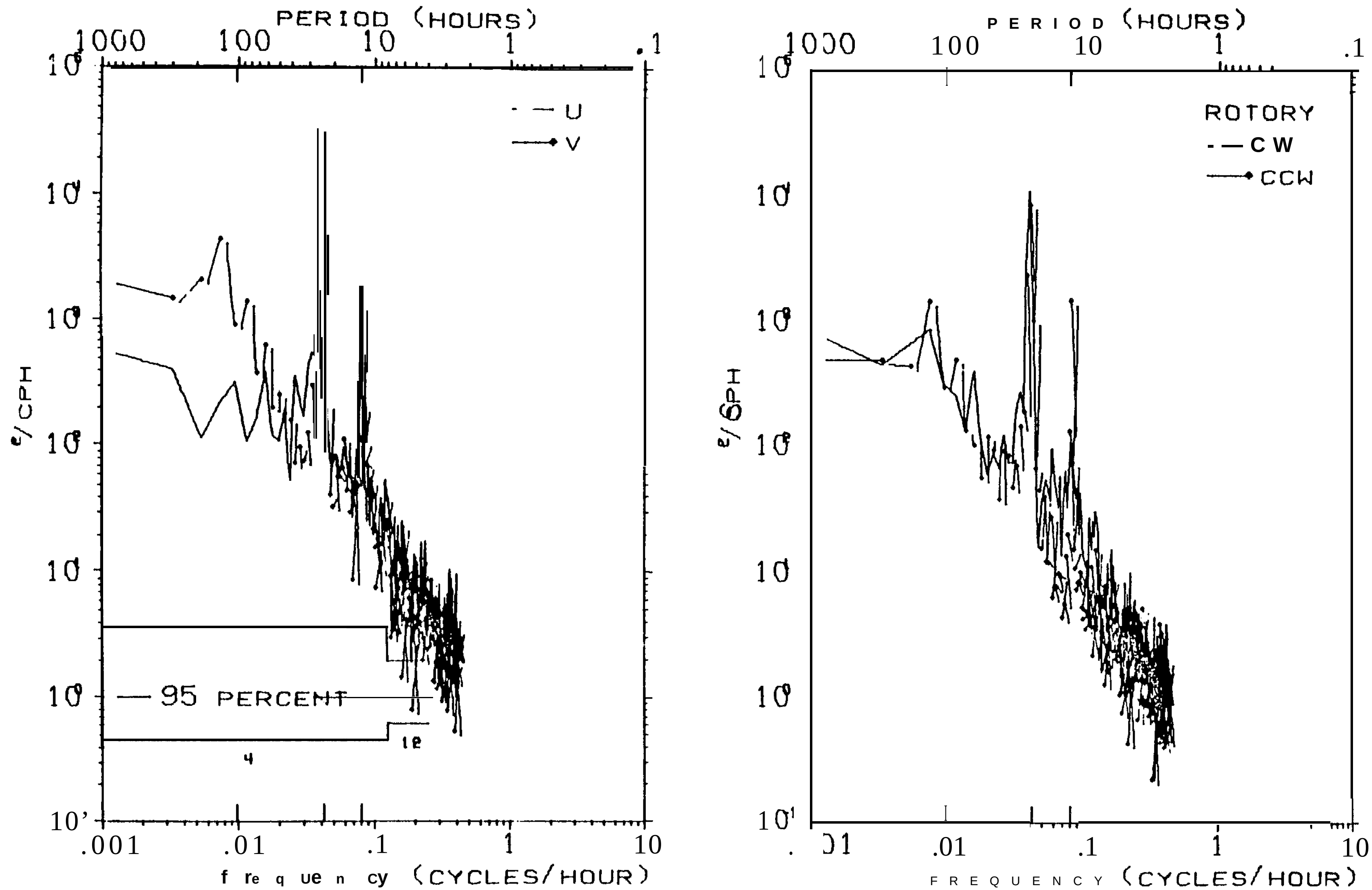


TIME SERIES OF VECTOR AVERAGED CURRENTS AT CM2 GEOPROBE, NS77
LOCATION = LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 6 SEP ?? TO 2300 25 SEP 77 (20.0 DAYS)
AVERAGING INTERVAL = 1.0 HOURS (1 POINTS)



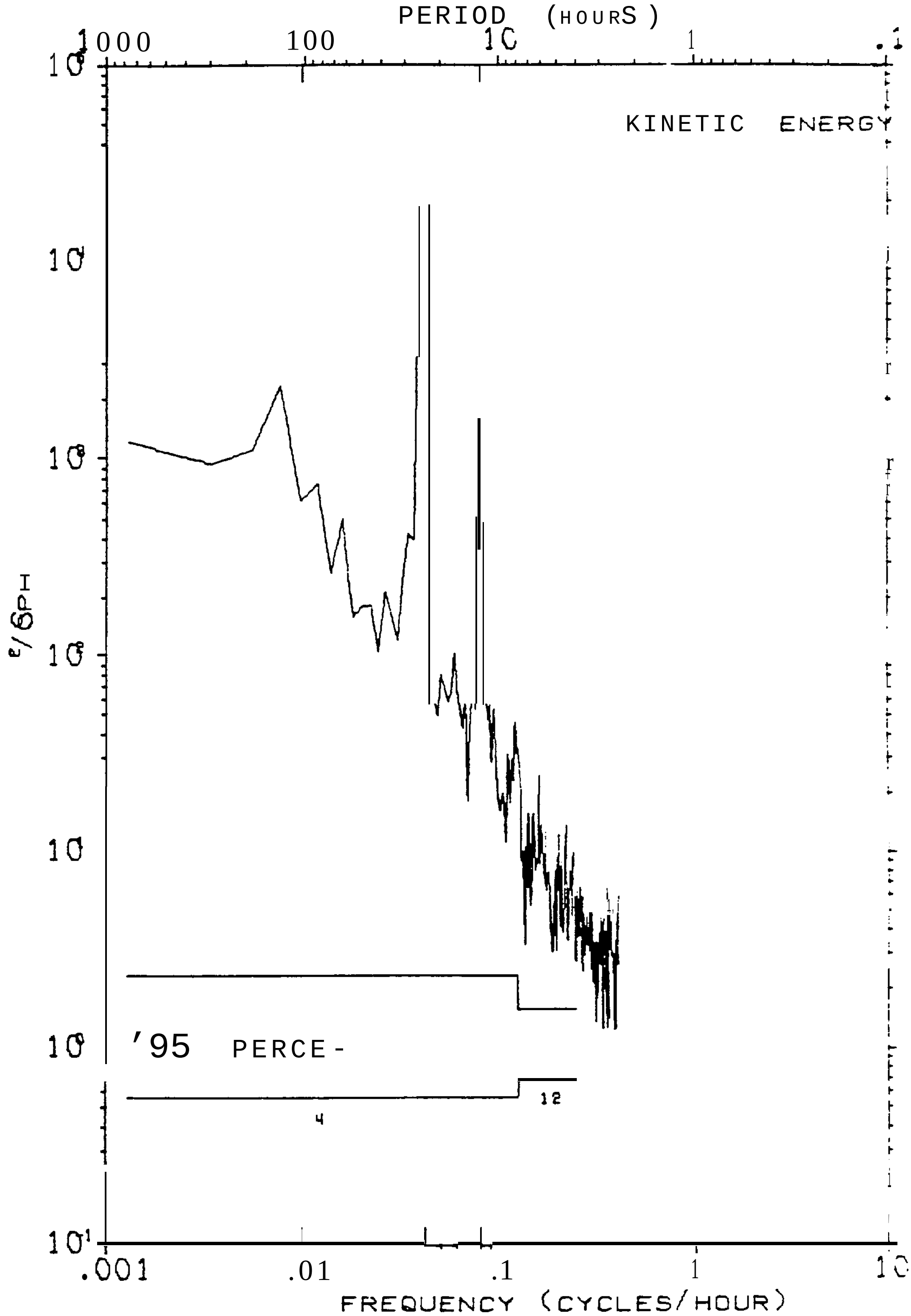
PROGRESSIVE VECTOR DIAGRAM OF CURRENTS AT CM2 GEOPROBE, NS77
LOCATION = LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 8 JUL 77 TO 2300 25 SEP 77 (80.0 DAYS)
● EVERY 2.0 DAYS BEGINNING AT 0000 8 JUL 77





U, V AND ROTORY SPECTRA OF CURRENTS AT CM2 GEOPROBE, NS77
LOCATION = LAT 64 00N, LONG 165 00W, DEPTH = 7.5 METERS
OBSERVATION PERIOD 0000 8 JUL 77 TO 2300 25 SEP 77 (80.0 DAYS)
N = 1920, DT = 1.0 HOURS, SMOOTHING DANIELL WINDOW

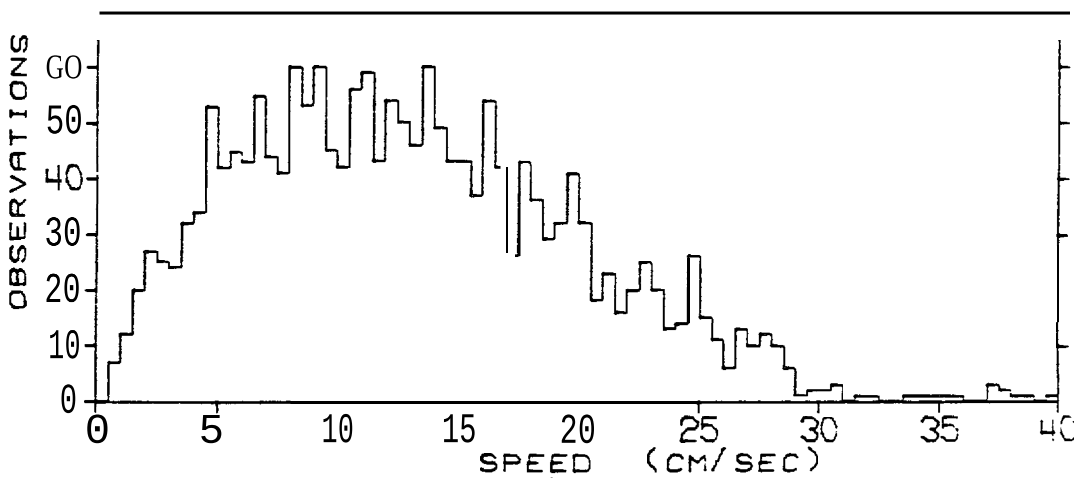
KINETIC ENERGY SPECTRUM OF CURRENTS AT CM2 GEOPROBE, NS77
LOCATION = LAT 64 ON, LONG 165 OOW, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 8 JUL 77 TO 2300 25 SEP 77 (80.0 DAYS)
N = 1920, DT = 1.0 HOURS, SMOOTHING DANIELL WINDOW

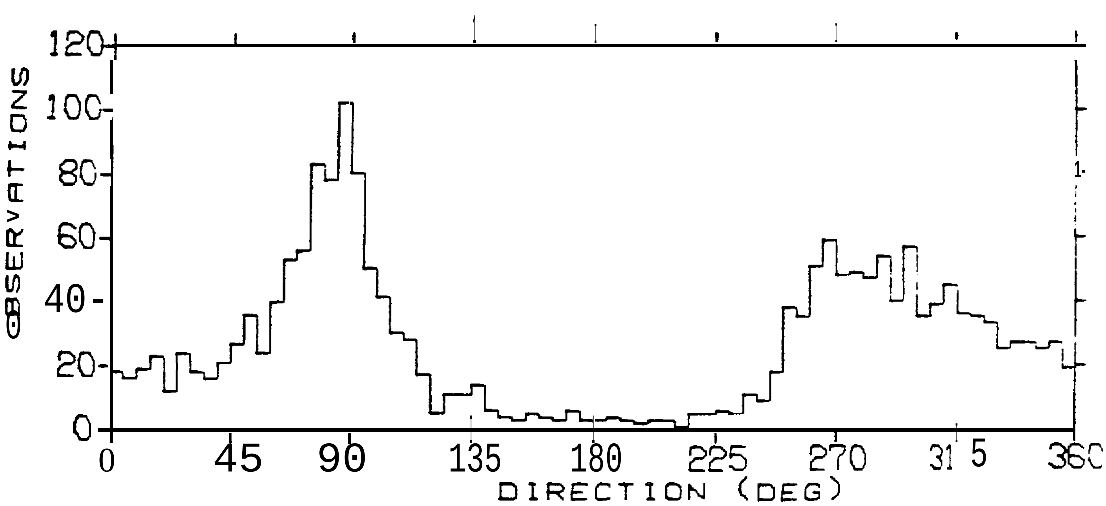


STATISTICS AND HISTOGRAMS OF CURRENTS AT CM3 - GEOPROBE, NS77
LOCATION = LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 8 JUL 77 TO 2300 25 SEP 77 (80.0 DAYS)
N = 1920 DT = 1.00 HOURS, UNITS = (CM/SEC)

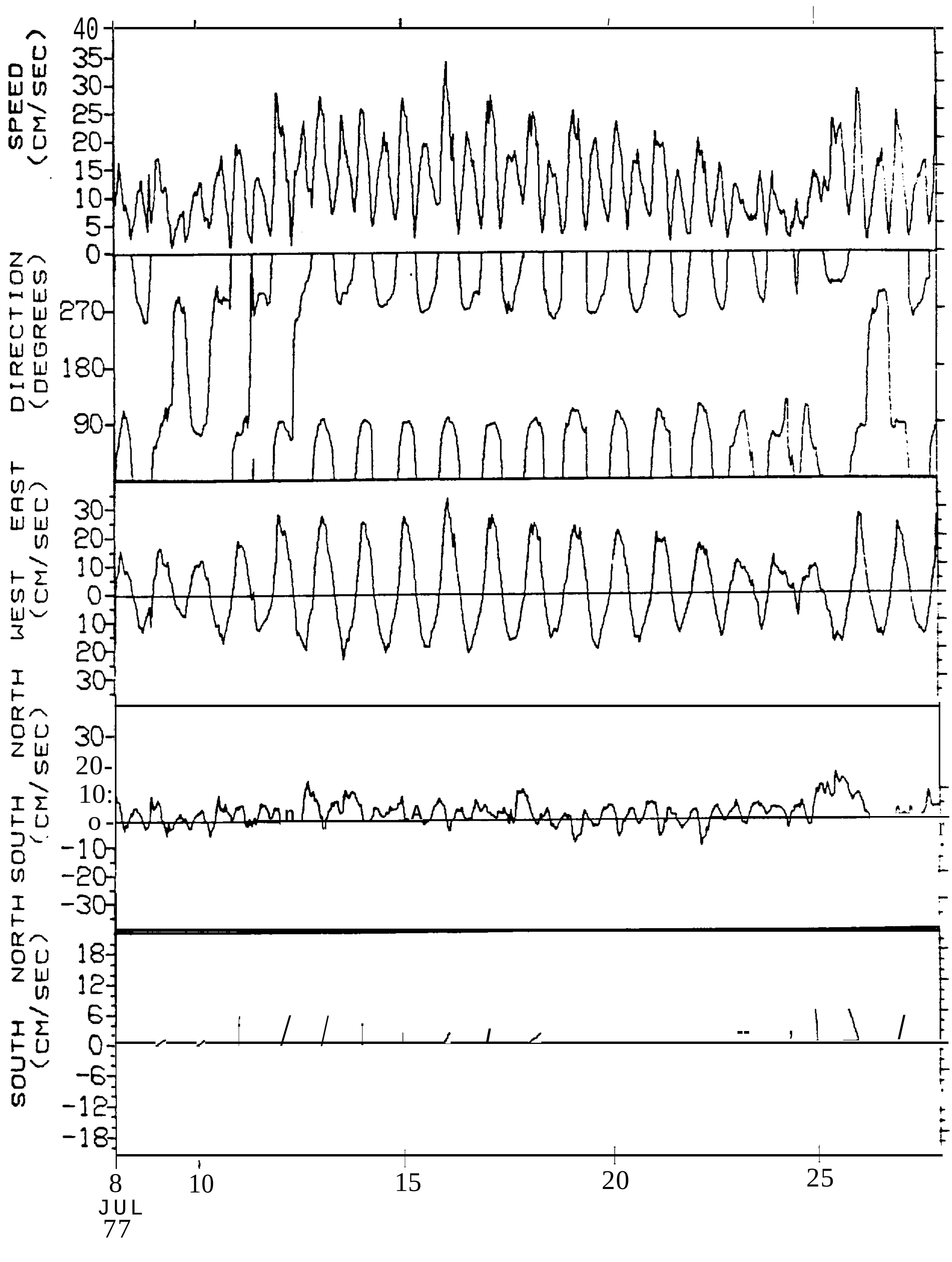
	MEAN	VARIANCE	ST-DEV	SKEW	KURT	MAX	MIN
S	13.00	47.84	6.92	0.558	3.020	39.68	0.66
U	1.42	155.1?	12.46	0.209	2.107	34.77	-2?.55
V	3.62	46.52	6.S2	1.113	5.413	37.24	-23.09

S = SPEED
U = EAST-WEST COMPONENT OF VELOCITY, EAST=POSITIVE U
V = NORTH-SOUTH COMPONENT OF VELOCITY, NORTH = POSITIVE V

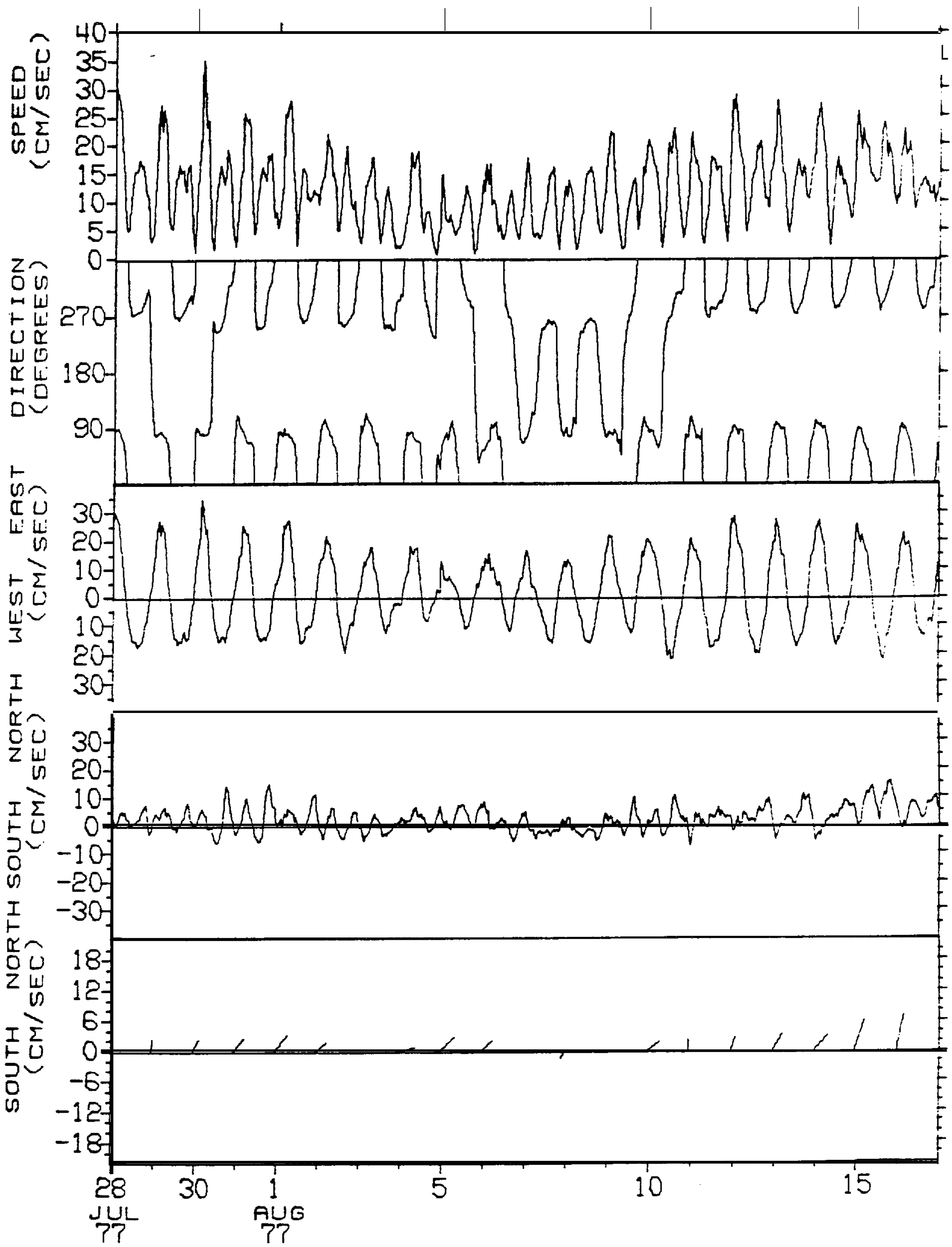




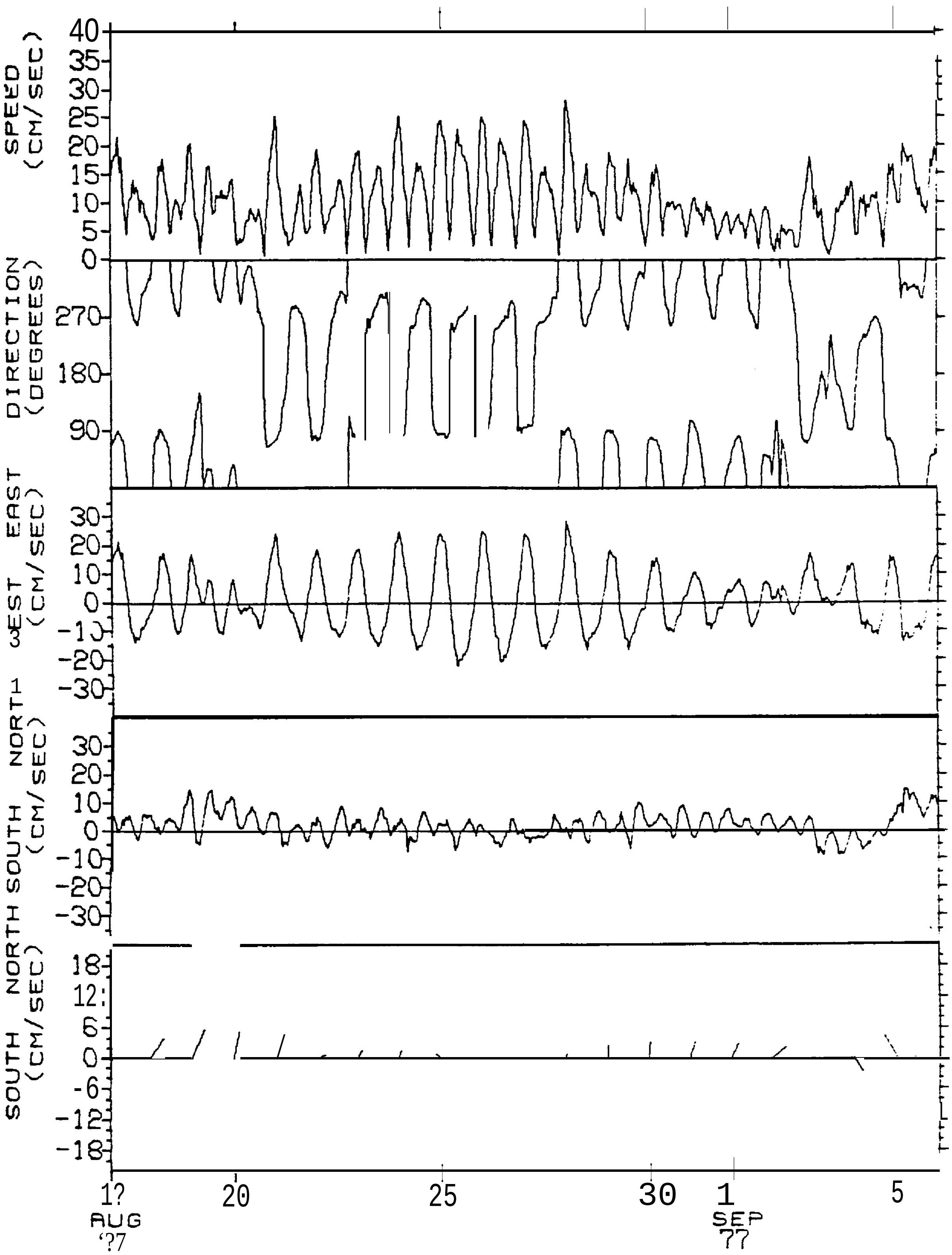
TIME SERIES OF VECTOR AVERAGED CURRENTS AT CM3 GEOPROBE, NS77
LOCATION = LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 8 JUL 77 TO 2300 27JUL 77 (20.0 DAYS)
AVERAGING INTERVAL = 1.0 HOURS (1 POINTS)



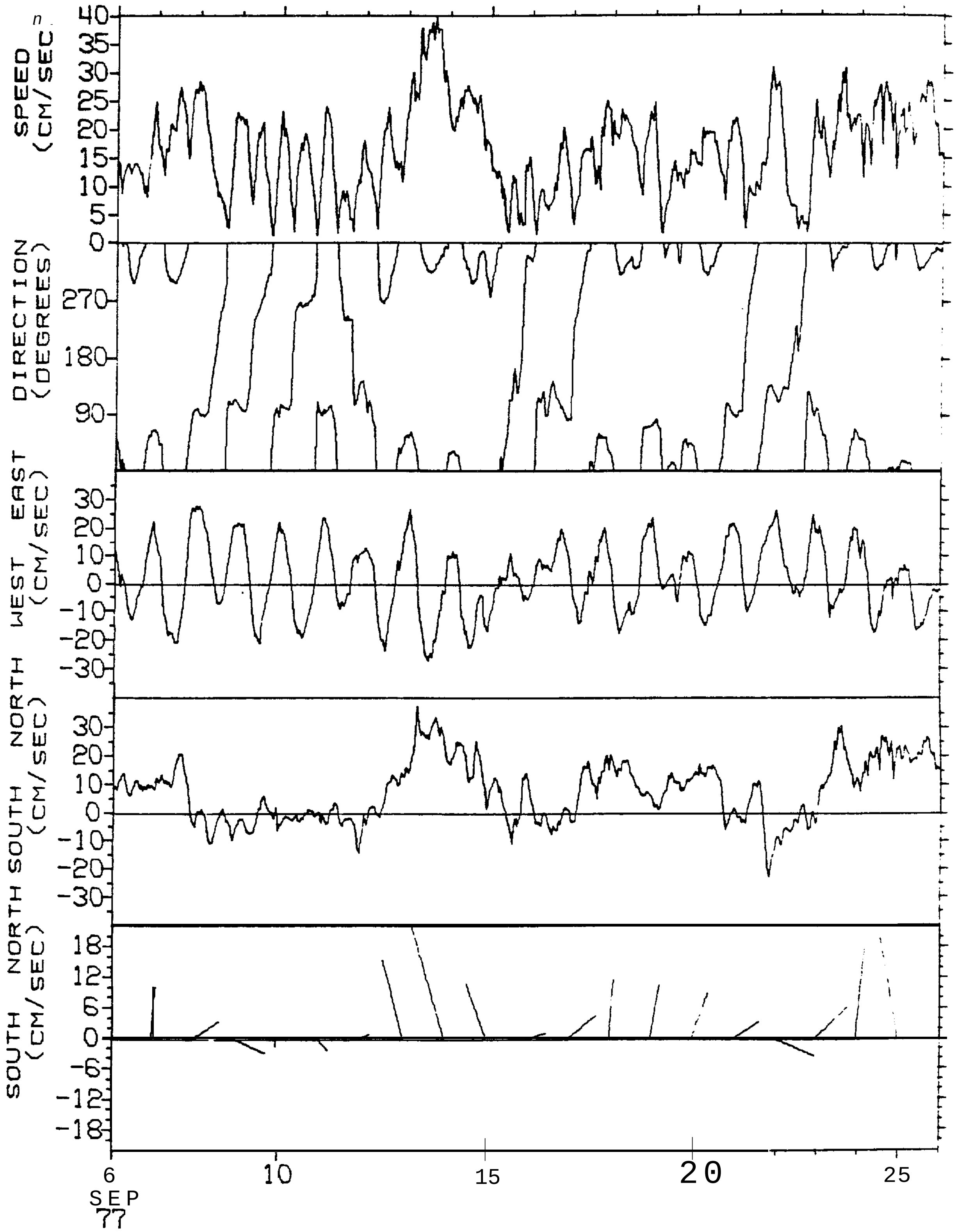
TIME SERIES OF VECTOR AVERAGED CURRENTS AT CM3 GEOPROBE, NS77
LOCATION = LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 28 JUL 77 TO 2300 16 AUG 77 (20.0 DAYS)
AVERAGING INTERVAL = 1.0 HOURS (1 POINTS)



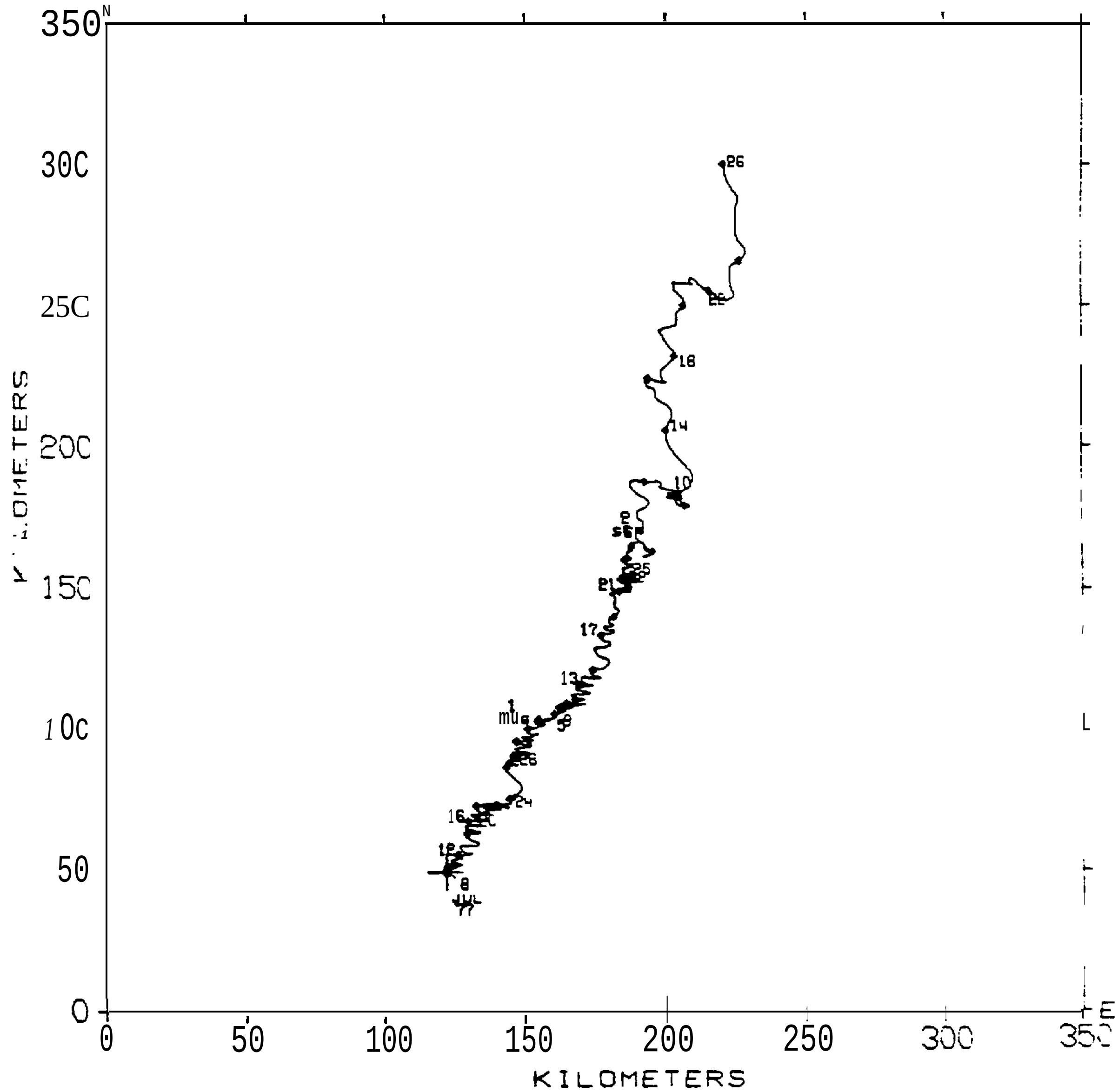
TIME SERIES OF VECTOR AVERAGED CURRENTS AT CM3 GEOPROBE, NS77
LOCATION = LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 17 AUG 77 TO 2300 5 SEP 77 (20.0 DAYS)
AVERAGING INTERVAL = 1.0 HOURS (1 POINTS)

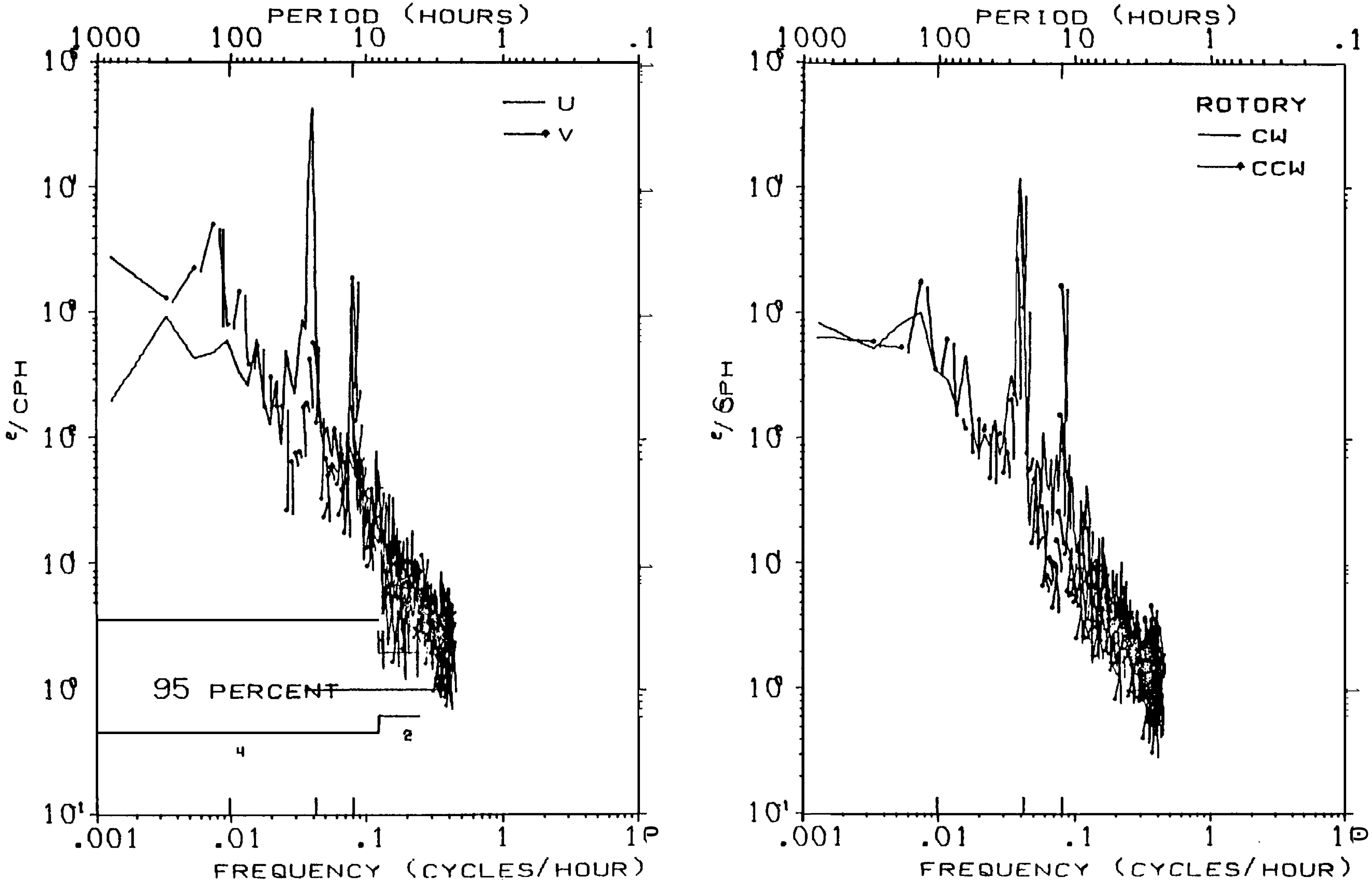


TIME SERIES OF VECTOR AVERAGED CURRENTS AT CM3 GEOPROBE,NS77
LOCATION LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 6 SEP 77 TO 2300 25 SEP 77 (20.0 DAYS)
AVERAGING INTERVAL = 1.0 HOURS (1 POINTS)



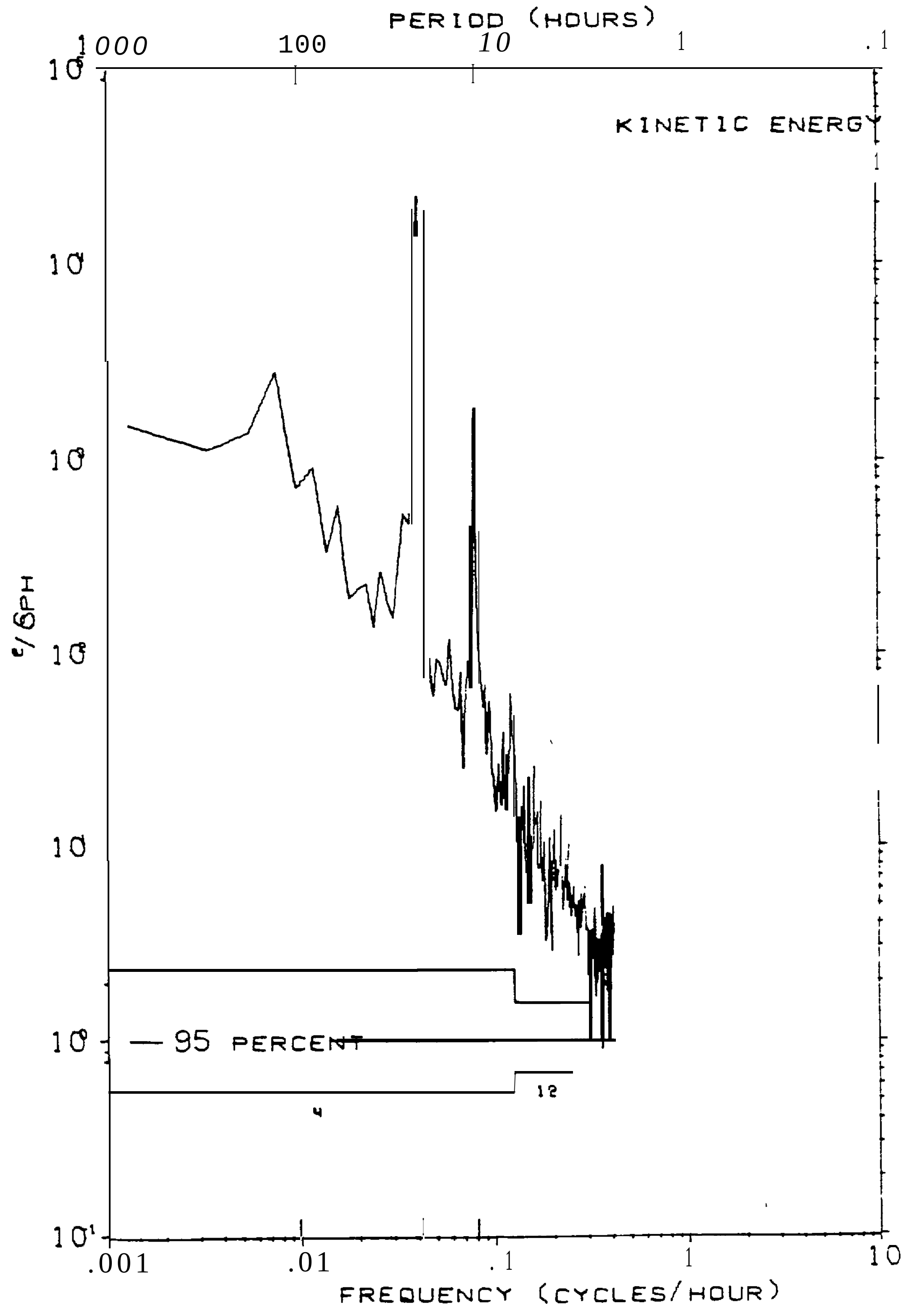
● REGRESSIVE VECTOR DIAGRAM OF CURRENTS AT CM3 GEOPROBE, NS77
LOCATION = LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 8 JUL 77 TO 2300 25 SEP 77 (80.0 DAYS)
● EVERY 2.0 DAYS BEGINNING AT 0000 8 JUL 77





U, V AND ROTORY SPECTRO OF CURRENTS AT CM3 - GEOPROBE, NST77
LOCATION = LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 8 JUL 77 TO 2300 25 SEP 77 (80.0 DAYS)
N = 1920, DT = 1.0 HOURS, SMOOTHING - DANIELL WINDOW

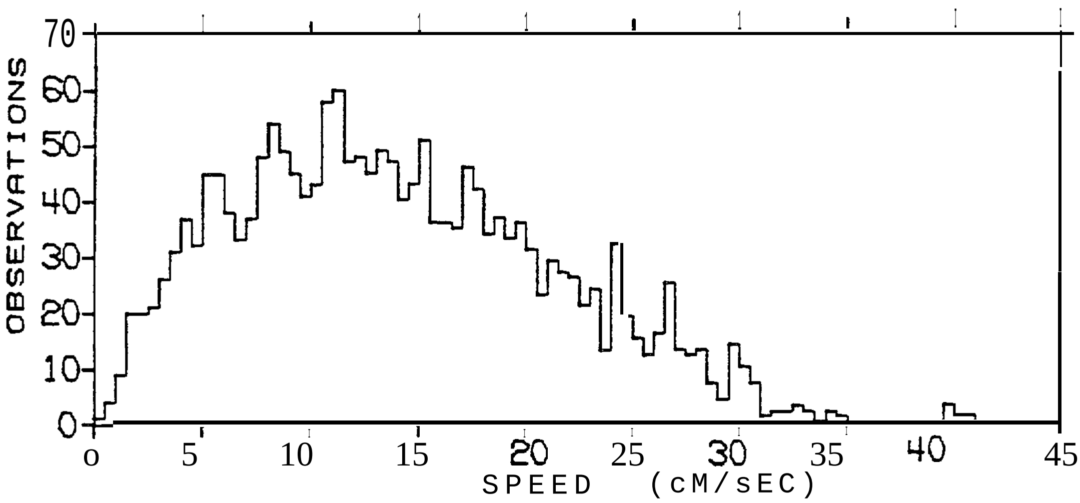
KINETIC ENERGY SPECTRUM OF CURRENTS AT CM3 GEOPROBE, NS77
LOCATION LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 8 JUL 77 TO 2300 25 SEP 77 (80.0 DAYS)
N = 1920, DT = 1.0 HOURS, SMOOTHING DANIELL WINDOW

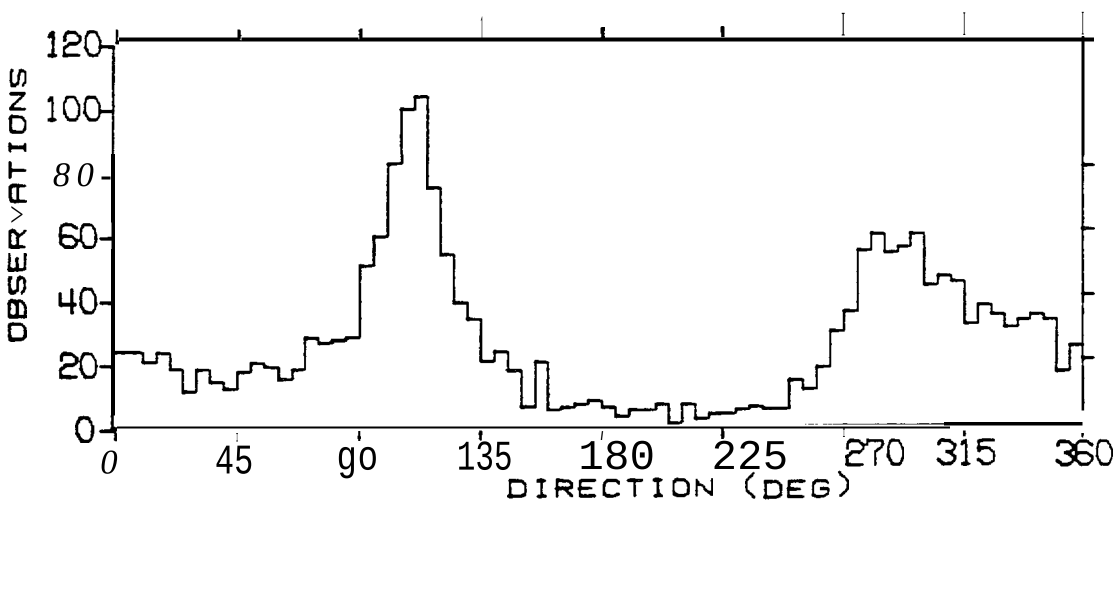


STATISTICS AND HISTOGRAMS OF CURRENTS AT CM4 GEOPROBE, NS77
LOCATION = LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 8 JUL 77 TO 2300 25 SEP 77 (80.0 DAYS)
N = 1920 DT = 1.00 HOURS, UNITS = (CM/SEC)

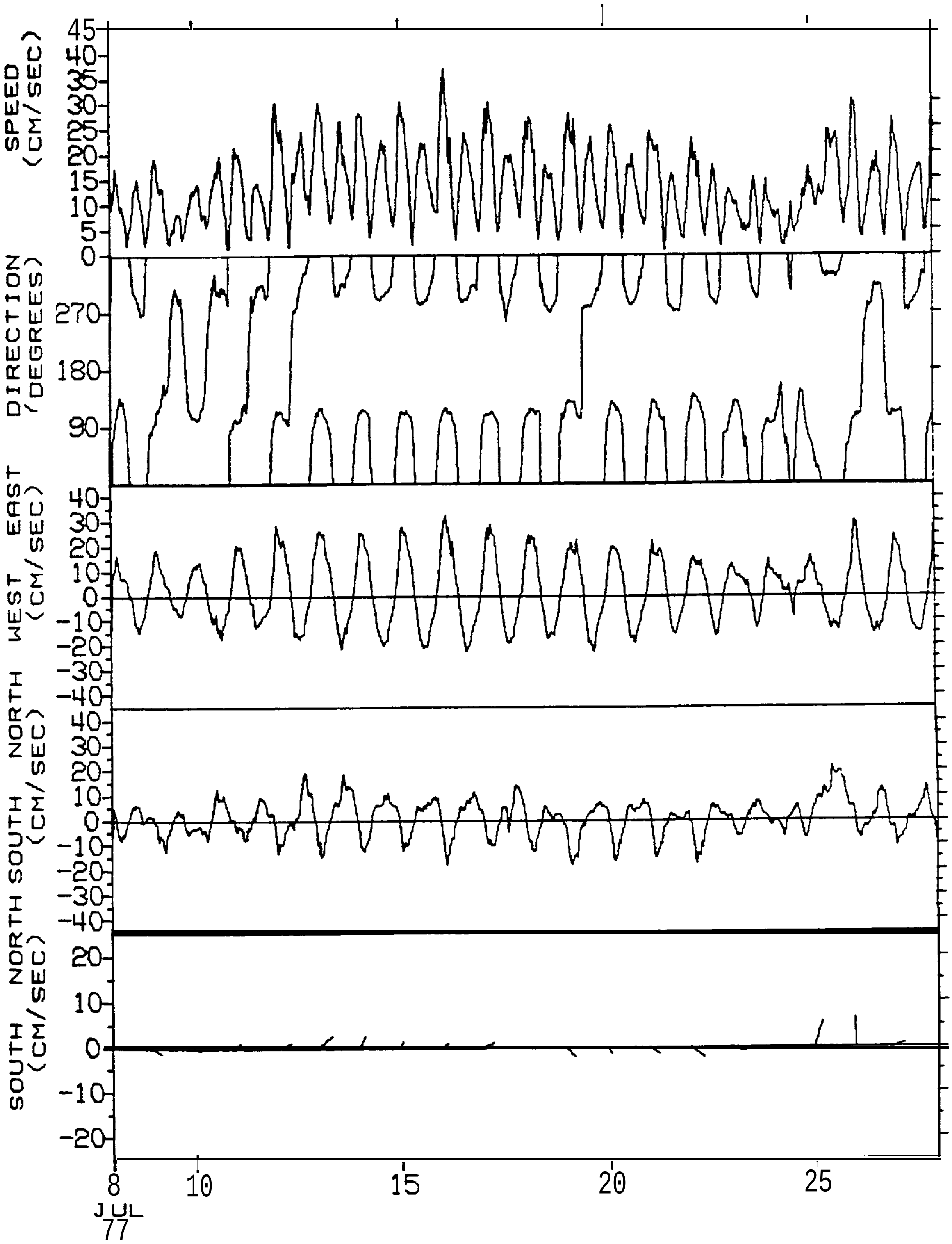
	MEAN	VARIANCE	ST-DEV	SKEW	KURT	MAX	MIN
S	14A:	56.05	7.49	0.543	2.966	43.10	0.16
U	2	159.37	12.62	0.135	2.099	36.86	-24.59
V	2.03	84.10	9.17	0.6?8	4.407	42.22	-32.04

S = SPEED
U = EAST-WEST COMPONENT OF VELOCITY, EAST = POSITIVE U
V = NORTH-SOUTH COMPONENT OF VELOCITY, NORTH = POSITIVE V

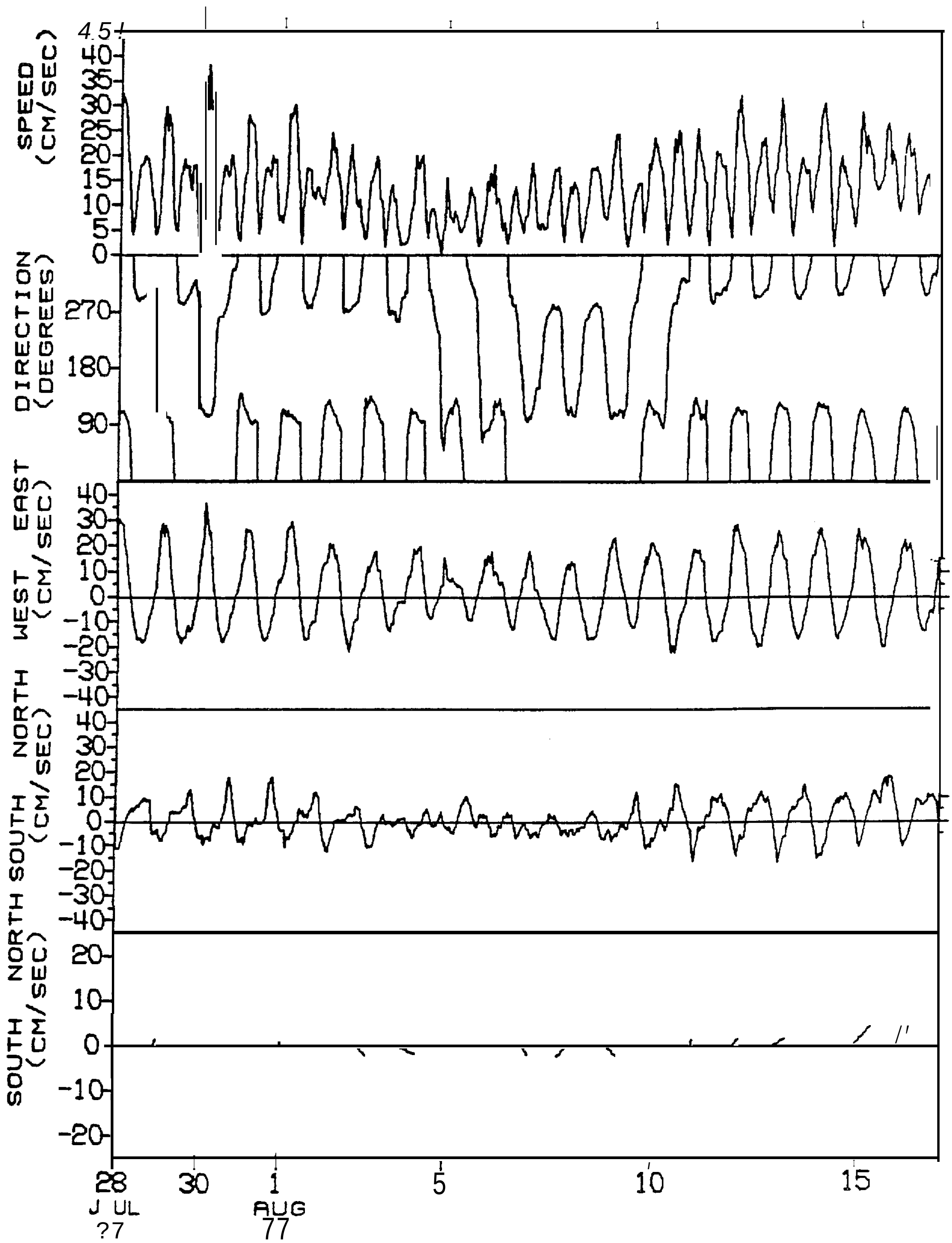




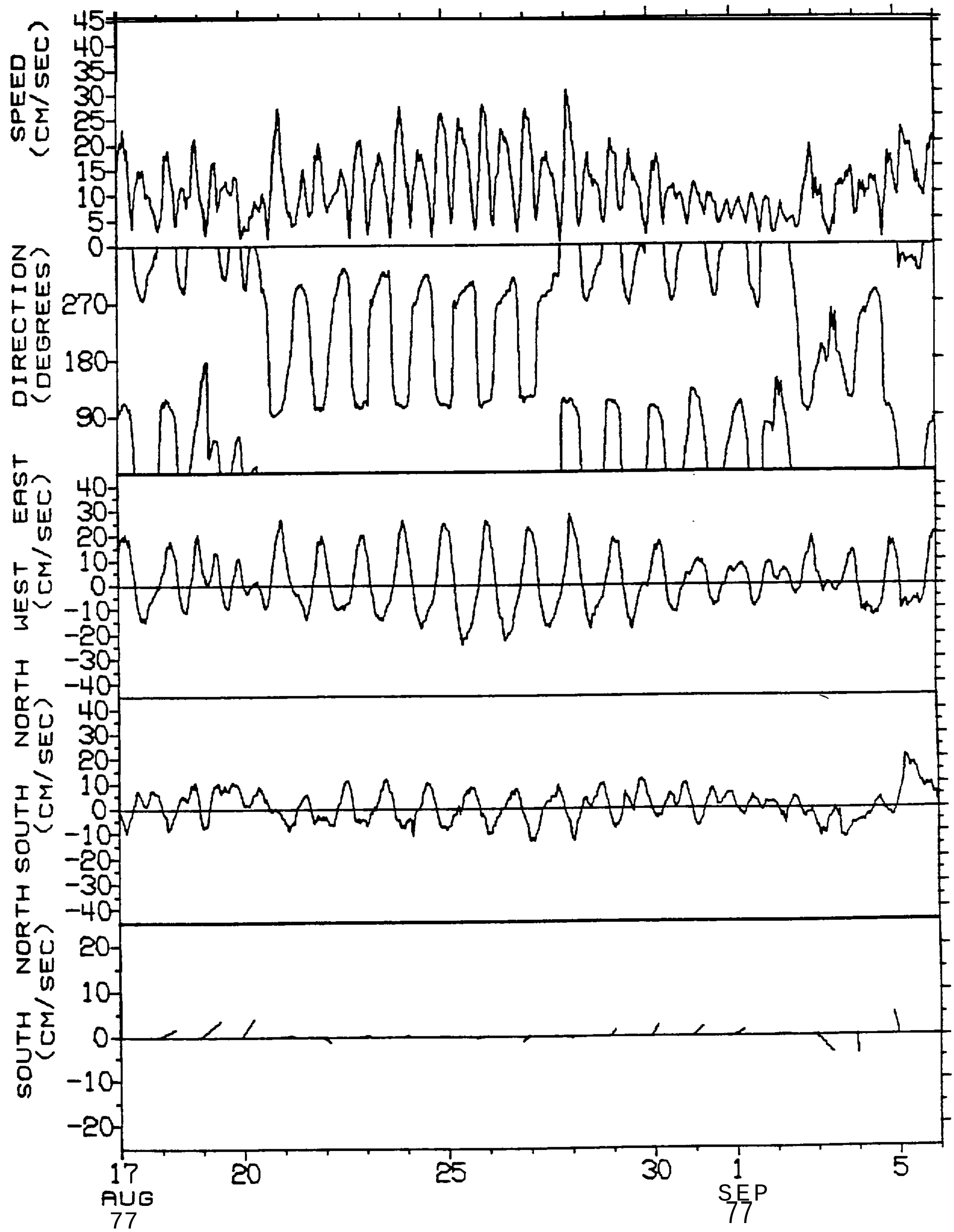
TIME SERIES OF VECTOR AVERAGED CURRENTS AT CM4 GEOPROBE LNS77
LOCATION = LAT 64 00N. LONG 165 00W. DEPTH 17.5 METERS
OBSERVATION PERIOD = 0000 8 JUL 77 TO 2300 27 JUL 77 (20.0 DAYS)
AVERAGING INTERVAL = 1.0 HOURS (1 POINTS)



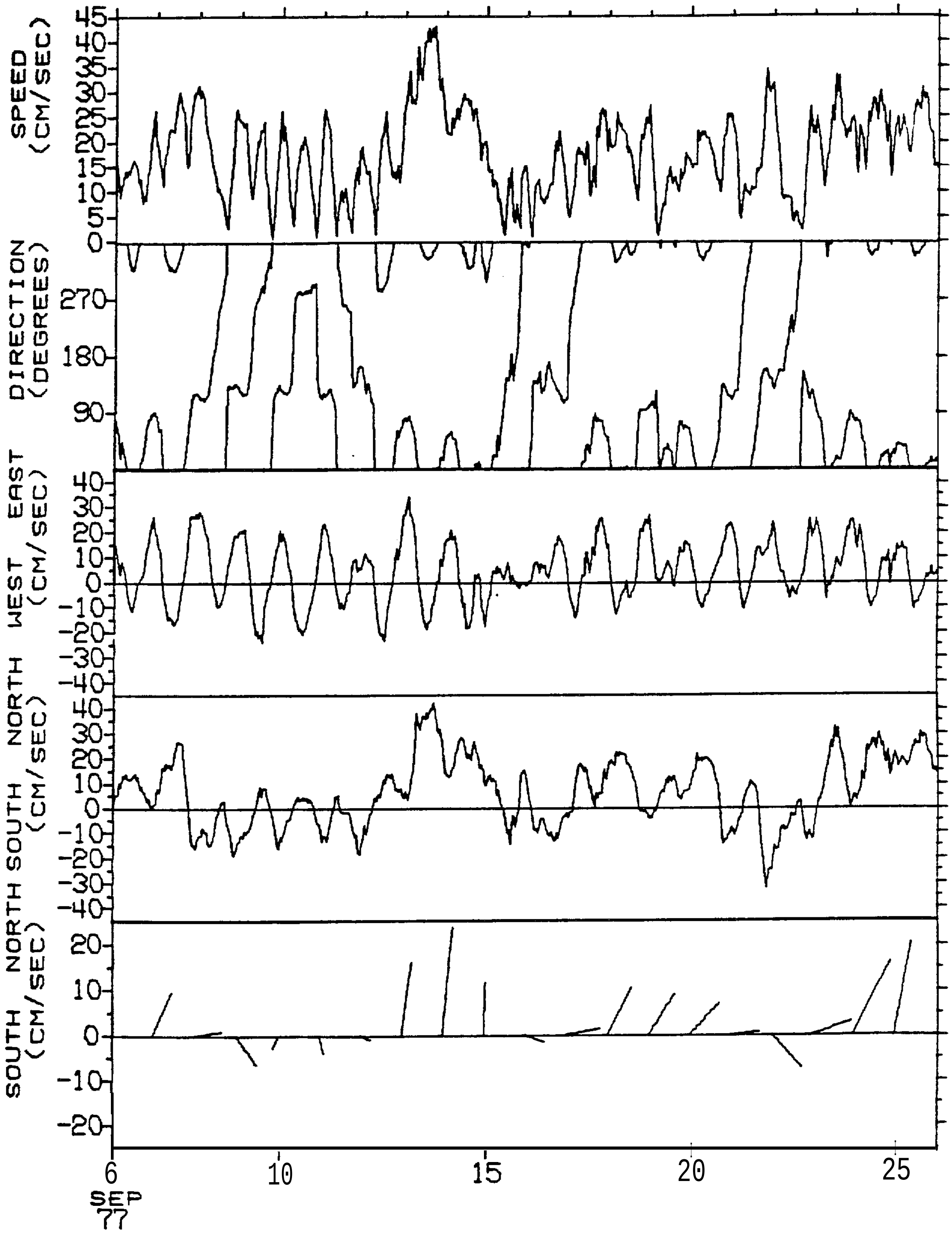
TIME SERIES OF VECTOR AVERAGED CURRENTS AT CM4 GEOPROBE, NS77
LOCATION = LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 28 JUL 77 TO 2300 16 AUG 77 (20.0 DAYS)
AVERAGING INTERVAL = 1.0 HOURS (1 POINTS)



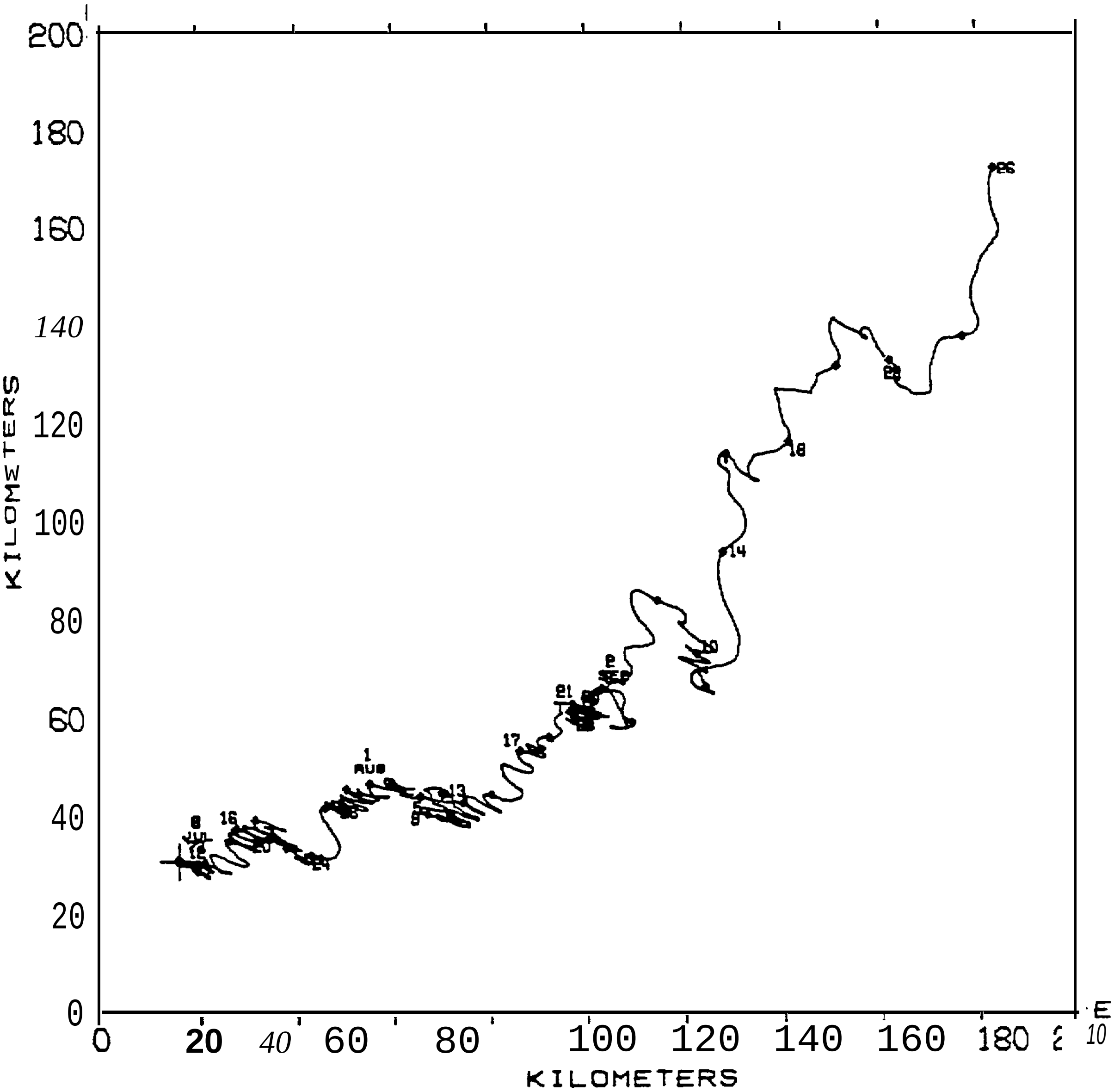
TIME SERIES OF VECTOR AVERAGED CURRENTS AT CM4 GEOPROBE, NS77
LOCATION = LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 17 AUG 77 TO 2300 5 SEP 77 (20.0 DAYS)
AVERAGING INTERVAL = 1.0 HOURS (1 POINTS)

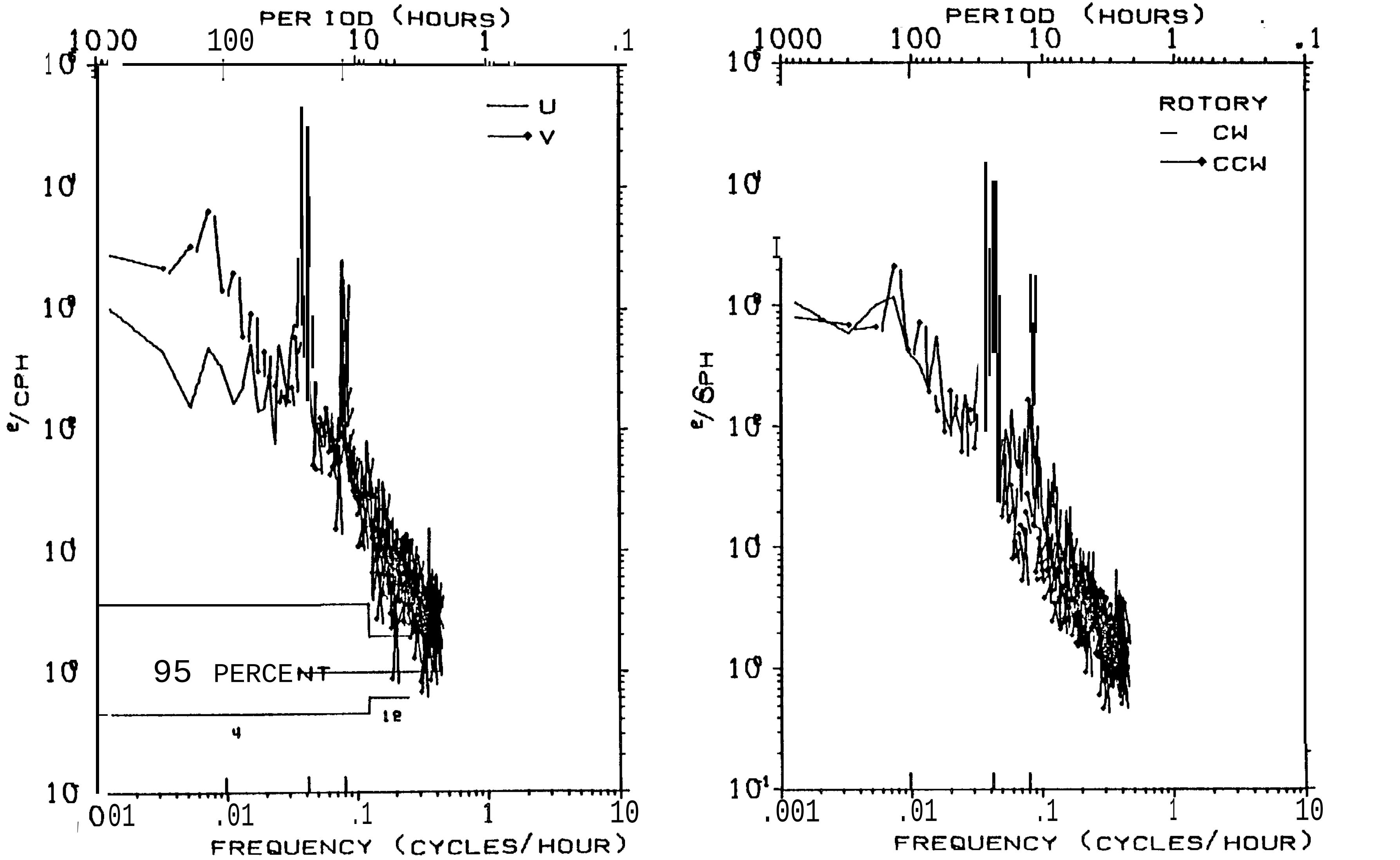


TIME SERIES OF VECTOR AVERAGED CURRENTS AT CM4 GEOPROBE, NS77
LOCATION = LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 6 SEP 77 TO 2300 25 SEP 77 (20.0 DAYS)
AVERAGING INTERVAL = 1.0 HOURS (1 POINTS)



● REGRESSIVE VECTOR DIAGRAM OF CURRENTS AT CM4 GEOPROBE NS77
LOCATION = LAT 64 00N, LONG 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 8 JUL 77 TO 2300 25 SEP 77 (80.0 DAYS)
◆ EVERY 2.0 DAYS BEGINNING AT 0000 8 JUL 77





U, V AND ROTORY SPECTRA OF CURRENTS AT CM4 GEOPROBE, NS77
LOCATION LAT 64 00N, L NCO 165 00W, DEPTH = 17.5 METERS
OBSERVATION PERIOD = 0000 8 JUL77 TO 2300 25 SEP7 7 (80.0 DAYS)
N = 1920, DT = 1.0 HOURS, SMOOTHING DANIELL WINDOW

KINETIC ENERGY SPE TRUM OF C U R R E N T S AT CM4 GEOPROBE , 5 77 ERS
LOCATION = LAT 64 00N, LONG 165 00W,
OBSERVATION PERIOD 0000 8 JUL 77 TO 2300 25 SEP 77 (80.0 DAYS)
N = 1920, DT 1.0 HOURS, SMOOTHING DANIELL WINDOW