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COMPARISON OF WIND SPEED AND DIRECTION MEASUREMENTS FROM VARIOUS METEOROLOGICAL BUOYS AND SENSORS

BY
C. Y. DER AND J. BULL

ES - 519

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MANAGEMENT PERSPECTIVE

The pair of experiments and analyses described in this report were undertaken by National Water Research Institute (NWRI), to investigate the factors effective the measurement of wind speed and direction from buoy platforms. Several reasons were behind these experiments.

The art of meteorological measurements taken from a medium sized buoy is in a developmental state as compared to land-based meteorology. For this reason, Atmospheric Environment Service (AES) approaches NWRI to assist them in the study of the errors in wind measurements generated by a moving platform and by the sensors being at various heights above the water level. Through the co-operation between NWRI and AES, the Lake Ontario experiment of 1973 was carried out to satisfy these needs.

Under the Canadian Oceanographic Data System (CODS) program and the Co-Operative Plan with Industry (COPI) program, NWRI had participated in the generation of a new design for medium sized buoys. Because there was a change in hull shape, the impact of this change on meteorology had to be investigated.

Field data from earlier experiments raised some questions on the relative correlation of data sets amongst buoys at close range and the variation between a buoy station and a land-based station. These uncertainties required addressing for the type of buoy used by NWRI.

Finally, the response time, sampling time and physical arrangement of wind sensors play a major part in the accuracy of measurement of wind speed and direction. An intercomparison of three sensor types on the buoy was carried out to increase the information on the effects of physical arrangements, to increase the confidence in sensors commonly used by NWRI and to give guidance to new sensor and sensing improvements. The results of these tests have influenced the design of the new meteorological buoy under way in NWRI.

J. S. Ford

PERSPECTIVE DE GESTION

Les deux expériences et analyses décrites dans le présent rapport ont été entreprises par l'Institut national de recherche sur les eaux (INRE), afin d'examiner les facteurs influant sur les mesures de vitesse et de direction du vent effectuées à partir de bouées. Ces expériences ont été entreprises pour plusieurs raisons.

Contrairement aux mesures faites sur terre, les mesures météorologiques effectuées sur des bouées de taille moyenne en sont encore au stade du développement. Pour cette raison, le Service de l'environnement atmosphérique (SEA) a approché l'INRE pour collaborer à l'étude des erreurs sur les mesures relatives au vent, dues au mouvement de la plate-forme et au fait que les détecteurs sont placés à des hauteurs variables au-dessus du niveau de l'eau. Cette coopération entre le SEA et l'INRE a donné naissance à l'expérience du Lac Ontario, en 1973, dont le but était d'étudier ces questions.

Dans le cadre du programme du Système de données océanographiques canadien (SDOC) et du programme de collaboration avec l'industrie (PCI), l'INRE a participé à la conception de nouvelles bouées de taille moyenne. Il y a eu des changements dans la forme de la coque, et il a fallu en étudier les incidences sur les mesures météorologiques.

Des résultats d'expérience précédentes ont soulevé plusieurs questions sur la corrélation relative entre des ensembles de données recueillies à partir de bouées rapprochées et sur les différences entre les mesures effectuées sur des bouées et celles effectuées sur terre. Ces incertitudes ont obligé l'INRE à revoir ses types de bouées.

Enfin, le temps de réponse, le temps de mesure et la configuration du détecteur jouent un rôle majeur dans la précision des mesures de vitesse et de direction du vent. Une comparaison de trois types de détecteurs placés sur des bouées a été entreprise afin de mieux connaître les effets de la configuration, d'augmenter la fiabilité des détecteurs couramment utilisés par l'INRE, et d'orienter les prochains travaux d'amélioration des instruments et des méthodes de détection. Les résultats de ces essais ont eu une influence sur la conception de la nouvelle bouée météorologique présentement à l'étude à l'INRE.

ABSTRACT

This unpublished report discusses two recent intercomparisons involving standard and modified NWRI wind speed and wind direction sensors on various buoy types. The overall objectives of these two studies included assessment of different buoy types as meteorological platforms, and improvement of wind direction sensing on a buoy platform. Two different buoy types, an aluminum hexagonal toroid and a standard NWRI fibreglass toroid were compared in the first study. Three wind direction sensors - a standard wind vane, a damped wind vane, and a buoy compass were compared in the second study.

Preliminary results show that although the aluminum hexagonal toroid pitches to a greater extent that the fibreglass toroid, this does not appear to degrade its performance as a meteorological platform. It has the additional advantages of increased ruggedness and lower cost. Wind direction measurements made with the buoy compass sensor, whereby the buoy itself is used as its own direction sensor, exhibited less variance than that obtained from the wind vane or damped vane sensors. The buoy compass configuration is therefore recommended as the preferred wind direction sensor for simple averaging applications. The technique is not recommended as a sole source of wind direction data in future systems, but it does provide good backup data. The sensors themselves are not necessarily recommended by this report for future designs.

RÉSUMÉ

Ce rapport non publié présente deux comparaisons récentes portant sur des versions standards et modifiées de détecteurs de vitesse et de direction du vent, de l'INRE, montés sur des bouées. Les objectifs généraux étaient d'évaluer le comportement de différents types de bouées comme plates-formes météorologiques, et d'améliorer la détection de la direction du vent sur une de ces plates-formes. Dans la première étude, deux types de bouées ont été examinés: un tore hexagonal en aluminium et un tore standard, en fibre de verre, de l'INRE. Dans la deuxième étude, on a comparé trois détecteurs de direction du vent: une girouette normale, un anémomètre à palettes d'amortissement, et une boussole placée sur une bouée.

Les premiers résultats ont montré que le tore hexagonal en aluminium tangue plus que le tore en fibre de verre mais que cela ne diminue apparemment pas sa performance comme plate-forme météorologique. Il présente en plus l'avantage d'être plus robuste et moins coûteux. Les mesures de direction faites avec la boussole placée sur une bouée, système dans lequel la bouée elle-même constitue le détecteur de direction, ont une variance inférieure à celle obtenue avec la girouette ou l'anémomètre à palettes d'amortissement. Ce système convient donc pour de simples déterminations de moyennes. Cette technique n'est pas recommandée comme seule source de données sur la direction du vent dans les futurs systèmes, mais elle fournit malgré tout de bonnes données complémentaires. En ce qui concerne les prochains modèles, les détecteurs eux-mêmes ne sont pas nécessairement recommandés par le présent rapport.

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1. INTRODUCTION

The National Water Research Institute has used medium scale meteorological buoys on an ongoing basis since the early 1970's. These buoys are used in many studies where climatological parameters are among those to be measured. Of the instrument set presently employed on these buoys two of the standard meteorological sensors, wind speed and wind direction are mechanical and moving-part by nature.

Consequently, various studies have been preformed to assess the influence of buoy motion on the measurement of these parameters and a number of modifications have been tested in an attempt to improve the quality of the data return. The results of two such recent intercomparison studies involving these systems are presented here. In the first study, identical sensors are fixed on both toroid and hexagonal buoy platforms' and the resultant wind speed and direction data sets intercompared. In the second study, one standard and two modified wind direction sensors are fixed on the some buoy and the resultant wind direction data sets intercompared.

2. SYSTEM HARDWARE DESCRIPTION

2.1 The Standard NWRI Meteorological Buoy

A photograph of the standard NWRI meteorological buoy is show- in figure 1A. The buoy consists of a toroidal fibreglass hull which supports a tripod superstructure. The meteorological sensors are mounted on arms near the top of the tripod while the data recorder is fixed to the lower deck. A navigational beacon and a radar reflector are mounted on the upper deck. A large vane orients the system into the wind.

2.2. THE CODS DEVELOPED BUOYS

2.2.1. THE ALUMINUM HEXAGONAL BUOY

The buoy referred to here as aluminum hexagonal torus (Fig. 1B) is built of pipe sections butt-welded together to form a hexagon as viewed from above.

The reserve buoyancy of this buoy compared to its mass is sixty percent higher than the standard buoy although the overall dimensions are similar. The relative durability of this buoy was inadvertently attested to through undamaged survival over a period of severe winter icing which badly cut and damaged the nearby fibreglass model.

2.2.2. A second fibreglass torus, this one designed and built by Hermes had an identical shape to the standard buoy of 2.1 above, although smaller in overall dimensions. The net buoyancy and mass are proportionately similar to the standard NWRI buoy (80 and 90 percent of, respectively).

2.3 SENSOR AND RECORDER DESCRIPTIONS

The data acquisition system is built around a "Hymet" recorder having the following specifications:

A/D	Conversion Encoder	:electro-mechanical, 10-bit successive approximation
	Accuracy	:$\pm$ 1 bit in 2^{10}
	Time	:8 sec/channel
	No of channels	:8
	Scan Time	:64 secs nominal
	Sampling Interval	:10 min interval between scans standard
	Recording	
	Medium	:600 ft, 1/4 in. magnetic tape
	Capacity	:55,000x10-bit words

A maximum of 8 meteorological parameters can be recorded by the package with unused channels assigned a fixed input. The channel allocations for the sensors are as follows:

Channel 4 - Relative Humidity

Description	: Modified Hygrodynamics # 15 -7012
Range	: 42% to 99% RH
Accurzcy	: ± 3% RH between 40° and 120° F (these are the manufacturer's specs)
Time Constant	: 40 min @ 20° C, 60 min @ 10°C

Channel 5 - Water Temperature

Description	: Thermistor in a 5Ω voltage divider circuit
Range	: 0° C to 35° C
Accuracy	: ± 0.2° C
Time Constant	: 5 min

Channel 6 - Spare

Channel 7 - Spare

Channel 8 - Real Time

Description	: CCIW/EDA SST-100 127 steps of 32mV initiated by an interval timer at 5 min intervals giving a 640 min recycle period
Accuracy	: 0.05% (crystal portion only)

The meteorological data, with the exception of wind speed, comprises a sampled data set with a sampling interval of 10 minutes. The wind speed sensor essentially integrates the measured wind speed with the anemometer driving a potentiometer through a gear reducer. A wind speed "sample" is thus a measurement of the wiper position at the sample time. The average wind speed over a ten minute time period is then the difference of two adjacent samples multiplied by a calibration function.

3. STUDY ONE: - THE 1978 LAKE ONTARIO BUOY INTERCOMPARISONS

As a followup to the Canadian Ocean Data Systems (CODS) program, an investigative study was implemented in the fall of 1978 with the objective of intercomparing the measurement sets from systems and two land-based meteorological stations all located in area close to NWRI Burlington pier station. Each of the three buoy systems were outfitted with identical NWRI Meteorological Packages (see section 2.3). The three systems differed in the type of buoy platform used, and hence in their respective response to the ambient wind and wave regime. Employed here were a standard NWRI fibreglass toroid, an aluminum hexagonal toroid and a non-standard fibreglass toroid with a special 7 m. mast extension supplied by AES. The mooring configuration and hardware were the same for the first two buoy systems; while the last system was given a heavier mooring for vertical stability to offset the increased mast height. The principal objective of this study was to determine if the different buoy types exhibited specific characteristic responses to various wind/wave forcing with consequent buoy-specific data contamination. Knowledge of this nature is useful in the selection of buoy types of various application; as each design has differing cost and reliability advantages.

Of the two land based stations, only the Burlington Pier site was equipped with the standard NWRI recording/sensor package. The L. Ontario tower system samples at a higher frequency and records directly an 1/2 magnetic tape. A system description is beyond the scope of this writing and is reported by Smith (1978).

3.1 METEOROLOGICAL STATION SPECIFICATIONS

Meteorological data was collected in the period from October 10 through November 20, 1978. The five stations are summarized in Table 1 shown on Figure 2.

Table 1

	Station Name	Location	Description	Sensor Height
1.	78-00M-16A	Lat: 043-17-06 Long: 079-41-57	-std NWRI met buoy -fibreglass toroid	-atm sensors 4 m above water surface
2.	78-00M-17A L. Ont. Hex (buoy)	Lat: 043-17-11 Long: 079-41-58	Hermes CODS buoy aluminum toroid	-atm sensors 4 m above water surface
3.	78-00M-18A L. Ont. AES	Lat: 043-17-09 Long: 079-42-08	AES CODS buoy fibreglass toroid	atm sensors 7 m above water surface
4.	78 Burlington Tower (fixed land-basement)	Lat: 043-16-13 Long: 079-45-34	Burlington Tower met station	atm sensors 10 m above water surface
5.	78-00M-03A Burlington Pier	Lat: 043-17-50 Long: 079-47-30	Burlington Pier met station	atm sensors 10 m above ground (12 m above water

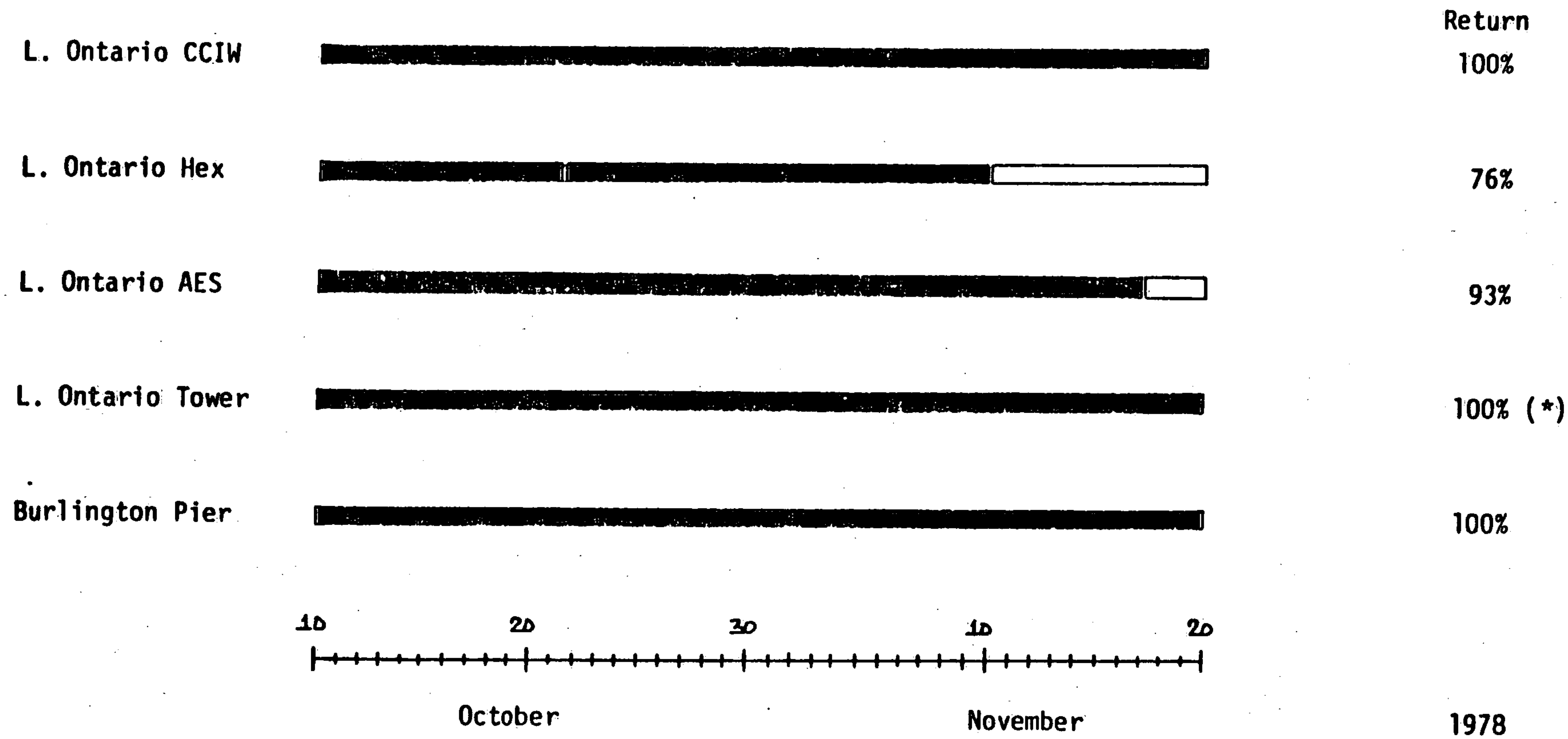
At all five stations, the following parameters were measured: wind speed (cm/sec), wind direction (deg from true north), air temperature (deg Celsius), relative humidity (percent) and water temperature (deg Celsius). The stations were monitored twice weekly at which time handled instrument readings were taken to check the data integrity.

3.2 DATA RETURN

The data return from the five stations was in excess of 90% for all stations with the sole exception of the aluminum hexagonal buoy (Station 78-00M-17A) which had a 76% data return. Faults with the recorder resulted in an 8½ hour data loss on October 21 as well as loss of data during the last 10 days of the experiment. Recorder problems

TABLE 2

DATA SUMMARY



* Although the Burlington tower returned 100% data in the field experiment, hardware difficulties have adversely degraded data quality for some parameters.

on the AES buoy M78-00M-18A (a jammed tape motor) caused only a three day data loss at this meteorological station. Table 2 summarises the data return history of the 1978 field experiment.

3.3 DATA PROCESSING

Four of the five stations reported here use the standard NWRI Meteorological Package which records data in bit-serial form on ¼ inch magnetic tape. A PDP-8 based translator system was used to read these field tapes and produce computer compatible 7 track BCD tapes from which the time series data was subsequently extracted and edited. Complete details of the interactive editing system used at NWRI is given by Hanson (1977). Briefly, the data is scanned and graphically displayed on a CRT monitor. Anomalous or questionable data points can be deleted and interpolated values substituted in their place in an interactive manner.

With the exception of the data from the Burlington Tower, all of the above data tapes were edited to produce ten minute time series data files. Standard programs were used to generate hourly averaged files from their ten minute counter parts; boxcar averaging techniques are employed. The Burlington Tower system records directly data on ½ inch computer compatible magnetic tape. At this time, there are no comparable facilities for the above type of editing on this data, hence, this data set contains some erroneous measurements. In particular, the water temperature data exhibits abnormal shifts and negative temperatures on occasion. It is believed that this is the result of an intermittent hardware failure with that particular sensor. This anomalies are typically large excursions from adjacent readings and easily identified.

3.4 PRELIMINARY DATA ANALYSIS

The data from this particular experiment has not yet been fully analyzed. Only the hourly-averaged wind speed and wind direction data sets have been compared. Some preliminary results, however, are presented here.

3.4.1. WIND SPEED INTERCOMPARISON

Figures 3 to 6 are wind speed scatter plots for the entire measurement period. The reference data set (ie. the data set to which all others are compared) was that from the standard NWRI buoy (Station 78-00M-16A). Figures 3 (Aluminum Hexagonal Buoy versus Standard NWRI Buoy) and 4 (AES Buoy versus Standard NWRI Buoy) show very similar scatter among the wind speed data sets. This is confirmed by the nearly identical correlation coefficients obtained from a standard linear regression. For wind speeds less than 6 m/s, the Aluminum Hexagonal Buoy does however exhibit a number of data points outside of the main scatter grouping. This may be related to a characteristic of hexagonal buoy which was observed in the field. It was noted that the buoy tended to align one of its corners normal to the prevalent wave front and "plow" through the crests. This caused the buoy to pitch much more than either the Standard NWRI Buoy or the AES Buoy. The data points that are outside the main scatter grouping may thus represent a particular episode of wind speed and wave action. Further analysis is required to establish if such a relationship exists. For wind speeds greater than 6 m/sec., the scatter increases in both plots. No significant differences in the scatter plots are apparent in this speed range.

Figures 5 (Burlington Tower versus Standard NWRI Buoy) and 6 (Burlington Pier versus Standard NWRI Buoy) show considerable scatter with progressively less correlation in the data apparently because of the greater distances between the various meteorological stations. In both plots, the scatter appears more or less uniform throughout the entire period.

3.4.2. WIND DIRECTION INTERCOMPARISON

The wind direction scatter plots are given in Figures 7 to 9. Once again, the correlation coefficients associated with the Aluminum Hexagonal and AES Buoys relative to the Standard NWRI Buoy are nearly identical. The scatter is essentially the same for both buoys. The data points appearing in the upper left and lower right corners results from the 0°/360° discontinuity in the direction measurement. As with wind speed, the wind direction data from the Burlington Tower and Burlington Pier stations show progressively more scatter.

3.5 CONCLUSIONS

With the analysis done for this report, there is no indication that the aluminum hexoid is unsuitable as a substitute for the conventional fibreglass toroid. Although field reports indicate that the hexagonal toroid pitches to a greater extent than a fibreglass toroid in a high wave field, data returns from the buoys in this field experiment do not show the large variance as might be expected from this particular buoy response to wave action. The lower cost and more rugged hexagonal buoy may thus be more advantageous and cost-effective than the standard fibreglass toroid in many current applications.

4. STUDY TWO: - THE 1979 HAMILTON HARBOUR WIND DIRECTION SENSOR INTERCOMPARISON

One of the recommendations of Donelan, et al[1] from their intercomparison of a buoy-based and a tower-based meteorological system was that a large vane be used to orient the buoy into the wind direction, thus making the buoy itself a direction sensor. In the fall of 1979, a compass was mounted to the frame of the buoy. Two other wind direction sensors were included in the system:- a standard CCIW wind vane and compass, and a modified CCIW wind vane and compass. The mechanical damping of the compass in the latter was increased with the addition of higher viscosity oil, effectively increasing the direction time constant to approximately one minute. The objectives of this study were as follows:

1. to determine the suitability of using the buoy as its own wind direction sensor and,
2. to determine if the response characteristics of the standard NWRI wind direction sensor could be improved by increasing its mechanical damping.

The buoy was deployed in Hamilton Harbour.

4.1 DESCRIPTION OF THE WIND DIRECTION SENSORS

Table 3 summarizes the specifications of the three wind direction sensors used in this study. All three sensors were mounted on the same buoy throughout the deployment.

Table 3

Hamilton Harbour Wind Direction Sensor Intercomparison

Sensor Specifications

	Wind Vane	Damped Van	Buoy Compass
Description	vane & modified Plessey M020C compass on tripod arm	vane & modified Plessey M020C compass on tripod arm	Aanderaa Model 1248 clamping compass fixe to buoy with orienting vane
Range	0-355° magnetic 0-5 kΩ potentiometer	0-355° magnetic 0-5 kΩ potentiometer	0-360° magnetic 0-2 kΩ potentiometer
Time Constant	0.5 sec (est.) for compass only	60 sec (est.) for compass only	3.5 sec (est.) for compass only
Accuracy	± 5 deg	± 5 deg	± 5 deg

These sensors are all fundamentally the same. When each sensor is to be read, a magnet assembly is clamped to a potentiometer ring. Direction is thus recorded as a potentiometric setting. Between readings, the magnet assembly is unclamped and allowed to seek a North heading.

4.2 PRELIMINARY DATA ANALYSIS

The measurement period of the study extended from August 13 to November 14. Scatter plots were generated from the wind direction data over the entire period as well as for specific sub-periods. These were subsequently compared with heading difference and wind speed time series. Vector and vector difference time series are also included.

4.2.1. Wind Direction Scatter Plots

Figures 10 and 11 are scatter plots generated by plotting wind direction data from the wind vane and damped vane sensors against the data from the buoy compass. The buoy compass data set was selected as the reference since it was expected that it would have the lowest variance. Data points within 10 degrees of each other were not plotted for practical considerations. Clearly, the wind vane exhibits more scatter than the damped vane when they are both compared against the buoy compass.

As it is well known that the wind vane tends to "flop" in light winds, scatter plots were drawn for three wind speed ranges ---0 to 2 m/s, 0 to 3 m/s, and 3 to 8 m/s. Figures 12 to 17 clearly demonstrate that much of the observed scatter of the wind vane occurs at the lower wind speeds. Specifically, the scatter bounded by 0-120 deg (wind vane) and 180-360 deg (buoy compass) in Figure 10 arises from wind speeds between 0 and 3 m/s (Figure 14). The damped vane (refer to Figure 11) tends to filter out the scatter in this region, but those data points that are plotted are also associated with the lower wind speeds (see Figure 15).

Figures 18 and 19 are scatter plots of the entire measurement period. This time, however, data points within 15 degrees of each other are not plotted. These plots show that the scatter between data sets is in excess of ± 15 degrees. Although the sensors are accurate to within ± 15 degrees. Although the sensors are accurate to within ± 5 degrees for quiescent conditions, this is much degraded under field conditions of combined vane/compass/buoy/ mooring motions.

The study period was also broken into fifteen day sub-periods. These are given in Figures 20 to 31. In all sub-periods, the data from the damped vane showed less scatter than that from the wind vane except for the time from October 16 to 31. This particular scatter is an anomaly; it is bounded by 90-180 deg (damped vane) and 0-120 deg (buoy compass) in Figure 29. This subperiod was examimed in more detail in Figures 35 to 37. It is clear from these figures that the scatter is associated with the damped vane sensor and not the buoy compass. The large variations in the wind vane - damped vane heading difference time series during 19 October, 0400 to 1200 hrs in Figure 44, seem to correlate to this scatter (as there are no corresponding variations in the wind vane - buoy compass heading difference time series for this same time period). However, there are no indications in the wind speed time series to explain the behavior of the damped vane. The underlying cause of this anomalous scatter remains unresolved to this point.

Figures 32 to 34 are the hourly data sets for each wind direction sensor plotted against each other. The wind vane data exhibits once again the largest variance of the three. Figures 38 to 40 are intercomparative scatter plots for another selected time period from 29 October to 6 November. No new behavior of the three wind direction sensors is apparent.

4.2.2 Heading Difference and Wind Speed Time Series

Combined time series for heading difference (Wind Vane - Damped Vane and Wind Vane - Buoy Compass) and wind speed are shown for selected periods in Figures 41 to 46. The largest heading differences seem to occur when there is a substantial drop in the wind speed. The converse is not generally true which suggests that previous wind and wave history are probably major determining factors in this regard. Also, the differences seem to largely originate from the wind vane sensor (eg. 13 Aug, 1900 hrs to 17 Aug, 1200 hrs (Figure 41); 10 Sept, 0000 hrs to 12 Sept, 1200 hrs (Figure 43); 20 Oct, 0000 hrs to 22 Oct, 0000 hrs (Figure 44); and 27 Oct, 1800 hrs to 31 Oct, 0600 hrs (Figure 45)).

4.2.3 Wind Vector and Wind Vector Difference Time Series

Wind vector and wind vector difference time series for specific periods are shown in Figures 47 and 48 repectively. In Figure 47, the wind vector time series for the wind vane has periods which remarkably seem to have been low pass filtered (eg. 13 Oct, 1200 hrs to 16 Oct, 0000 hrs; 18 Oct, 0000 hrs to 18 Oct, 0600 hrs). There are other periods such as 16 Oct, 0000 hrs to 17 Oct, 0000 hrs where the damped vane shows much less scatter in the wind vectors. The buoy compass wind vectors fall between the other two in terms of scatter in this time period. It would appear that each of these different sensors operates "better" than each of the others in specific wind conditions and wave regimes, if "better" is meant to imply less scatter in the wind vector plots.

Two wind vector difference time series are shown in Figure 48 for the period from 19 to 21 October. The anomalous behavior of the damped vane which was discussed previously is evident near the beginning of the time series (19 Oct, 0400 hrs to 19 Oct, 1200 hrs; top time

time series). Apart from this episode, however, the wind vector differences for the wind vane compared to the buoy compass tend to be larger than the corresponding vector differences for the damped vane. Donelan, et al[1] showed that for a steady wind speed W and an unskewed distribution of wind direction deviations θ' from the mean $\overline{\theta}$, the difference between scalar and vector magnitude estimates for wind speed is given by:

$$\Delta W = W\left(1 - \overline{\cos\theta'}\right)$$

which for angles $\theta' < 60°$ is closely approximated by,

$$\Delta W = \left\{\frac{\pi}{180}\right\}^2 \frac{\overline{\theta'^2}}{2} = 1.52 \times 10^{-4}\ \sigma_\theta^2$$

Where σ_θ^2 is the variance of wind direction.

The assumption is that θ and W are independent. W is replaced by $\overline{W}$ in the case of unsteady winds. Thus, the percentage error in the vector wind estimate is optimized by minimizing the apparent σ_θ^2, that is by using a very good tracking wind vane - compass assembly and/or by increasing the damping of the sensor complex. As compared to the wind vane sensor, both the damped vane and buoy compass wind direction sensors make use of the latter optimization technique.

4.3 CONCLUSIONS

A preliminary analysis of the data obtained from the Hamilton Harbour intercomparison study confirms that the variance in wind direction measurements is largest for the wind vane sensor and smaller for the damped vane and the buoy compass sensors.

It was thought by Donelan, et al (Ref. 1) that a buoy compass sensor would likely be in greater error in very light winds because of biases in the buoy shape or the mooring fixutures. However, the error does not appear to be excessively large for the conditions encountered in Hamilton Harbour. In a less sheltered location, a buoy compass wind direction sensor is expected to show larger errors, especially for low wind speed - high wave regimes such as when the wind abruptly changes direction. Good correlation was observed amongst buoys at close range but correlation was much poorer amongst land based stations and buoys.

5. RECOMMENDATIONS

The aluminum hexagonal toroid is a viable alternative to the standard NWRI fibreglass toroid. It has the advantages of increased ruggedness and lower cost of manufacture. Its tendency to pitch more than the fibreglass toroid in a high wave regime does not appear to be a serious liability. All things considered, the hexagonal toroid is recommended as the optium choice for most applications.

Wind direction measurement can be improved by using a large vane mounted on the buoy to orient it to the wind. There is no advantage to be gained by using a damped wind vane over a buoy compass sensor. The latter will respond well in all but very light winds, and has the advantage of less complexity.

No work has yet been done to determine if a buoy compass will function satisfactorily on a hexagonal toroid. There is the question of systematic errors which may arise if the toroid tends to orient in preferred directions for specific wind/wave conditions because of its two axes of symmetry in the plan view. Further study in this area is needed to determine the optium vane size and orientation relative to the hexagon's axes.

REFERENCES

1. Donelan, M. A., Elder, F. C. and Beesley, D. March 1979 "Evaluation of Measurements from the Canada Centre for Inland Waters Meteorological Buoy". UNPBLISHED REPORT.

2. Hanson, B, "Editing Time Series Data Using an Interactive Graphies Approach", Proceedings of the Digital Equipment Users Society, Banff, Alta, Feb. 1977.

3. Smith, G., C.O.D.S. Final Report Phase II Hermes Electronics Ltd., Dartmouth, N.S. March 1978 pp. 4, 10 and 11

4. Birch, K. N. et al. "A Computer Based System for Data Acquisition and Control of Scientific Experiments on Remote Platforms". Proceedings Oceans'76. I.E.E.E. pp. 25B-6 to 8

F I G U R E S

FIGURE CAPTIONS

1. Photograph of a standard instrumented NWRI meteorological buoy.

1B Toroid Buoy

2. Location of the Buoys

3. Lake Ontario Buoy Intercomparison
   Scatter plot of wind speed data from the aluminum hexagonal buoy versus the data from the standard NWRI fibreglass buoy.
   The slope 'm', constant 'C', and correlation coefficient 'r' are indicated. (10 October to 20 November, 1978)

4. As in 3, but AES instrumented buoy versus NWRI buoy.

5. As in 3, but Burlington Tower versus NWRI.

6. As in 3, but Burlington Pier versus NWRI buoy.

7. Scatter plot of wind direction data from the aluminum hexagonal buoy versus the data from the standard NWRI fibreglass buoy.

8. As in 7, but AES instrumented buoy versus NWRI buoy.

9. As in 7, but Burlington Pier versus NWRI buoy.

10. Hamilton Harbour Wind Direction Sensor Intercomparison
    13 August to 14 November, 1979
    Scatter Plot of wind direction data from the wind vane versus the data from the buoy compass. Data points within 10 degrees are not plotted.

11. As in 10, but damped vane versus buoy compass.

12. As in 10, but wind vane versus buoy compass for wind speeds from 0 - 2 m/s.

13. As in 12, but damped vane versus buoy compass.

14. As in 12, but for wind speeds from 0 - 3 m/s.

15. As in 14, but damped vane versus buoy compass.

16. As in 12, but for wind speeds from 3 - 8 m/s.

17. As in 16, but damped vane versus buoy compass.

18. As in 10, but data points within 15 degrees are not plotted.

19. As in 11, but data points within 15 degrees are not plotted.

20. Hamilton Harbour Wind Direction Sensor Intercomparison
13 August to 28 August, 1979
Scatter plot of wind direction data from the wind vane versus the data from the buoy compass.

21. As in 20, but damped vane versus buoy compass.

22. As in 20, but 29 August to 13 September, 1979.

23. As in 22, but damped vane versus buoy compass.

24. As in 20, but 14 September to 29 September, 1979.

25. As in 24, but damped vane versus buoy compass.

26. As in 20, but 30 September to 15 October, 1979.

27. As in 26, but damped vane versus buoy compass.

28. As in 20, but 16 October to 31 October, 1979.

29. As in 28, but damped vane versus buoy compass.

30. As in 20, but 1 November to 14 November, 1979.

31. As in 30, but damped vane versus buoy compass.

32. Hamilton Harbour Wind Direction Sensor Intercomparison
13 August to 14 November, 1979.
Scatter plot of hourly wind direction data from the wind vane versus the data from the buoy compass.

33. As in 32, but damped vane versus buoy compass.

34. As in 32, but wind vane versus damped vane.

35. Hamilton Harbour Wind Direction Sensor Intercomparison
19 October to 27 October, 1979
Scatter plot of wind direction data from the wind vane versus the data from the buoy compass.

36. As in 35, but damped vane versus buoy compass.

37. As in 35, but wind vane versus damped vane.

38. As in 35, but 29 October to 6 November, 1979.

39. As in 38, but wind vane versus damped vane.

40. As in 38, but damped vane versus buoy compass.

41. Hamilton Harbour Wind Direction Sensor Intercomparison.
14 August to 21 August, 1979
Heading difference and wind speed time series.

42. As in 41, but 20 August to 27 August, 1979.

43. As in 41, but 8 September to 16 September, 1979.

44. As in 41, but 18 October to 25 October, 1979.

45. As in 41, but 24 October to 31 October, 1979.

46. As in 41, but 28 October to 2 November, 1979.

47. Hamilton Harbour Wind Direction Sensor Intercomparison
11 October to 22 October, 1979
Wind vector time series.

48. Hamilton Harbour Wind Direction Sensor Intercomparison
19 October to 21 October, 1979
Wind vector difference time series.

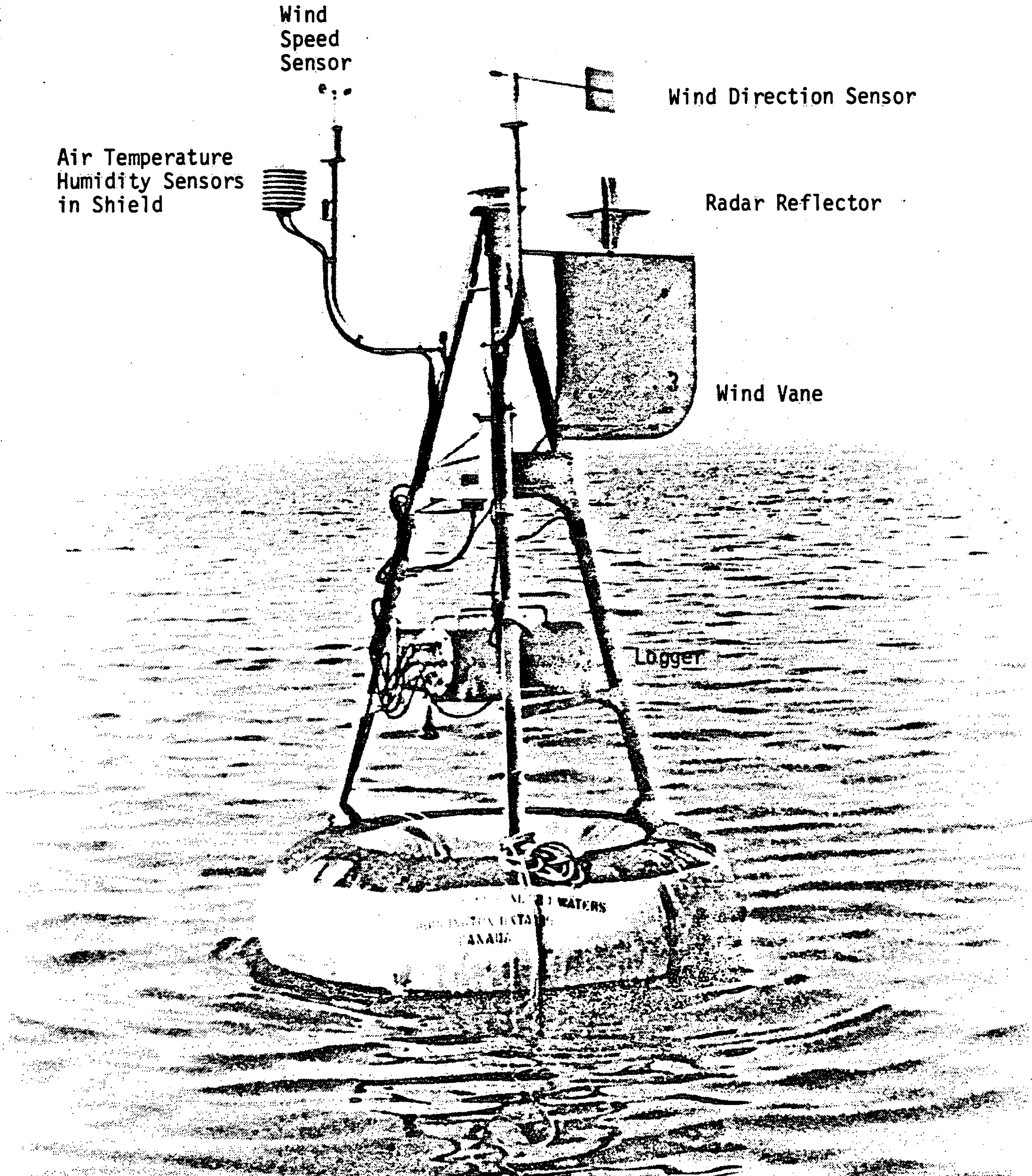

Wind
Speed
Sensor
Wind Direction Sensor
Air Temperature
Humidity Sensors
in Shield
Radar Reflector
Wind Vane
Logger

Figure 1A

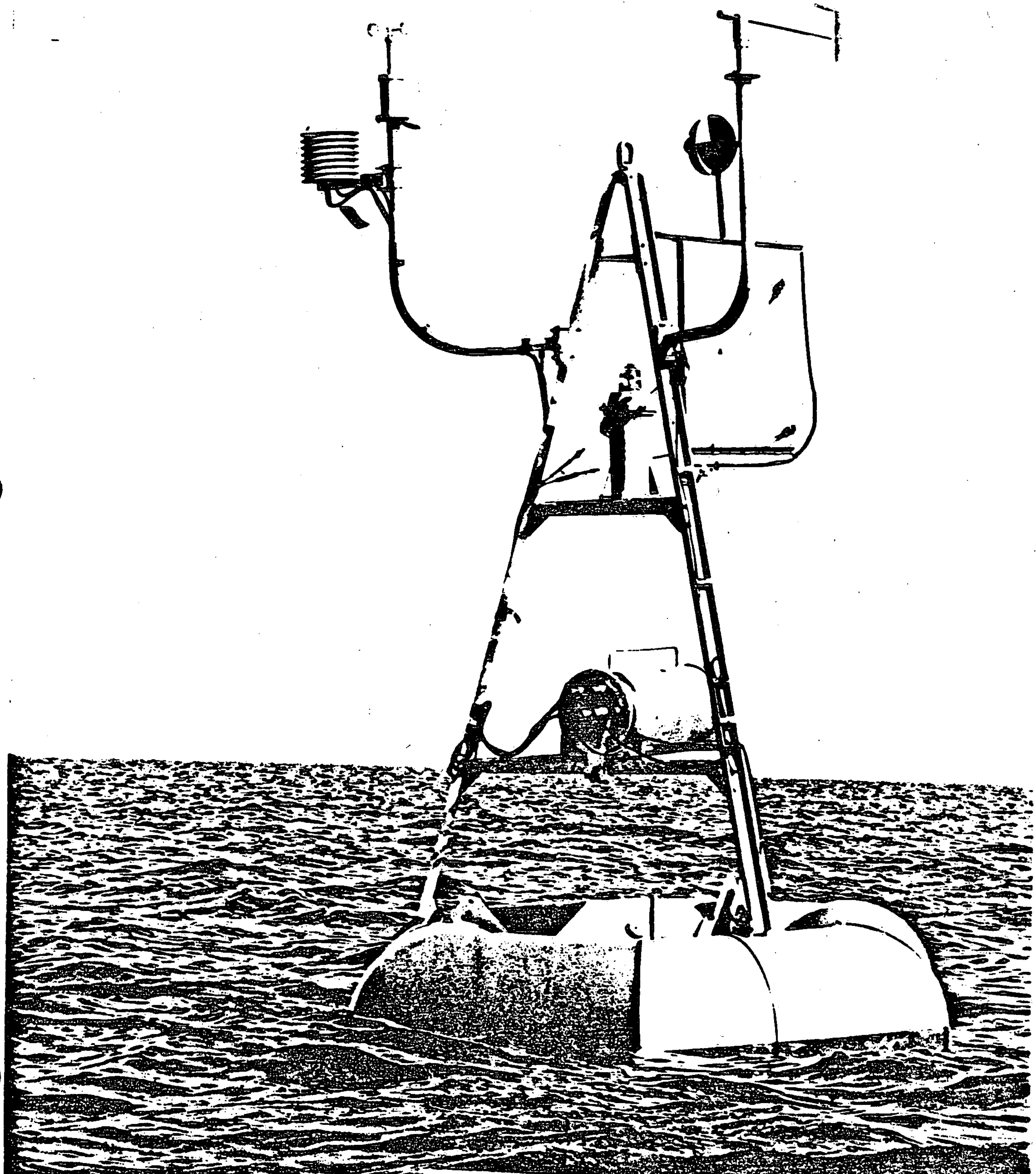


FIGURE 1 B

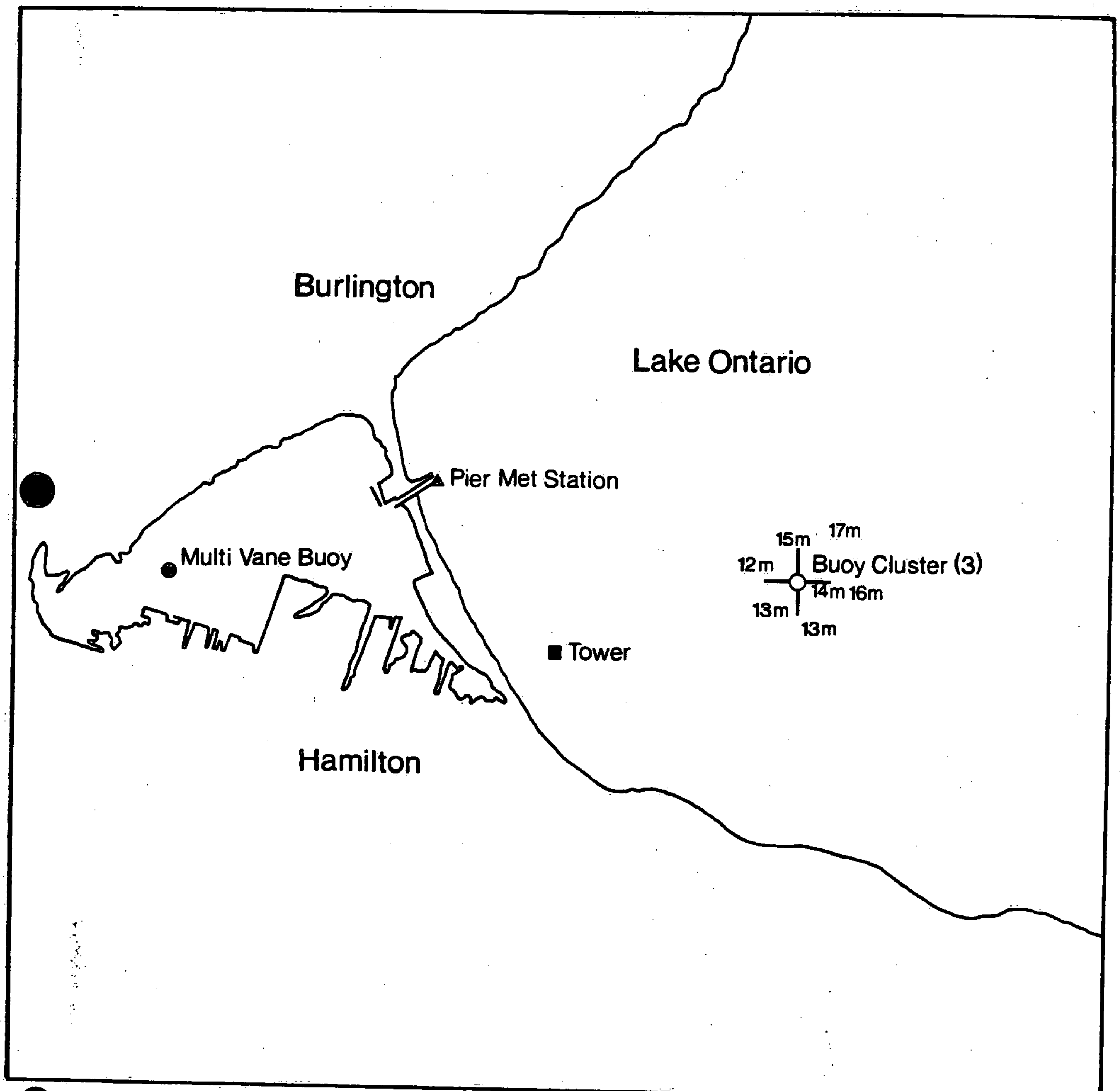

Burlington
Lake Ontario
Pier Met Station
Multi Vane Buoy
15m
17m
12m
Buoy Cluster (3)
14m 16m
13m
13m
Tower
Hamilton

Figure 2

WIND SPEED COMPARISON

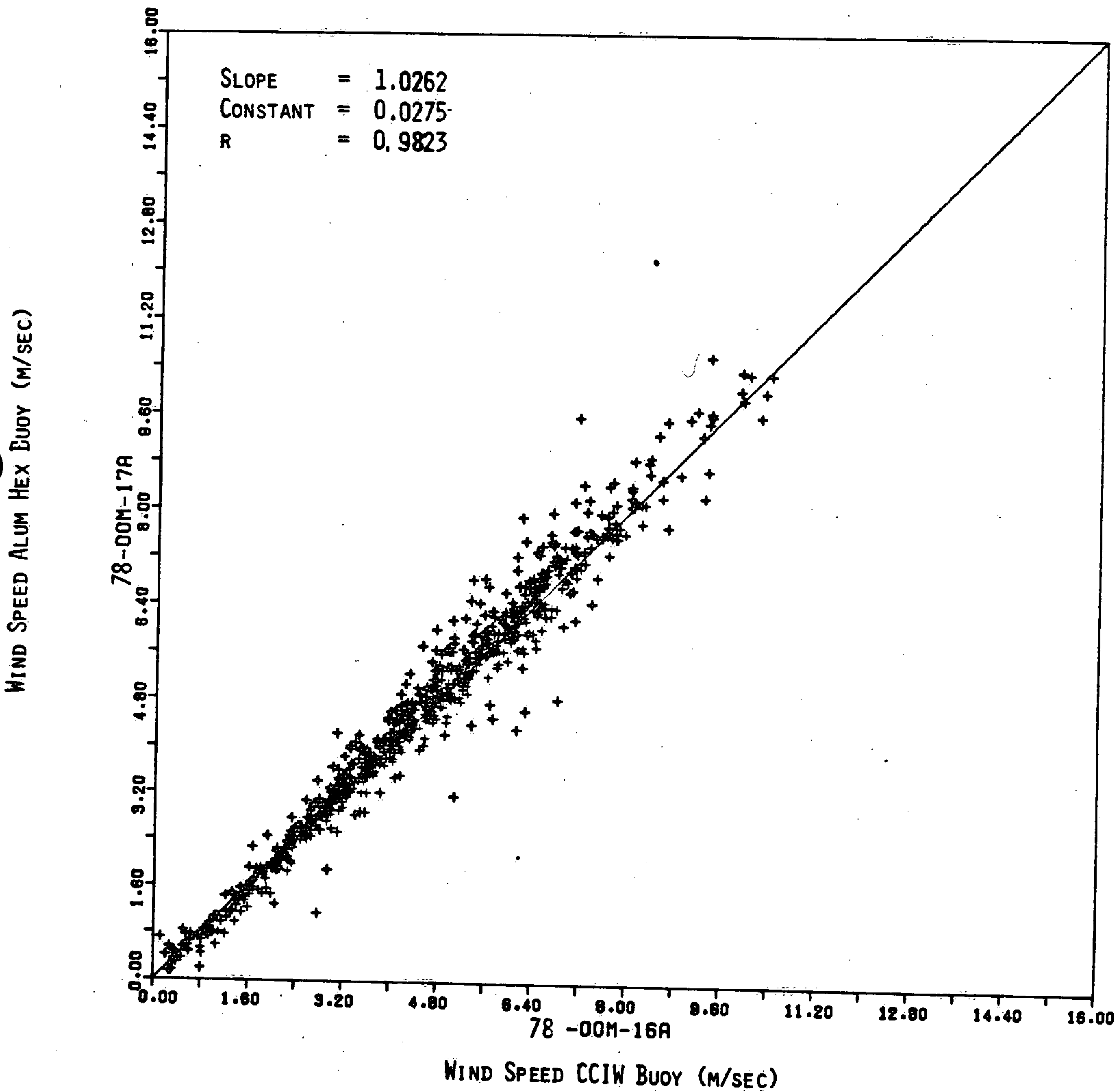


FIGURE 3

WIND SPEED COMPARISON

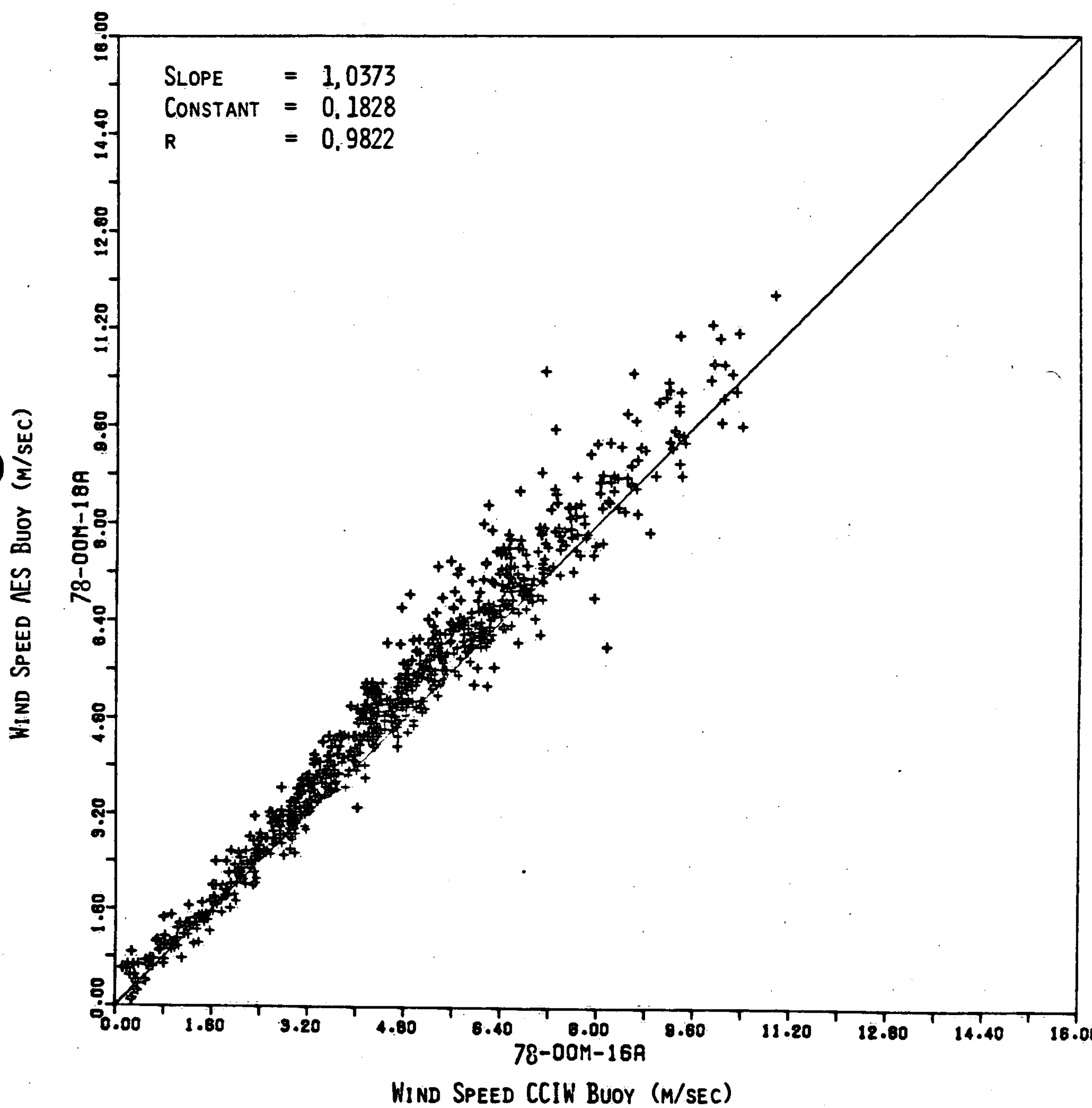


FIGURE 4

WIND SPEED COMPARISON

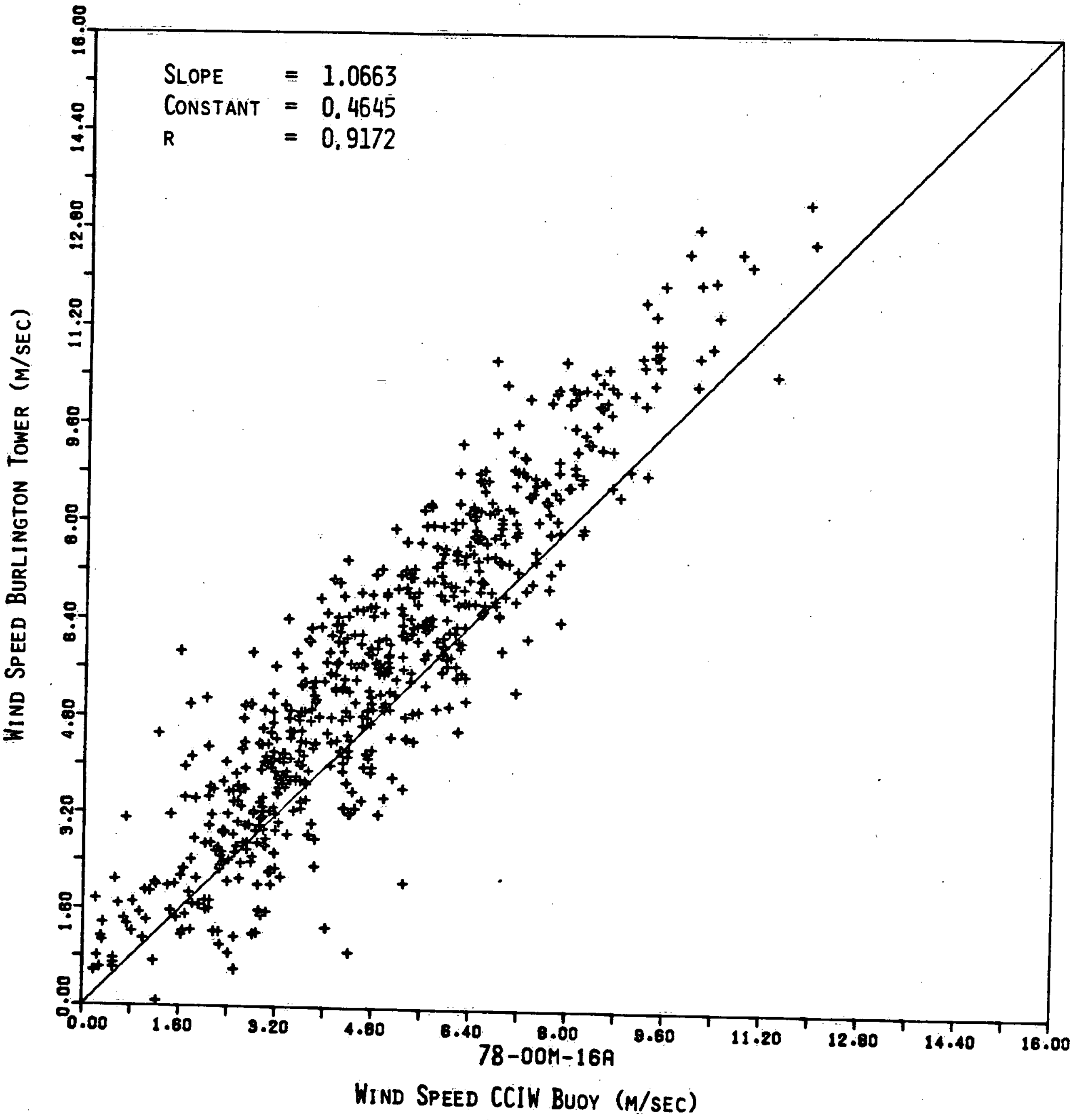


FIGURE 5

WIND SPEED COMPARISON

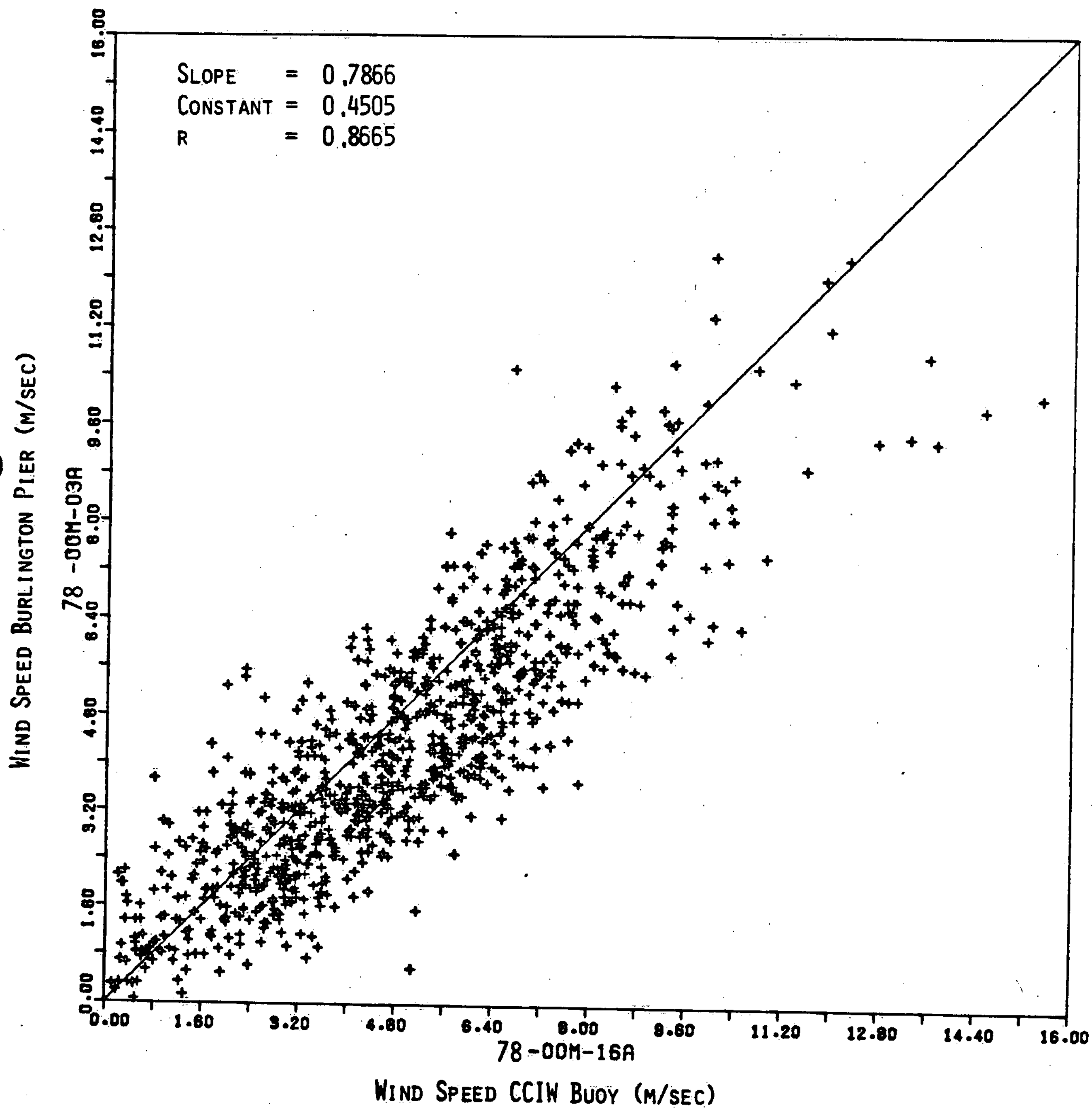


FIGURE 6

WIND DIRECTION COMPARISON

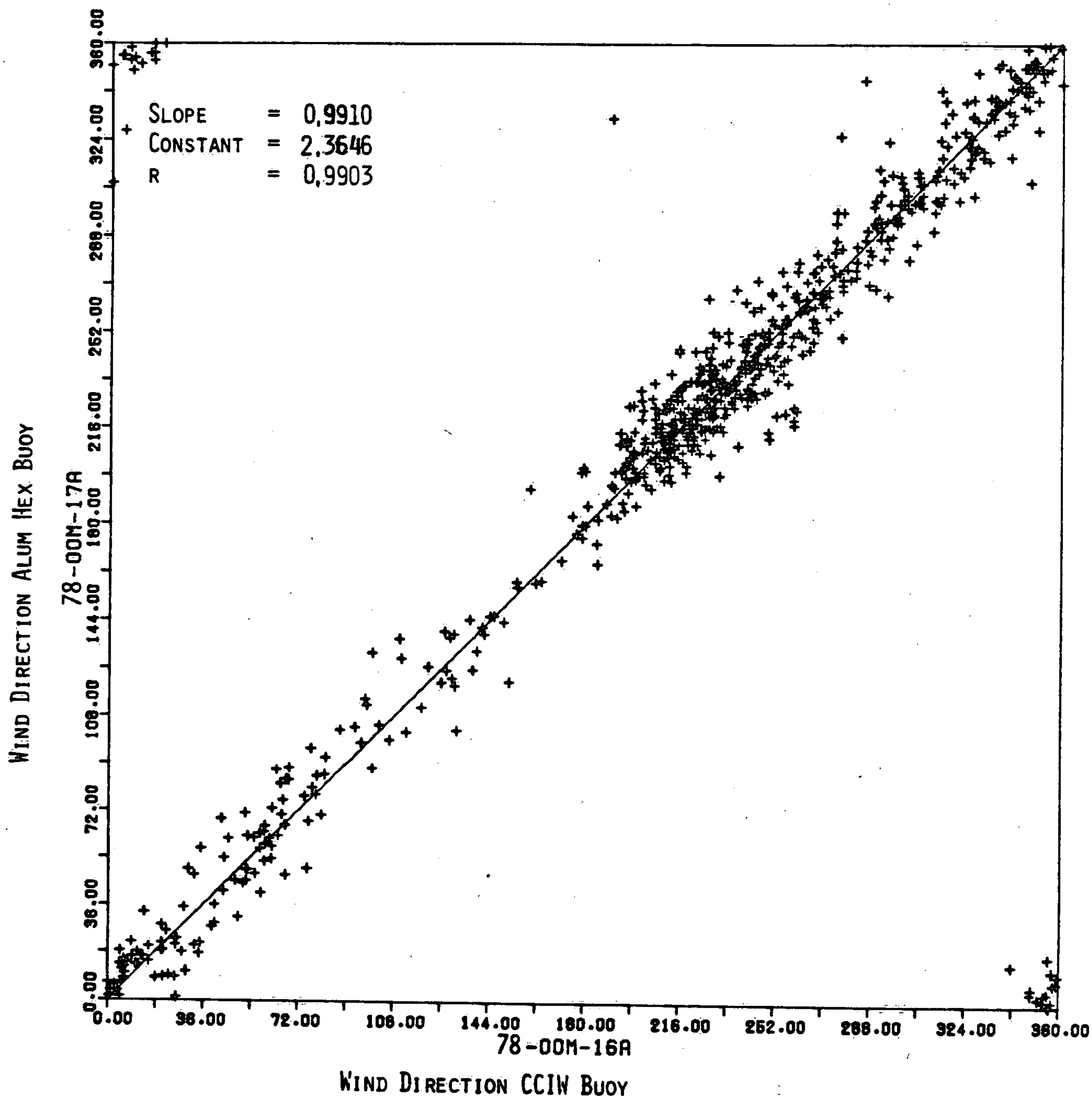


FIGURE 7

WIND DIRECTION COMPARISON

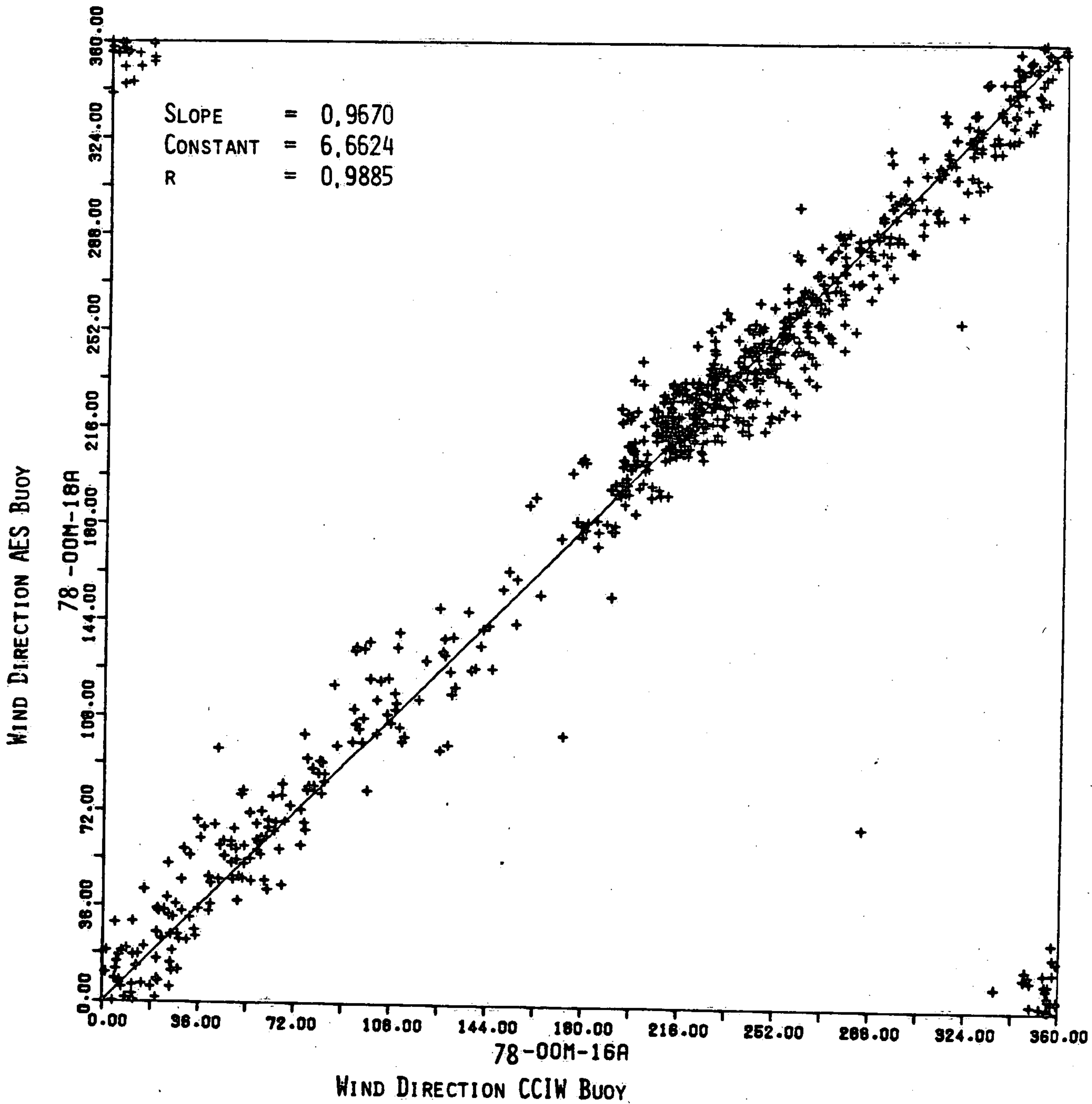


FIGURE 8

WIND DIRECTION COMPARISON

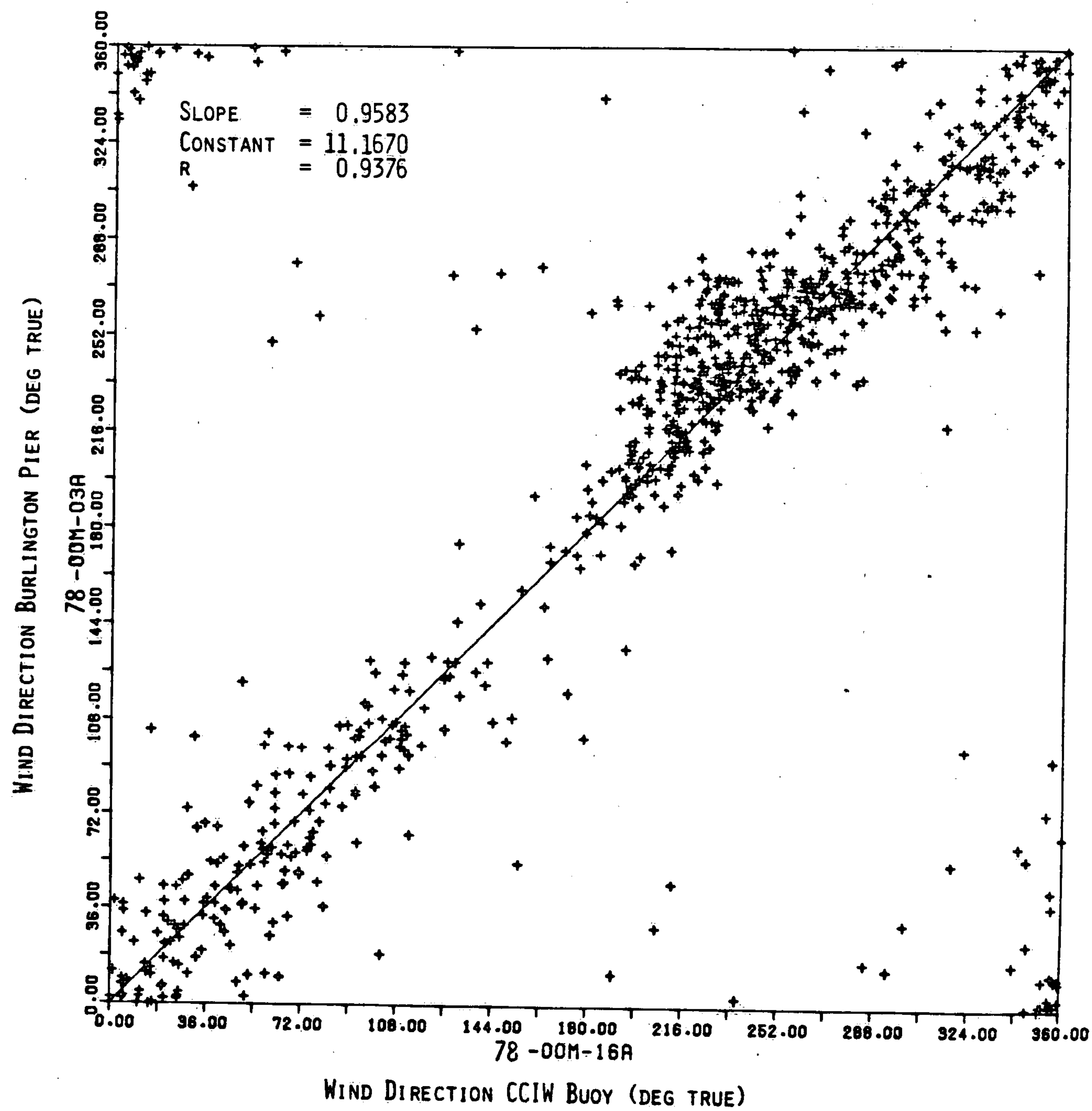


FIGURE 9

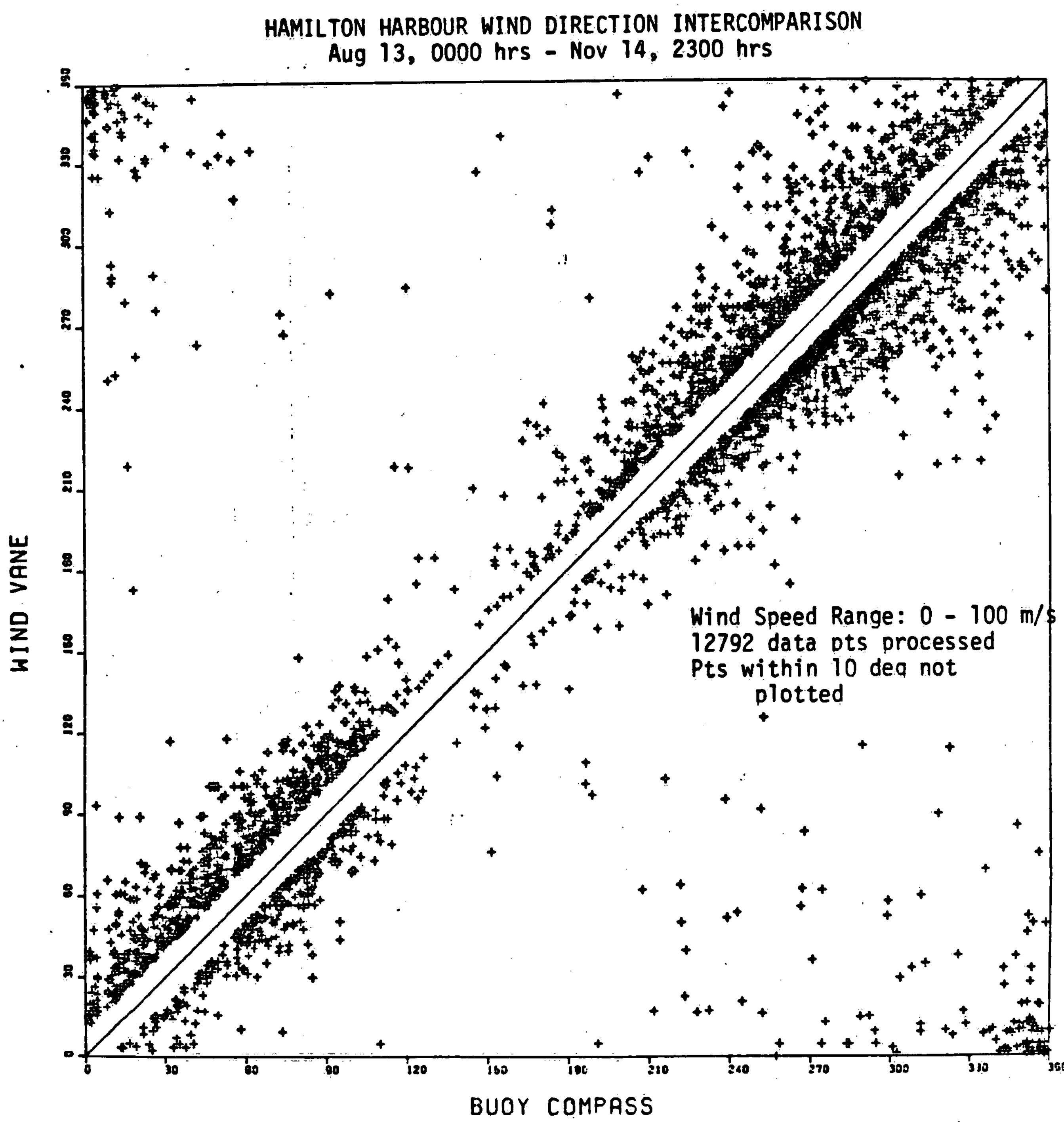

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON
Aug 13, 0000 hrs - Nov 14, 2300 hrs
WIND VANE
BUOY COMPASS
Wind Speed Range: 0 - 100 m/s
12792 data pts processed
Pts within 10 deq not plotted
0
30
60
90
120
150
180
210
240
270
300
330
360

FIGURE 10

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Aug 13, 0000 hrs - Nov 14, 2300 hrs

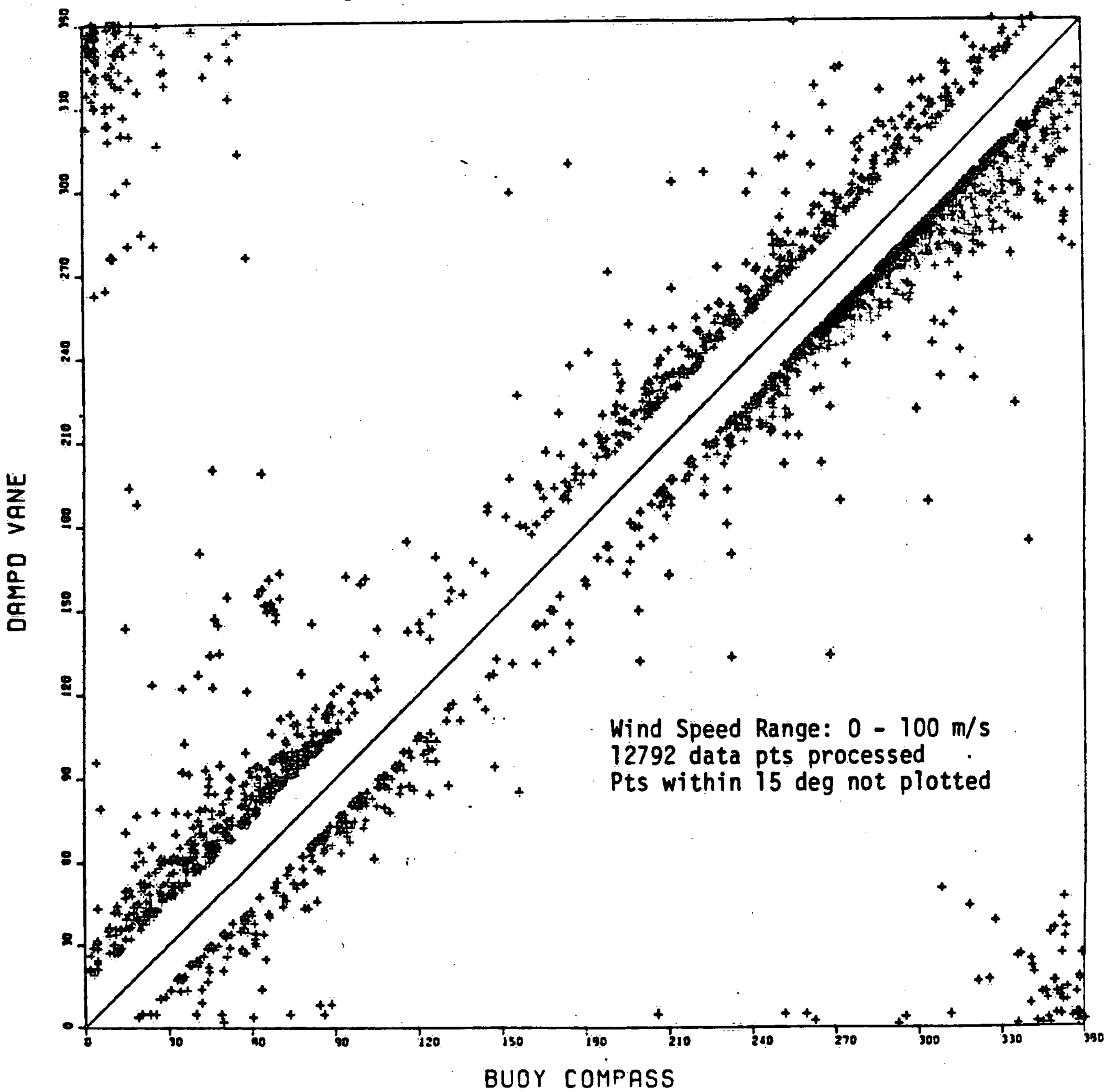


FIGURE 11

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON
Aug 13, 0000 hrs - Nov 14, 2300 hrs

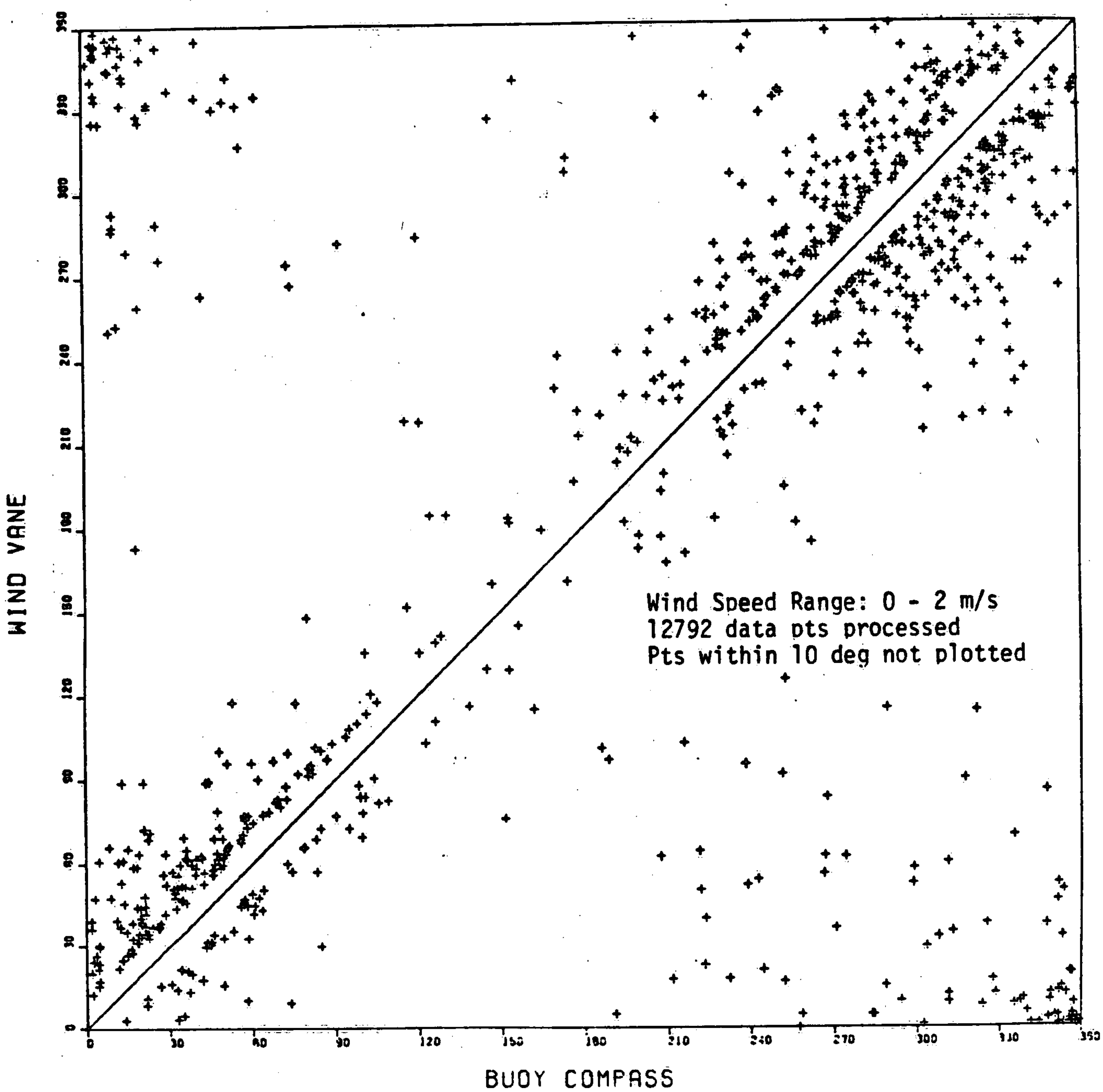


FIGURE 12

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON
Aug 13, 0000 hrs - Nov 14, 2300 hrs

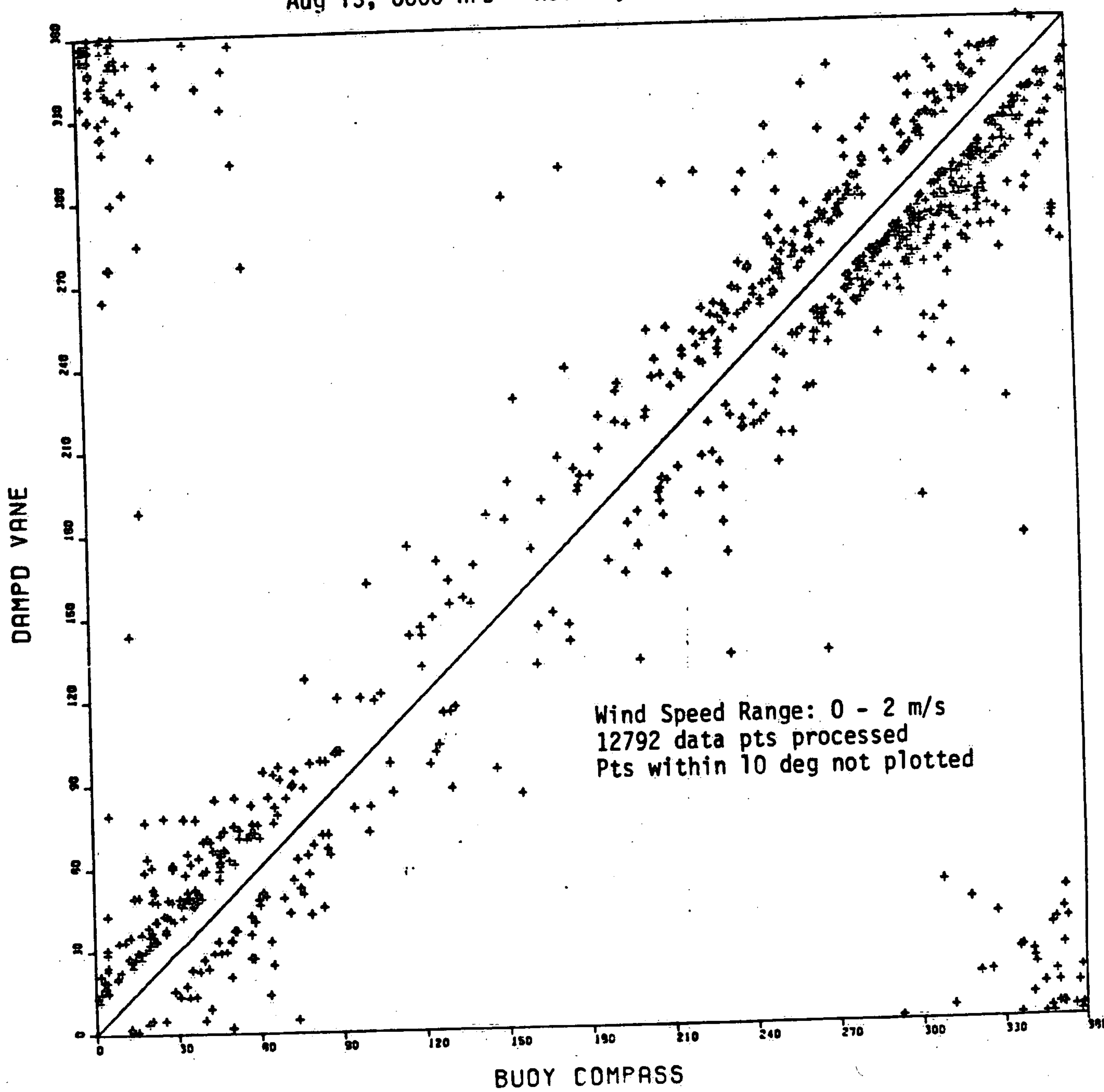


FIGURE 13

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON
Aug 13, 0000 hrs - Nov 14, 2300 hrs

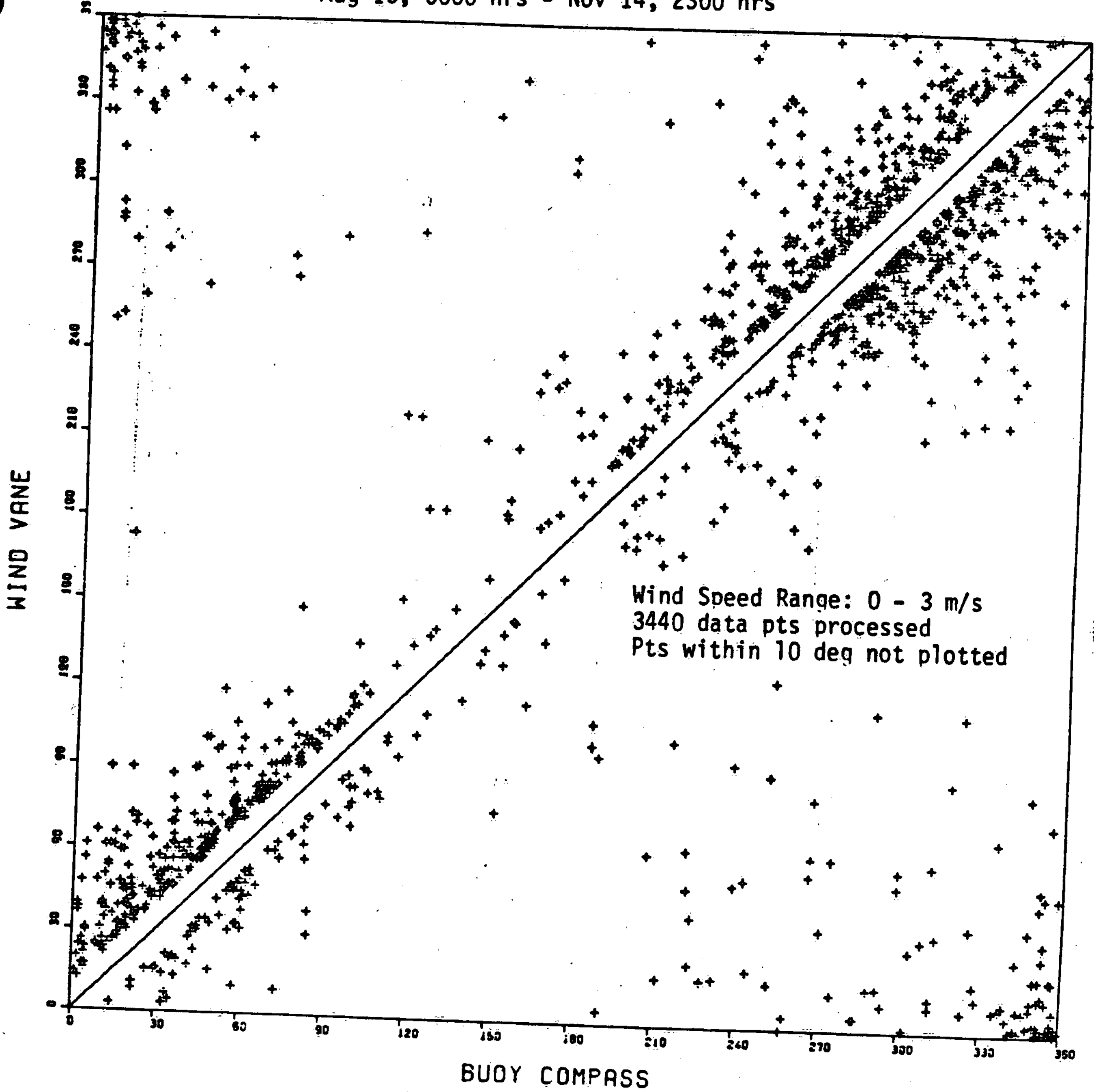


FIGURE 14

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Aug 13, 0000 hrs - Nov 14, 2300 hrs

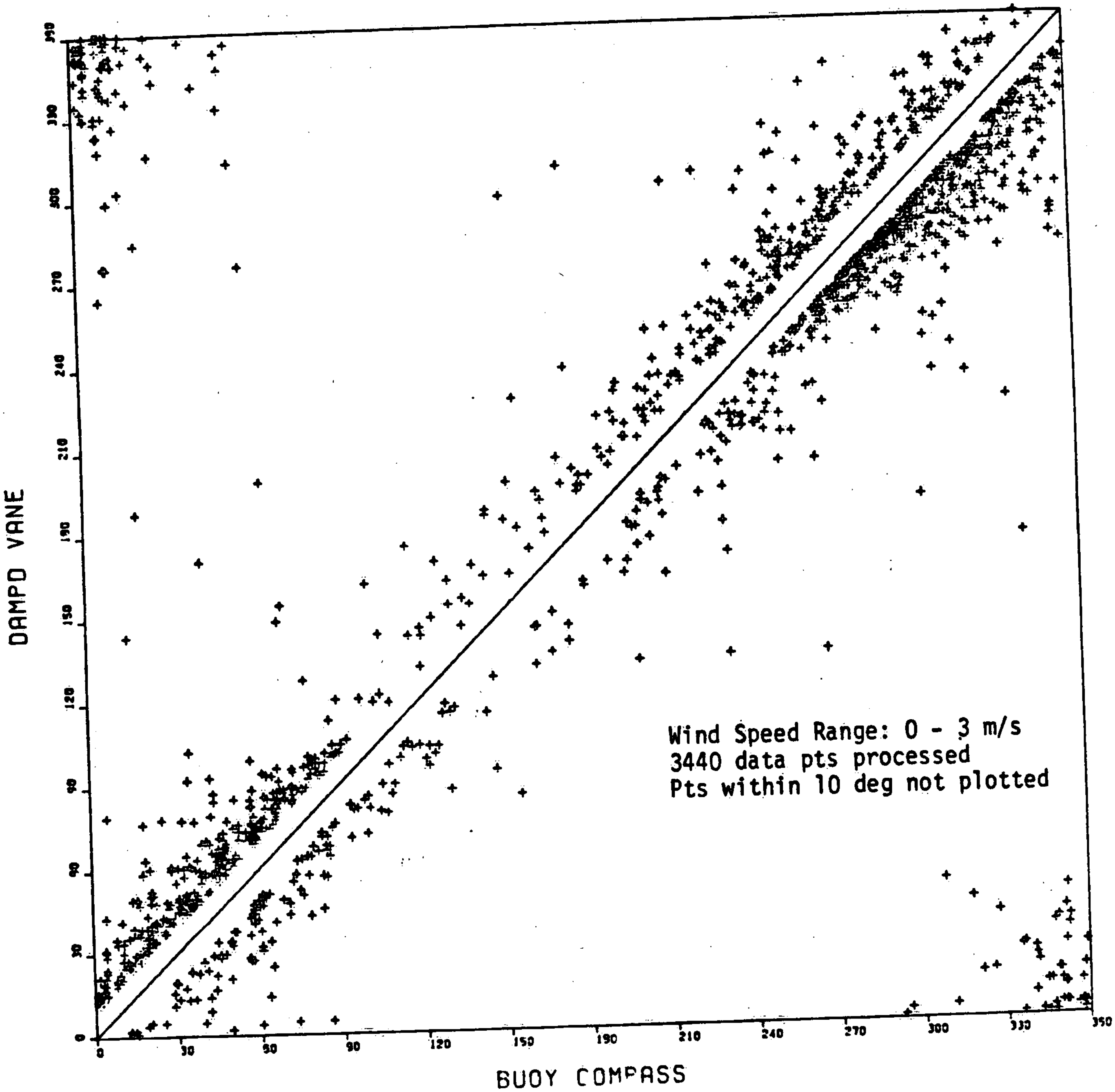


FIGURE 15

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON
Aug 13, 0000 hrs - Nov 14, 2300 hrs

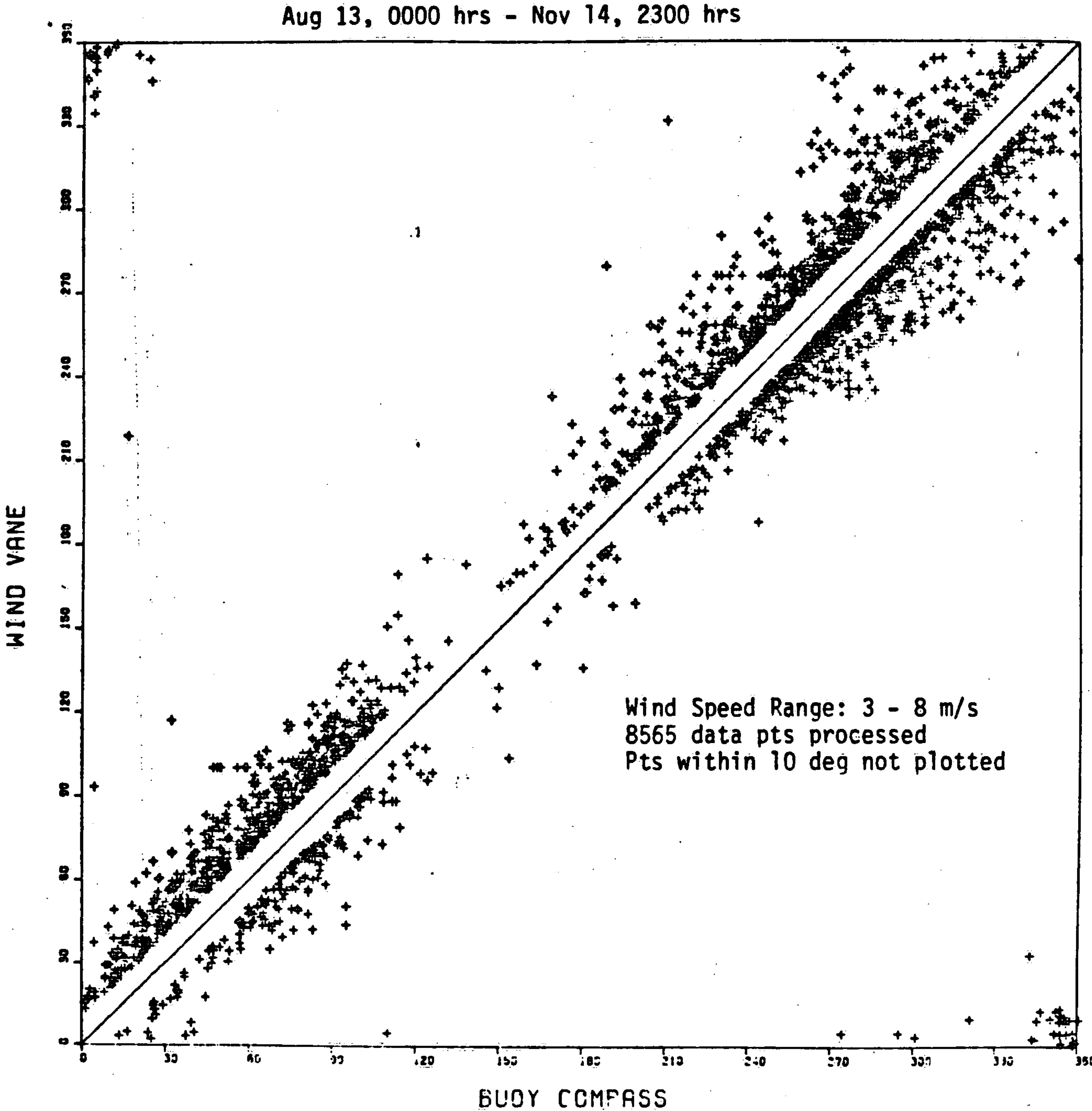


FIGURE 16

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Aug 13, 0000 hrs - Nov 14, 2300 hrs

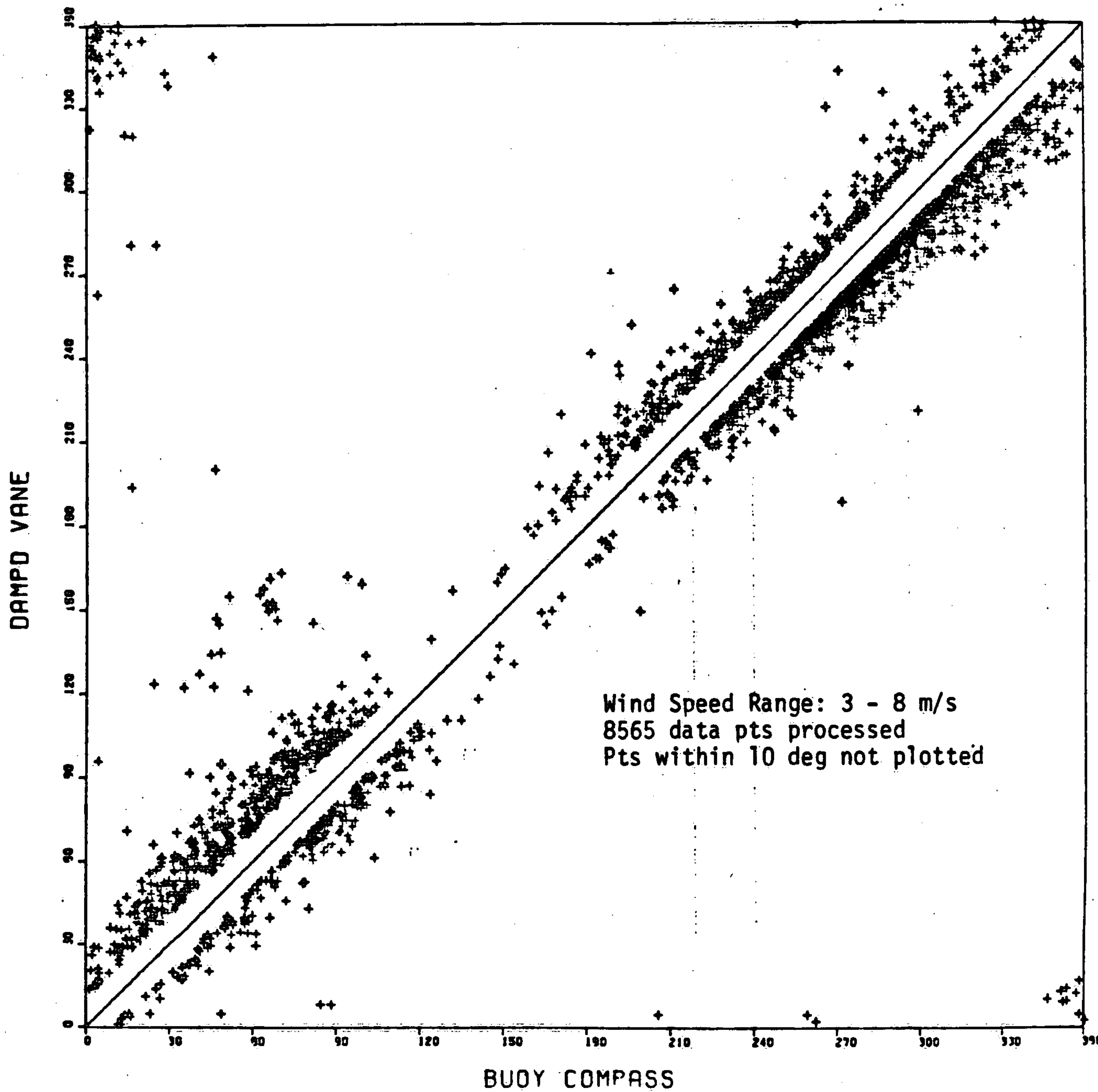


FIGURE 17

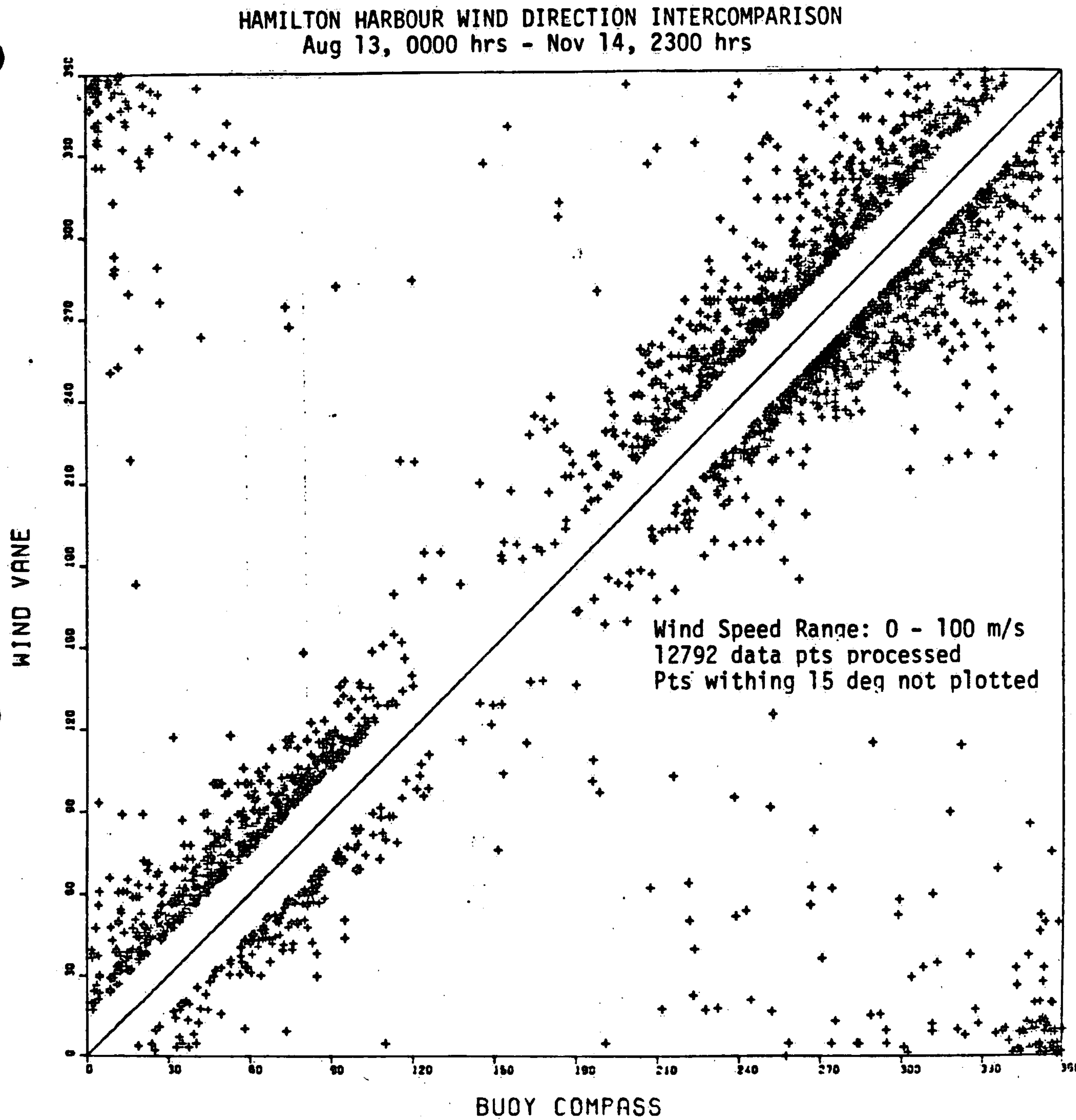

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON
Aug 13, 0000 hrs - Nov 14, 2300 hrs
WIND VANE
BUOY COMPASS
Wind Speed Range: 0 - 100 m/s
12792 data pts processed
Pts withing 15 deg not plotted

FIGURE 18

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Aug 13, 0000 hrs - Nov 14, 2300 hrs

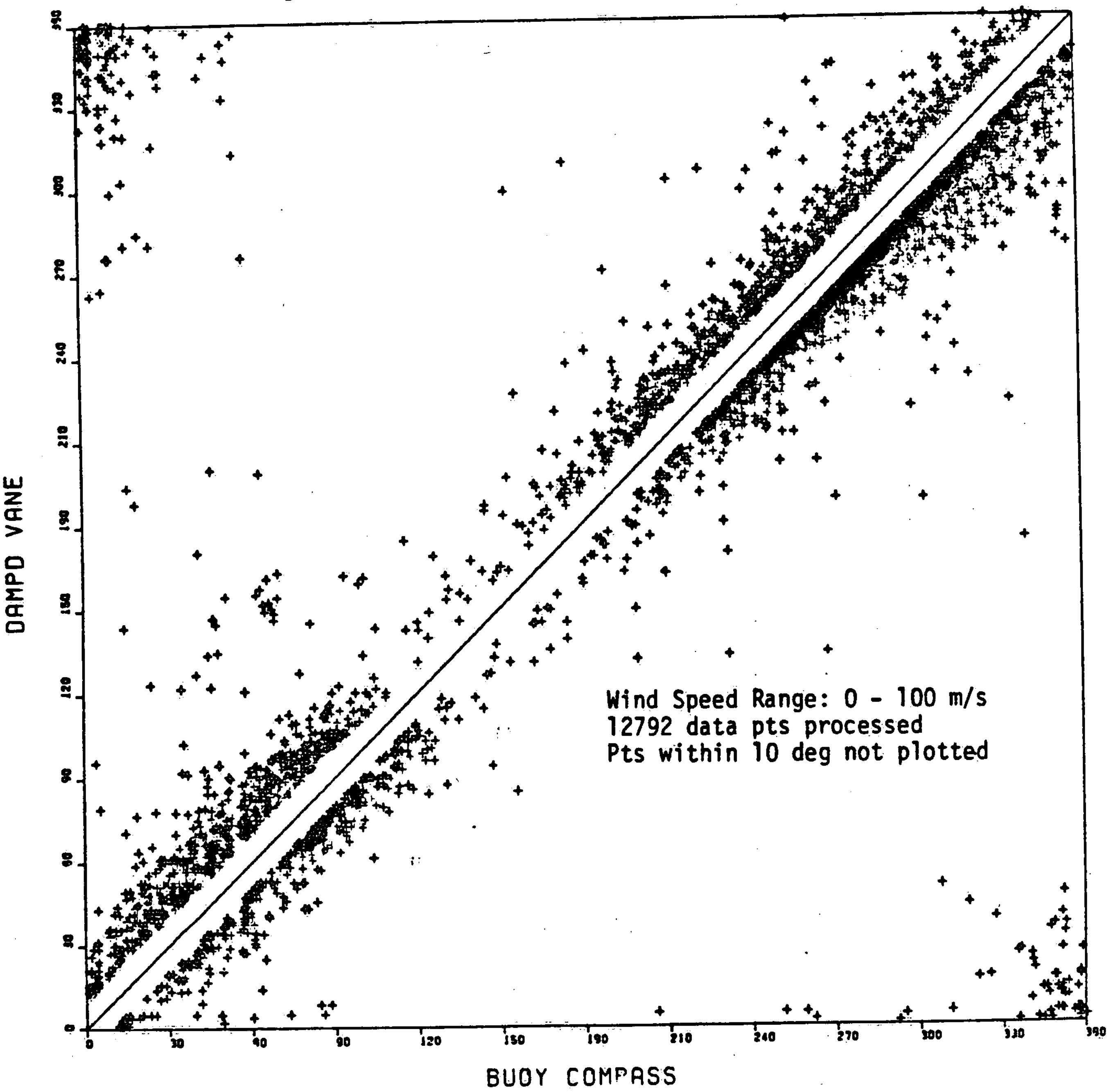


FIGURE 19

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Aug 13, 1900 hrs - Aug 28, 2300 hrs

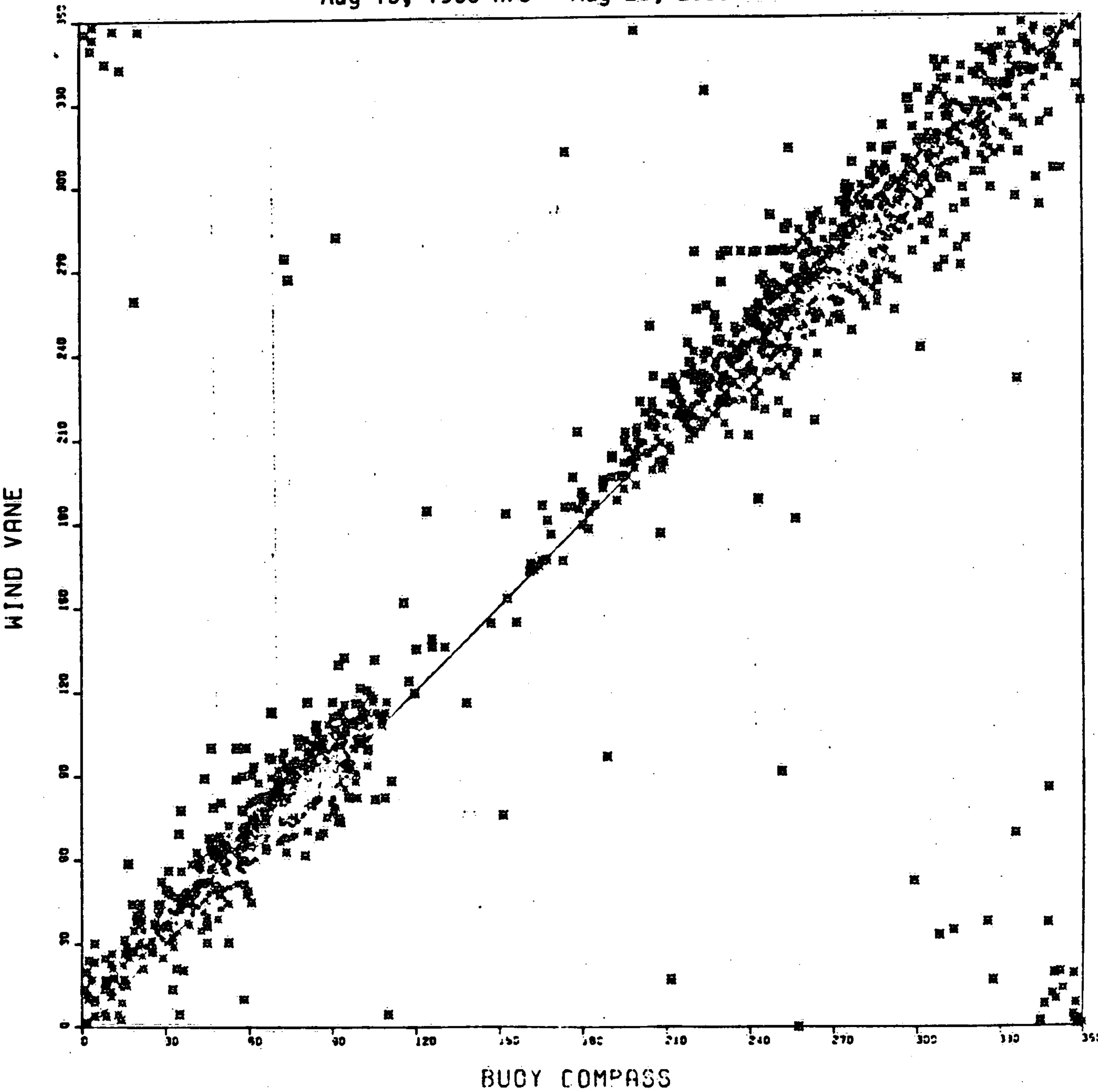


FIGURE 20

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Aug 13, 1900 hrs - Aug 28, 2300 hrs

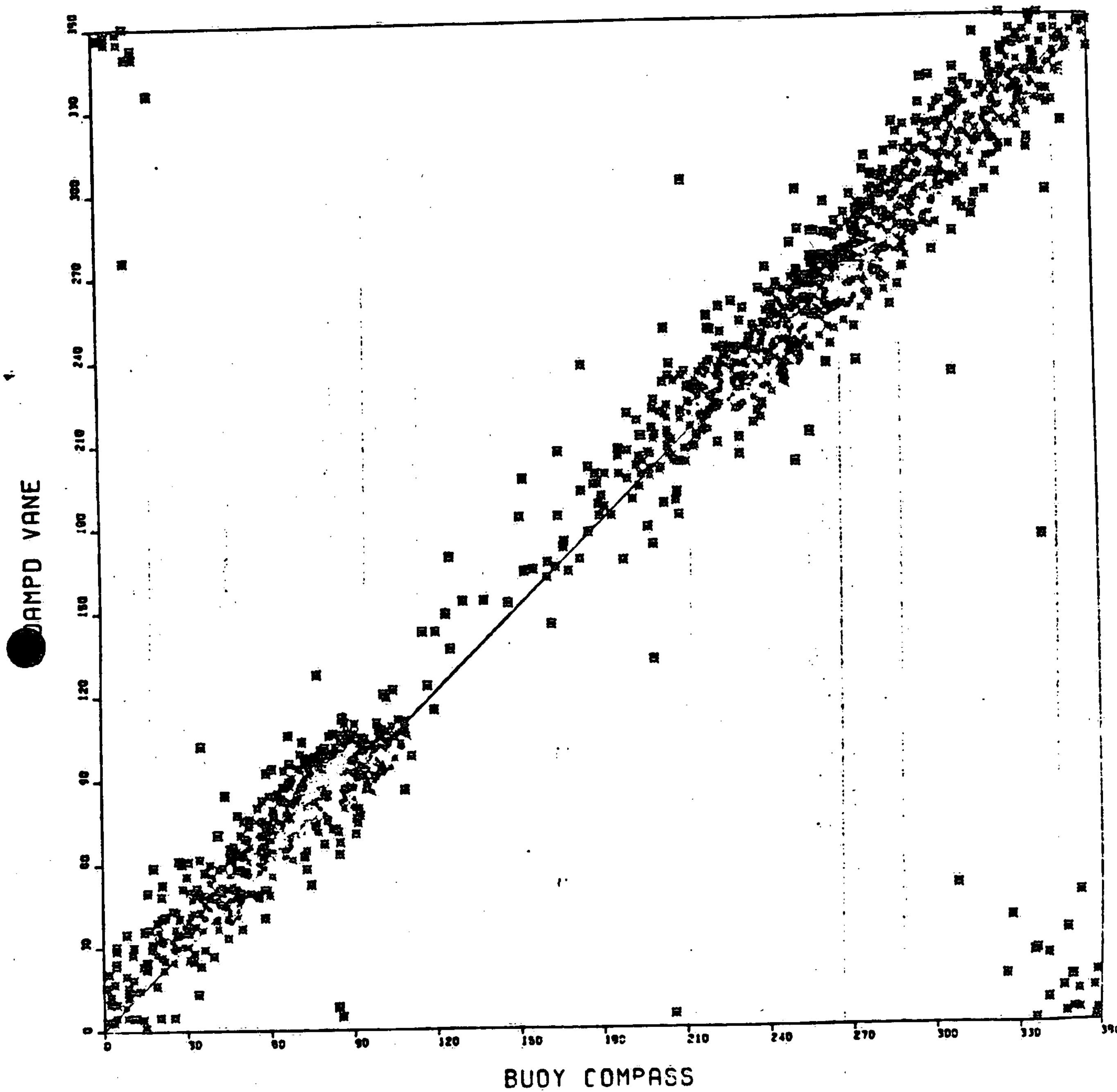


FIGURE 21

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Aug 29, 0000 hrs - Sept 13, 2300 hrs

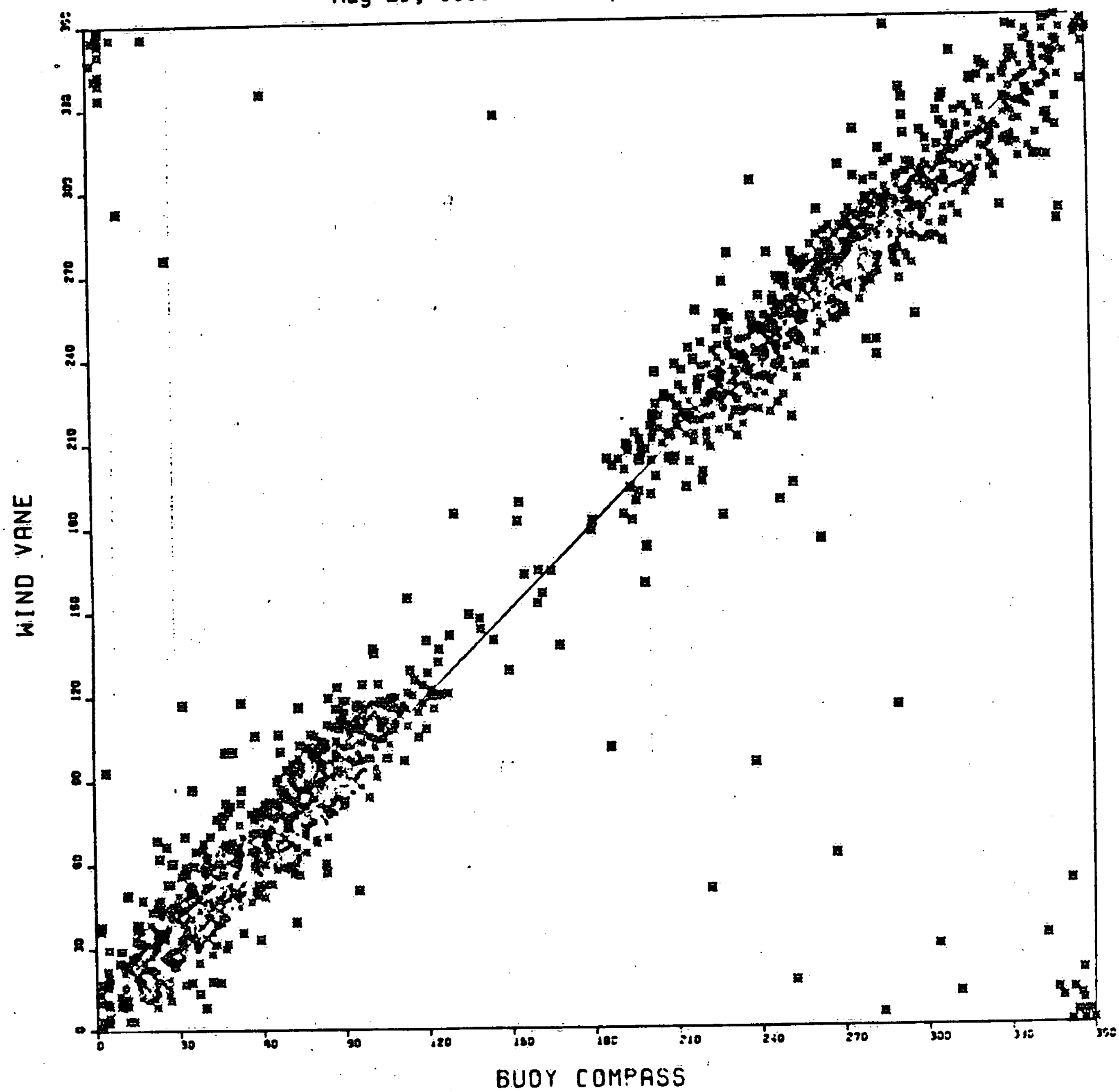


FIGURE 22

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Aug 29, 0000 hrs - Sept 13, 2300 hrs

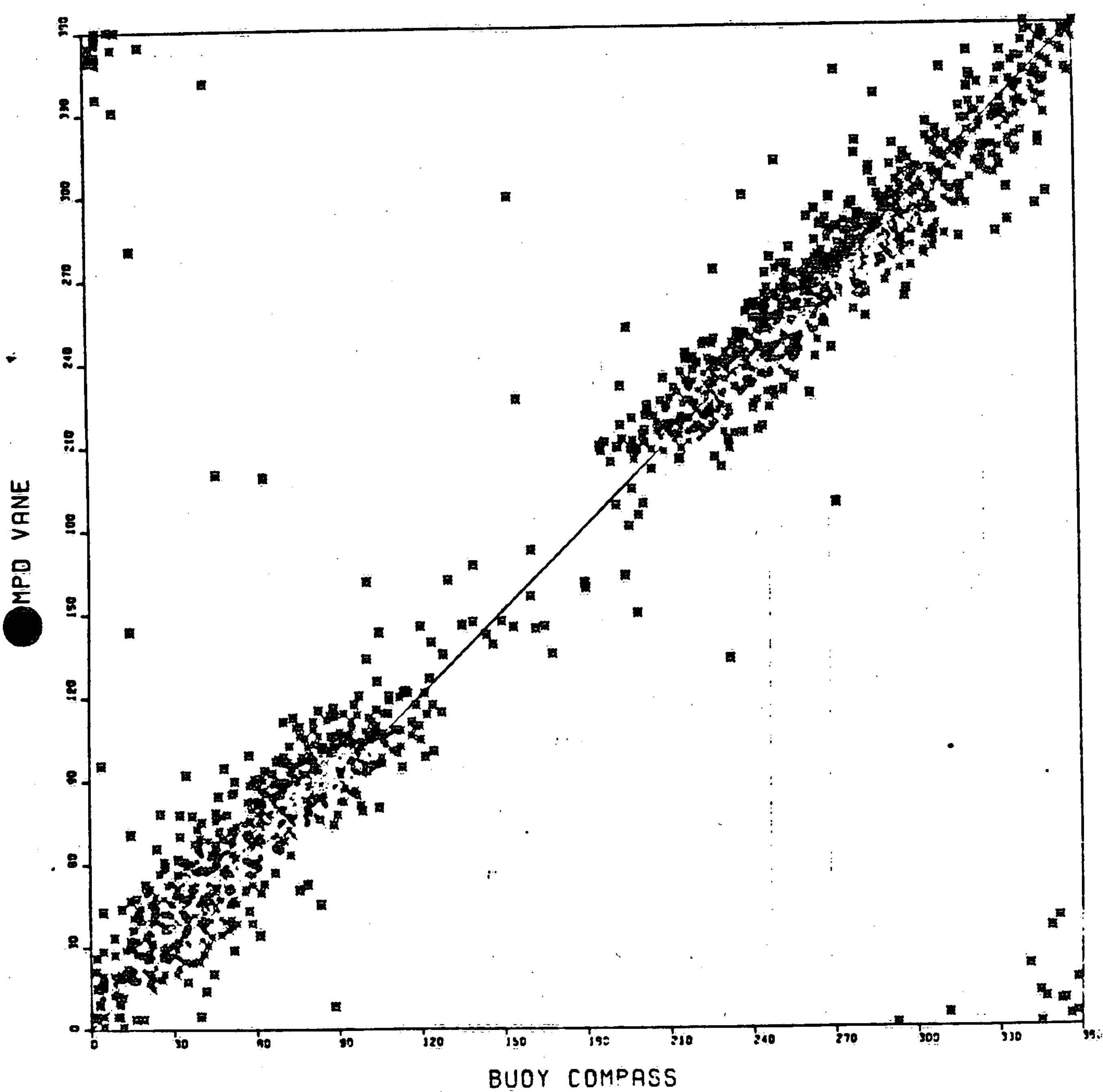
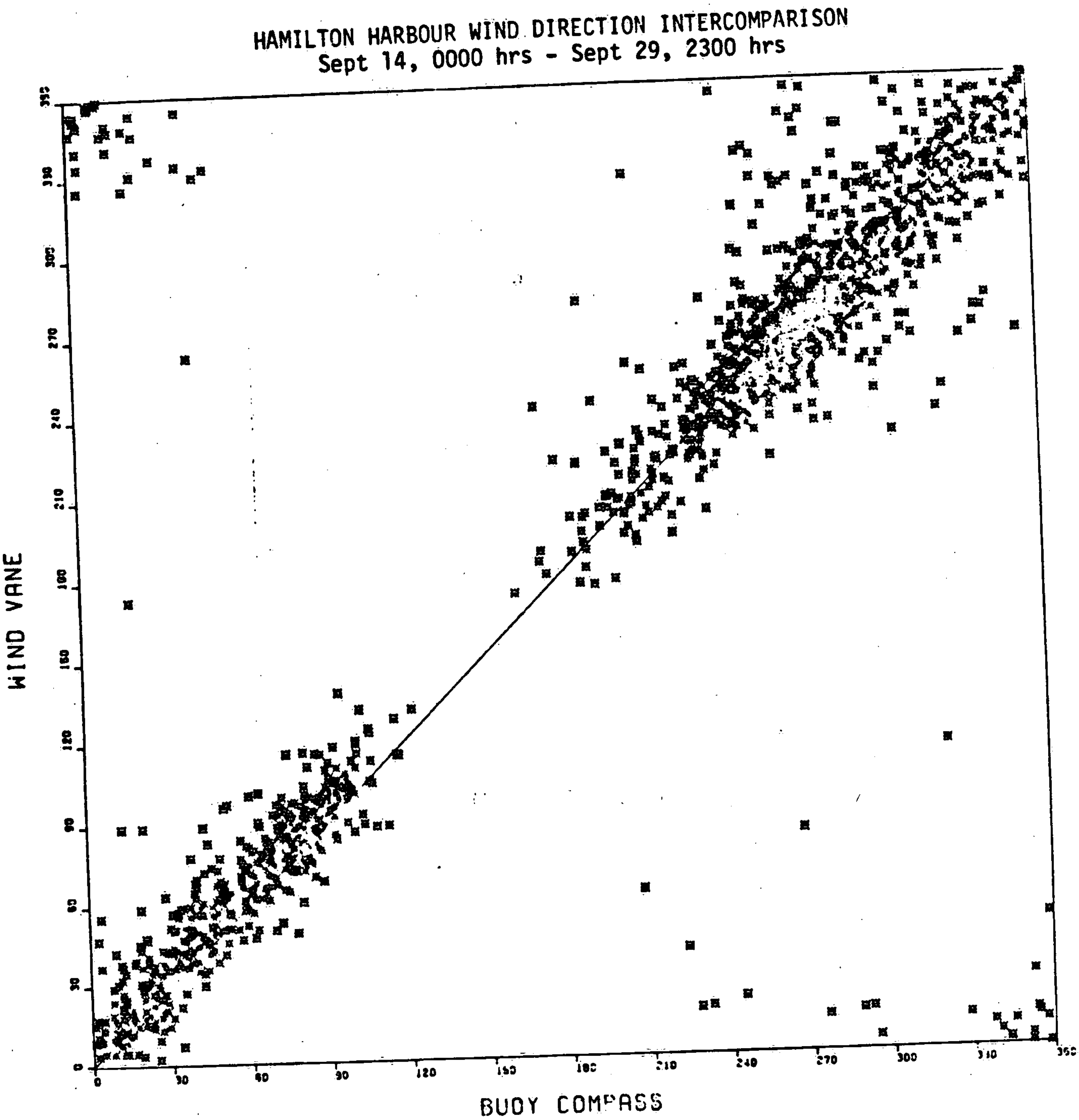


FIGURE 23



HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON
Sept 14, 0000 hrs - Sept 29, 2300 hrs
WIND VANE
BUOY COMPASS

FIGURE 24

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Sept 14, 0000 hrs - Sept 29, 2300 hrs

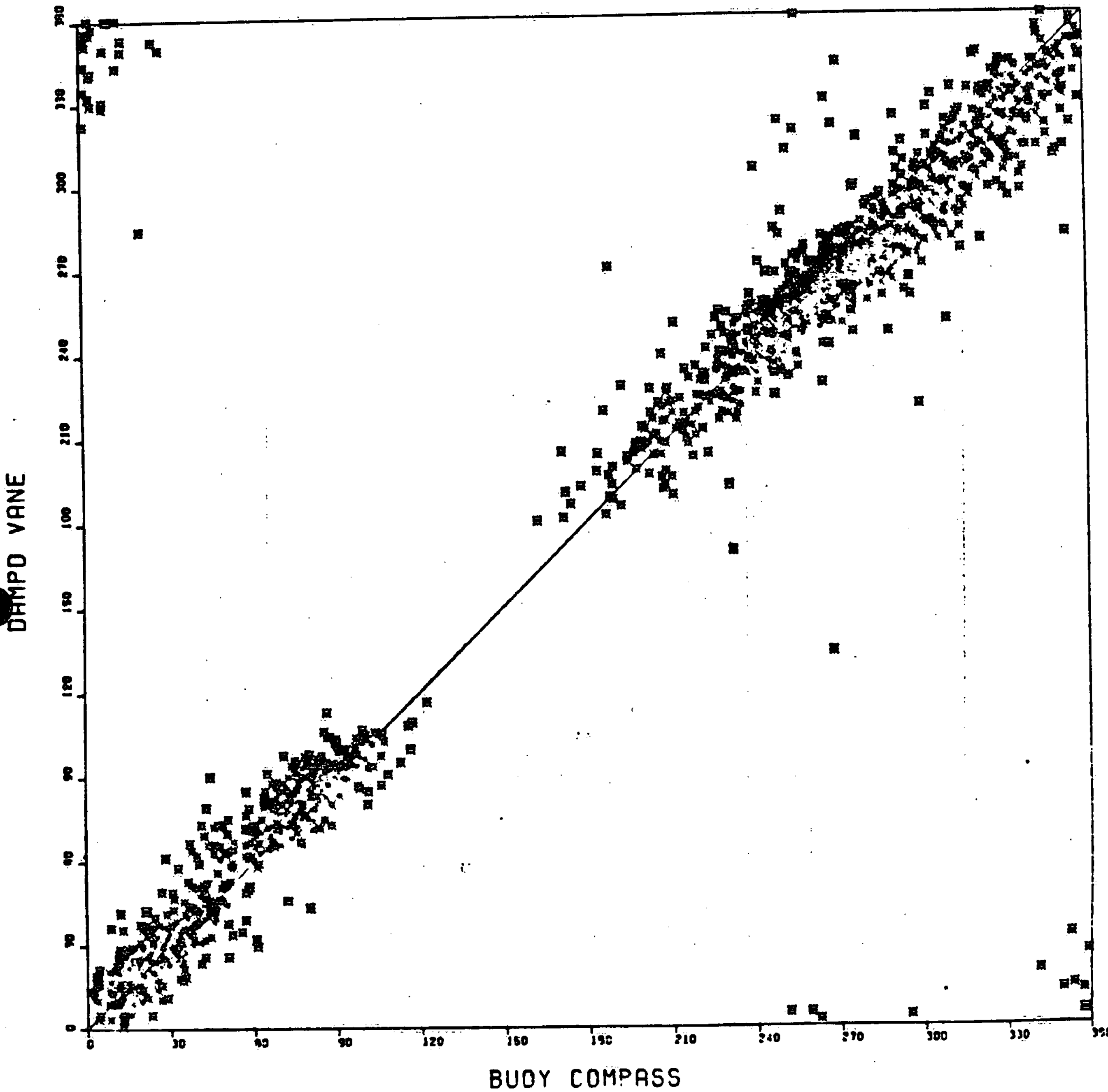


FIGURE 25

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON
Sept 30, 0000 hrs - Oct 15, 2300 hrs

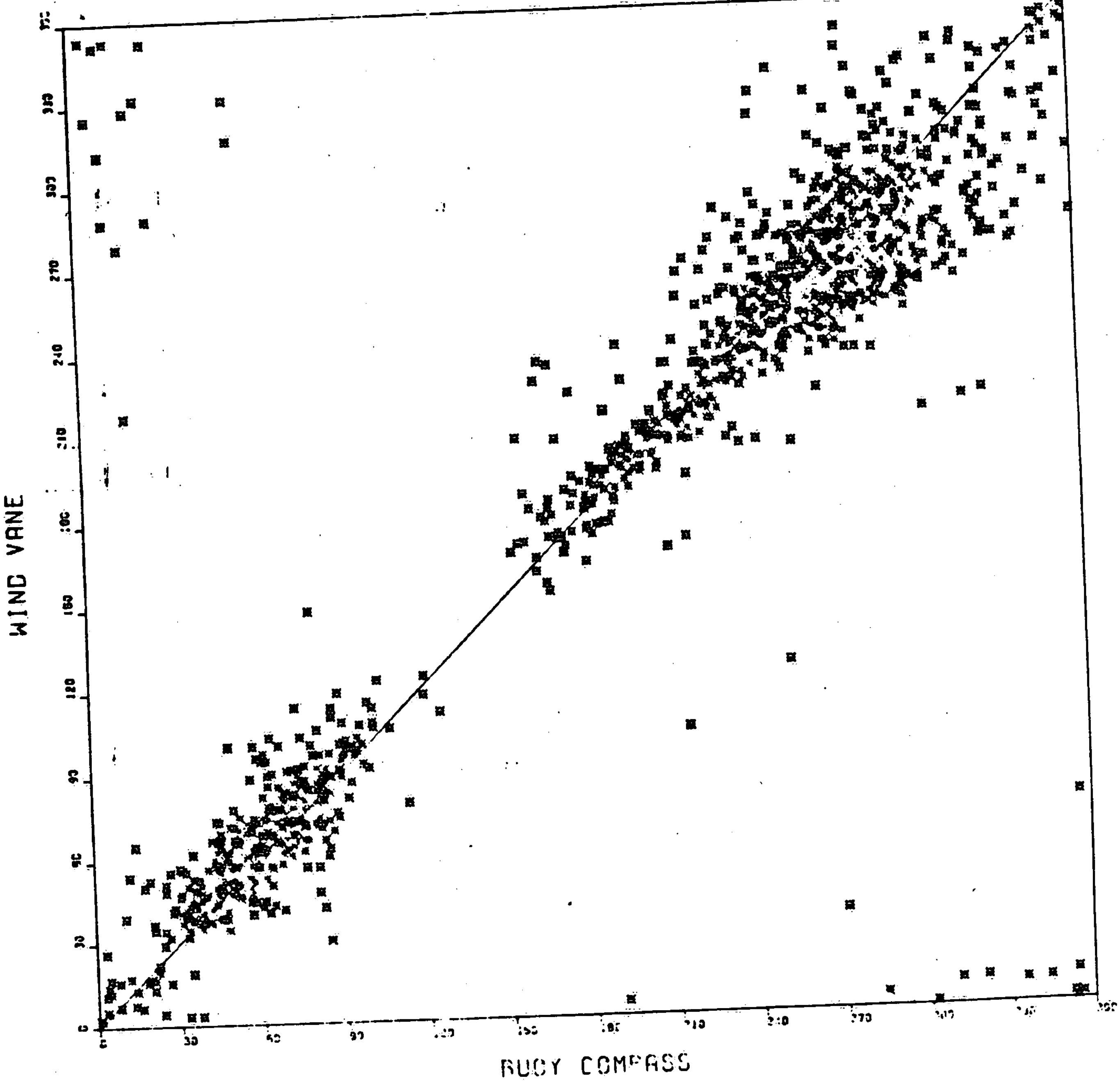


FIGURE 26

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Sept 30, 0000 hrs - Oct 15, 2300 hrs

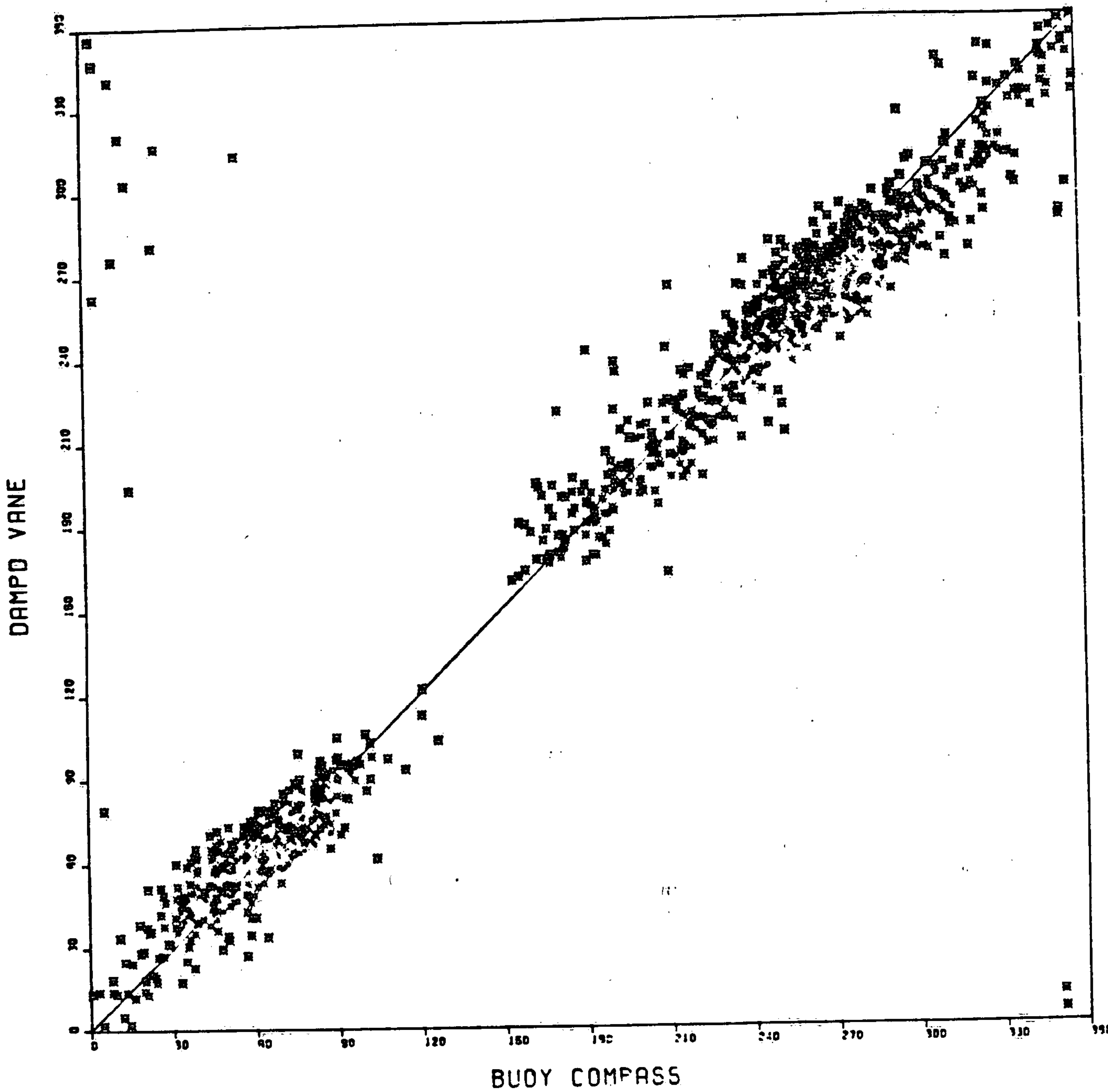


FIGURE 27

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON
Oct 16, 0000 hrs - Oct 31, 2300 hrs

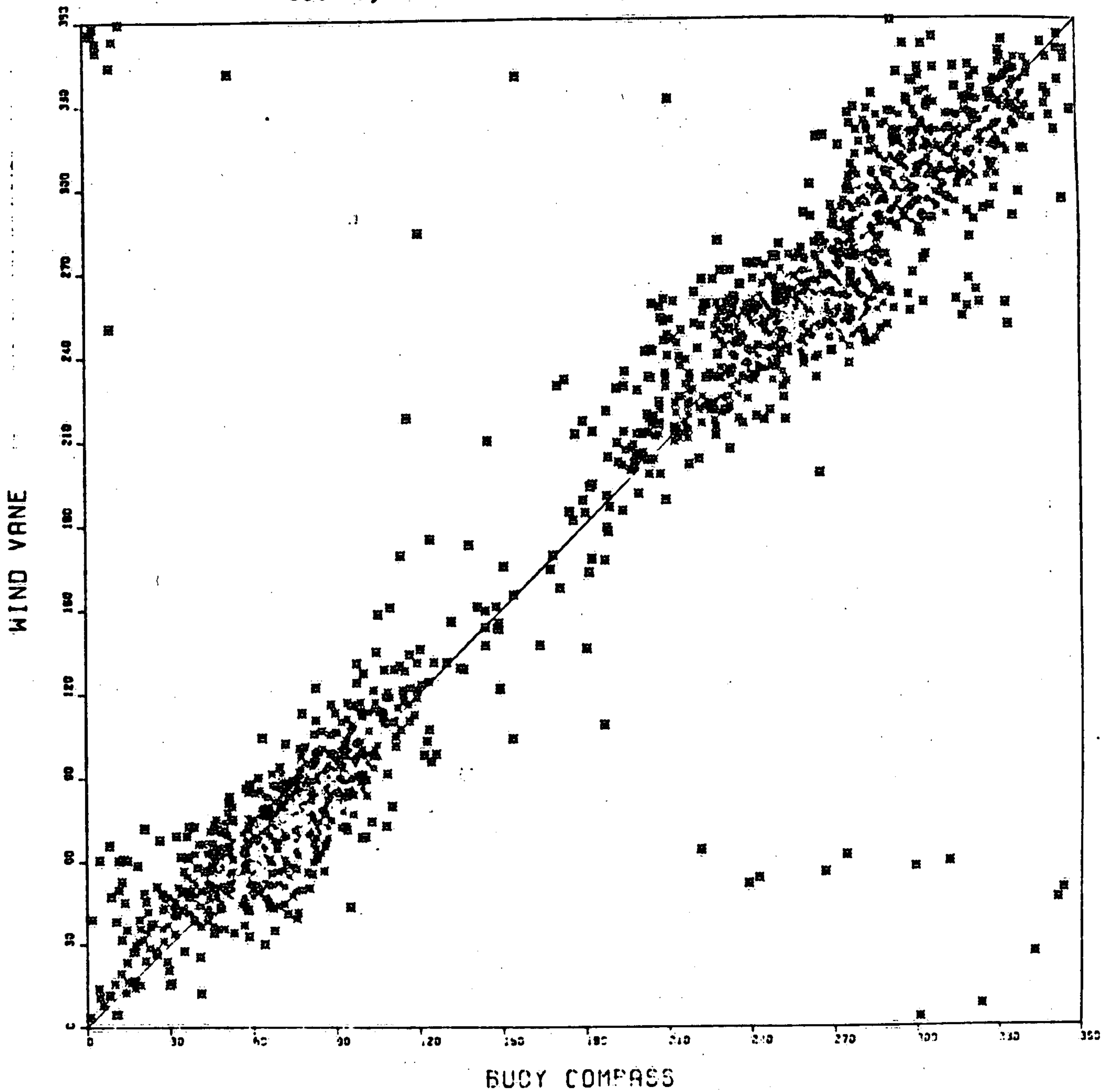


FIGURE 28

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Oct 16, 0000 hrs - Oct 31, 2300 hrs

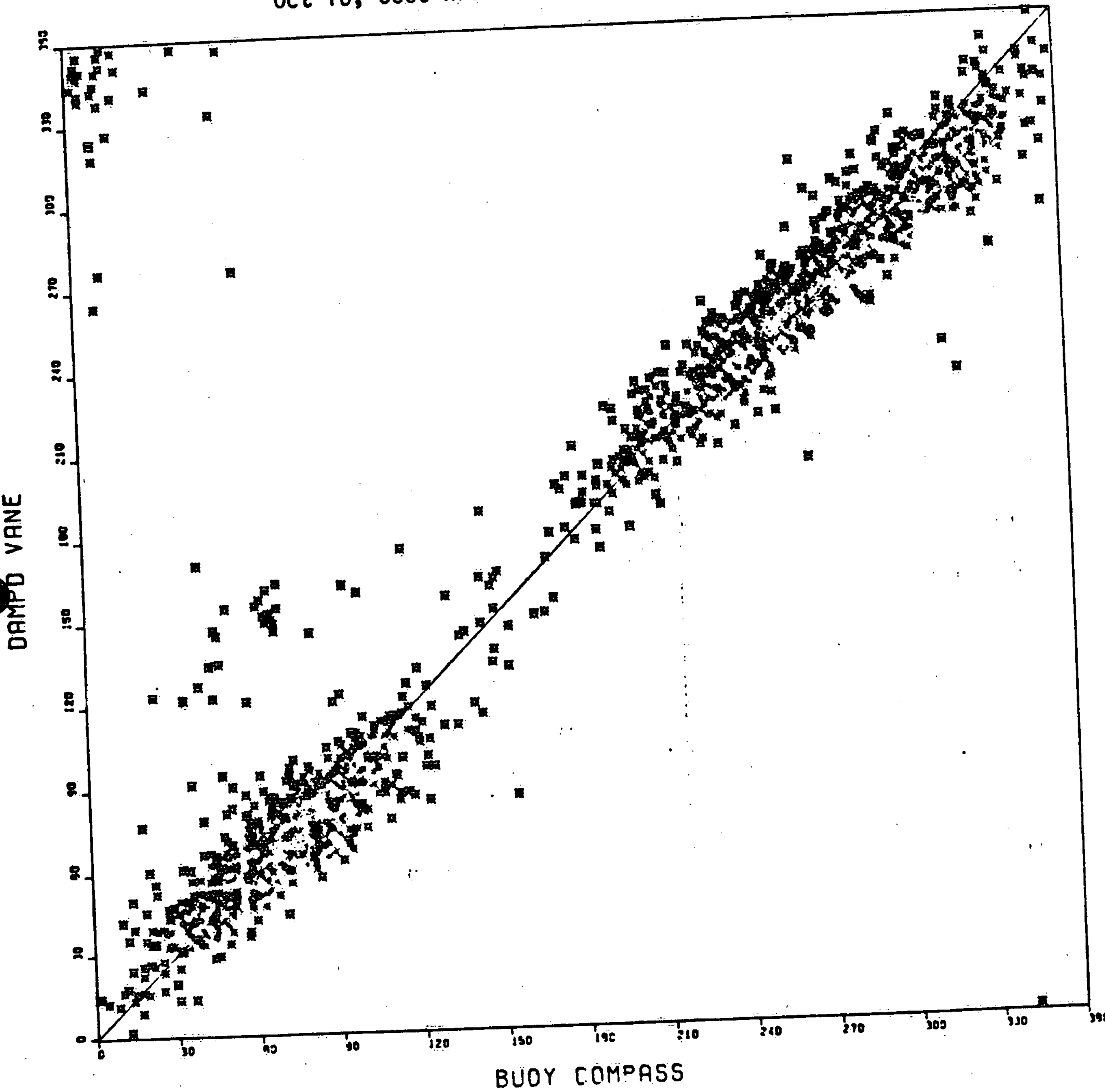


FIGURE 29

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Nov 1, 0000 hrs - Nov 14, 1200 hrs

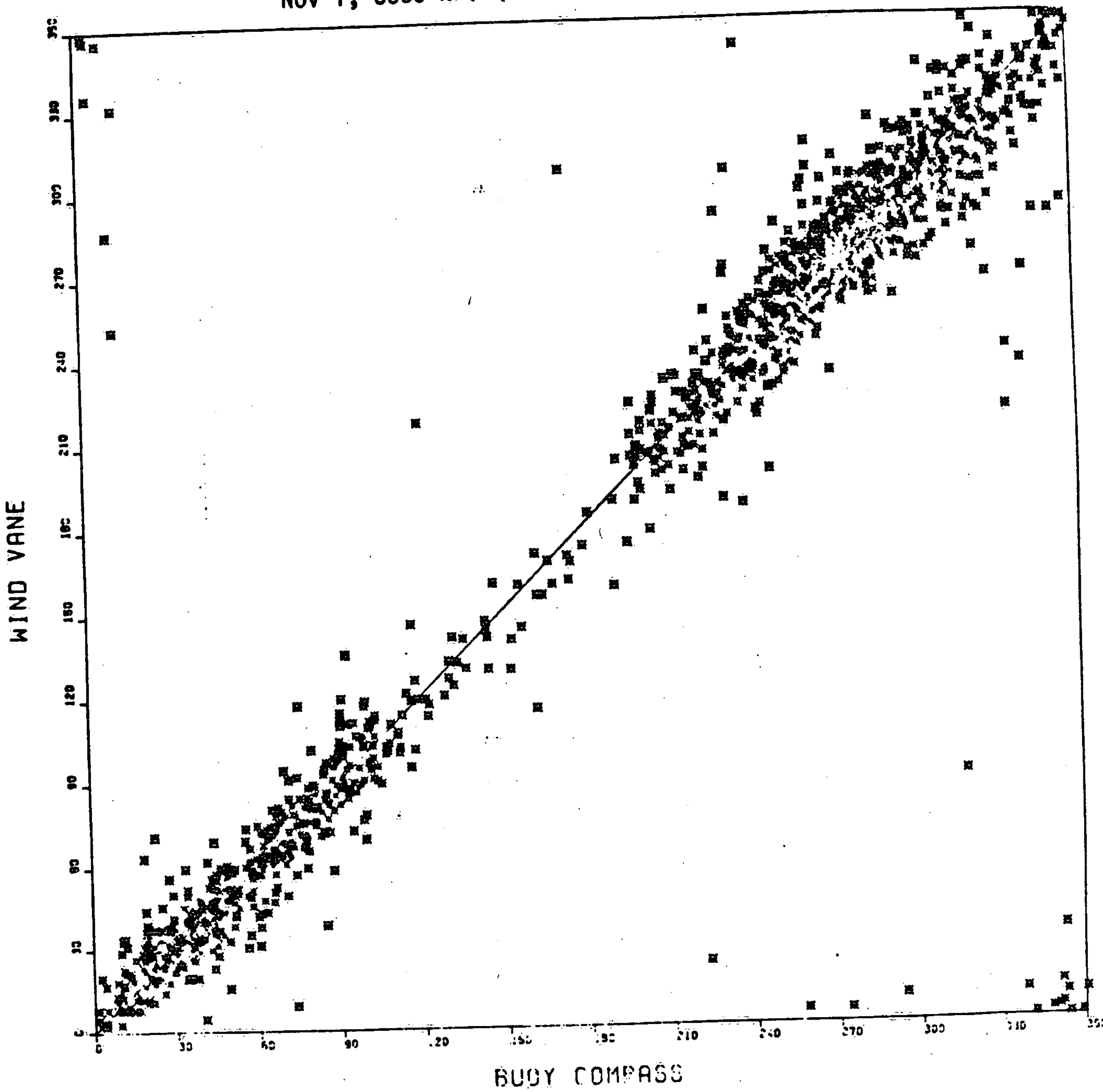


FIGURE 30

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Nov 1, 0000 hrs - Nov 14, 1200 hrs

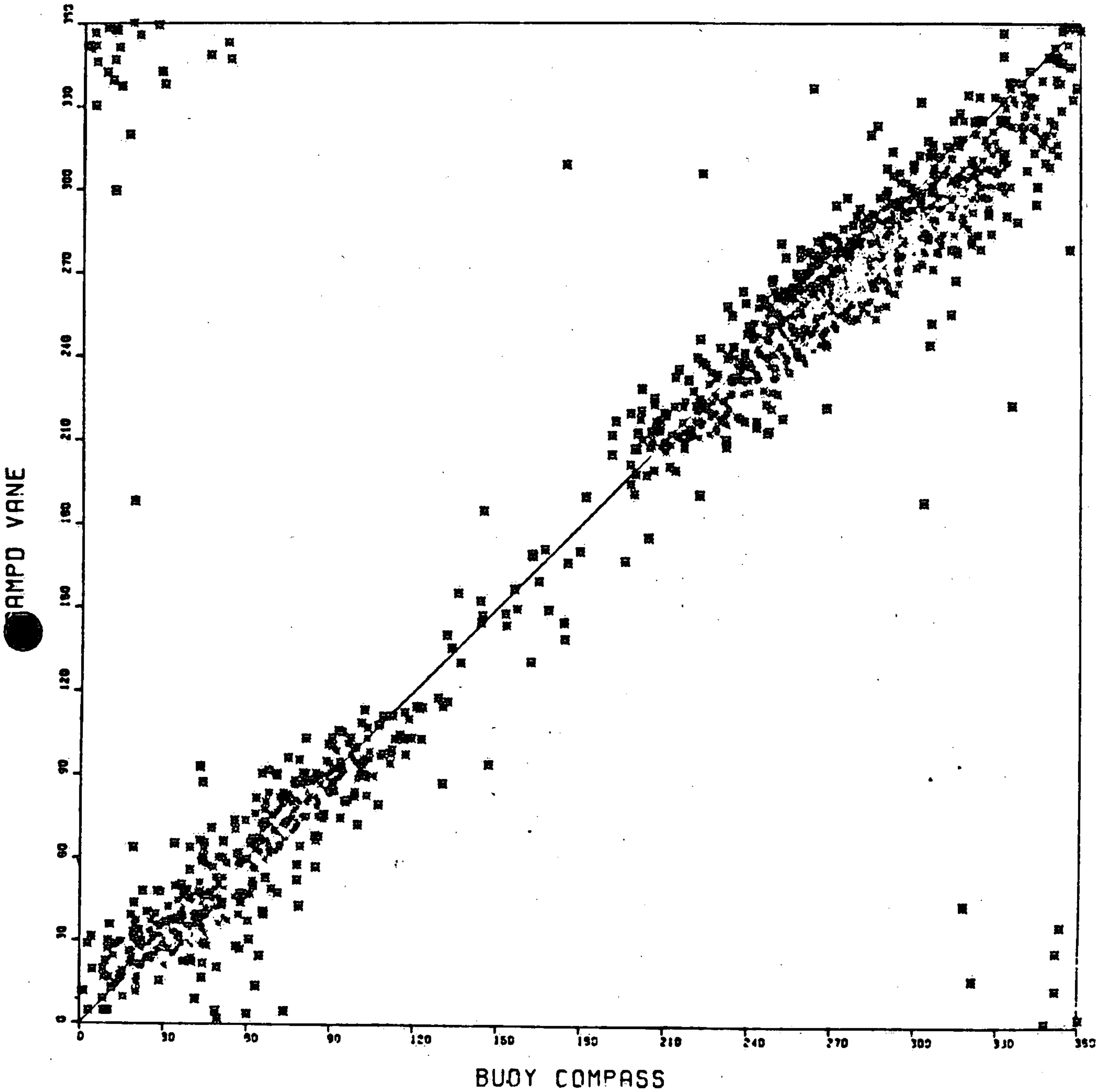


FIGURE 31

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Aug 13, 0000 hrs - Nov 14, 2300 hrs

DIRECTION SCATTER PLOT
START =7908130000.STOP =7911150000.
MINWSP =0.0 MAXWSP =100.0
STATION 79-00M-10A
SCATTER ANGLE =10.0

2157. POINTS READ
459. POINTS PLOTTED
1698. POINTS WITHIN 10.0 DEGREES NOT PLOTTED
Hourly Data

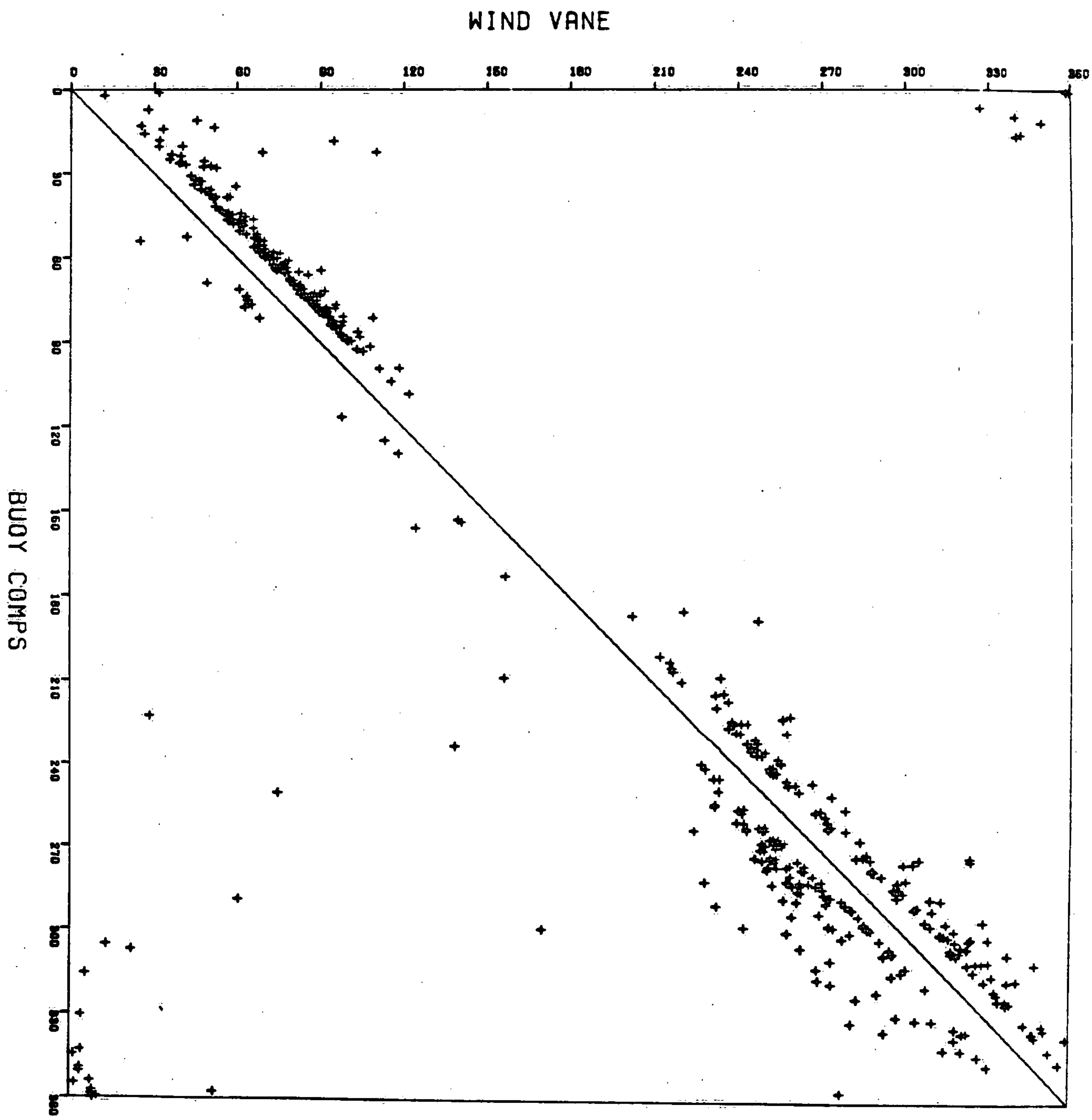


FIGURE 32

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Aug 13, 0000 hrs - Nov 14, 2300 hrs

2157. POINTS READ
491. POINTS PLOTTED
1726. POINTS WITHIN 10.0 DEGREES NOT PLOTTED
Hourly Data

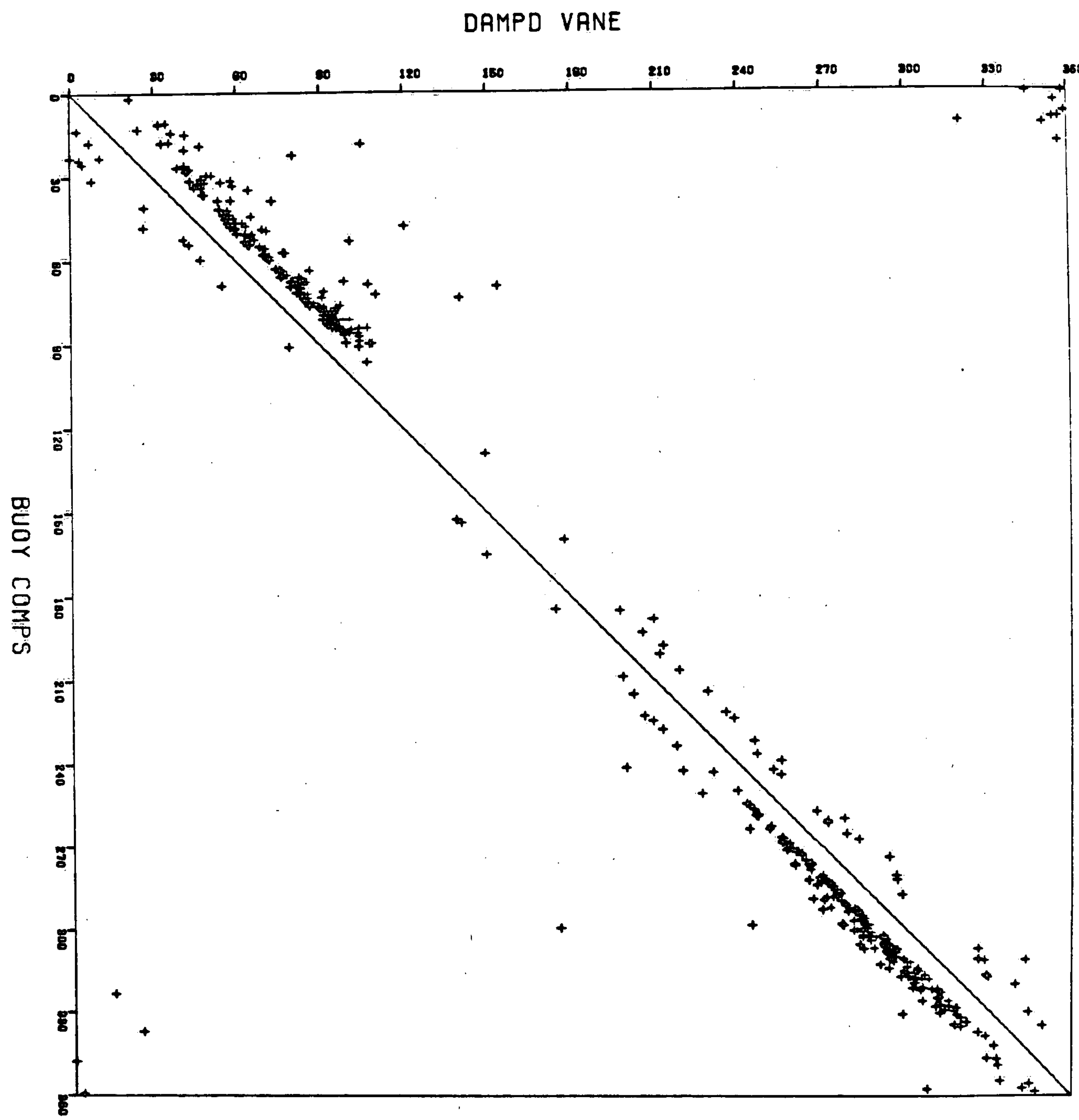


FIGURE 33

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Aug 13, 0000 hrs - Nov 14, 2300 hrs

2157. POINTS READ
446. POINTS PLOTTED
1711. POINTS WITHIN 10.0 DEGREES NOT PLOTTED

Hourly Data

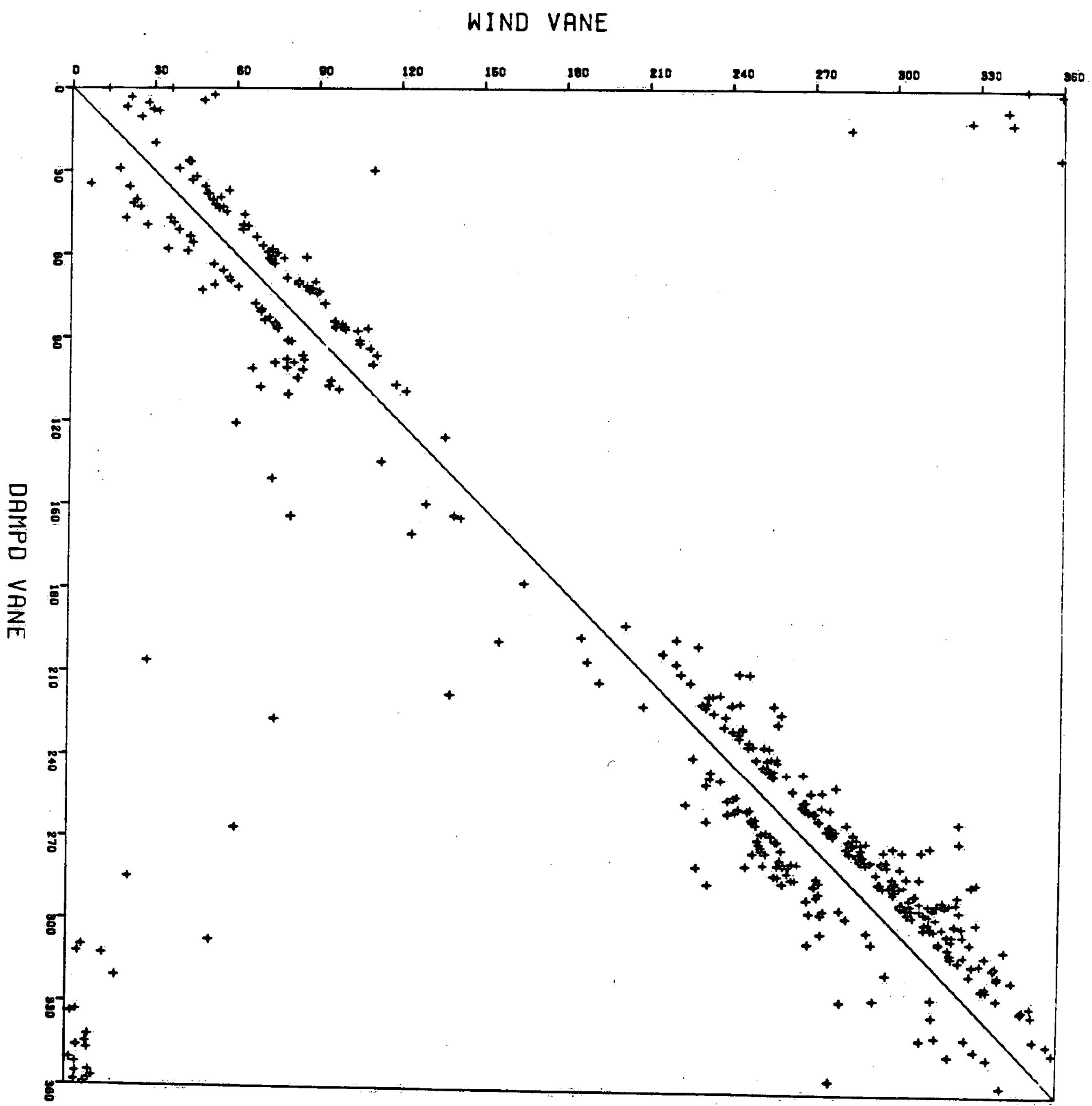


FIGURE 34

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Oct 19, 0000 hrs - Oct 27, 0000 hrs

DIRECTION SCATTER PLOT
START =7910190000.STOP =7910270000.
MINWSP =0.0 MAXWSP =100.0
STATION 79-00M-10A
SCATTER ANGLE =10.0

1153. POINTS READ
571. POINTS PLOTTED
582. POINTS WITHIN 10.0 DEGREES NOT PLOTTED
10 minute data
Selected time period

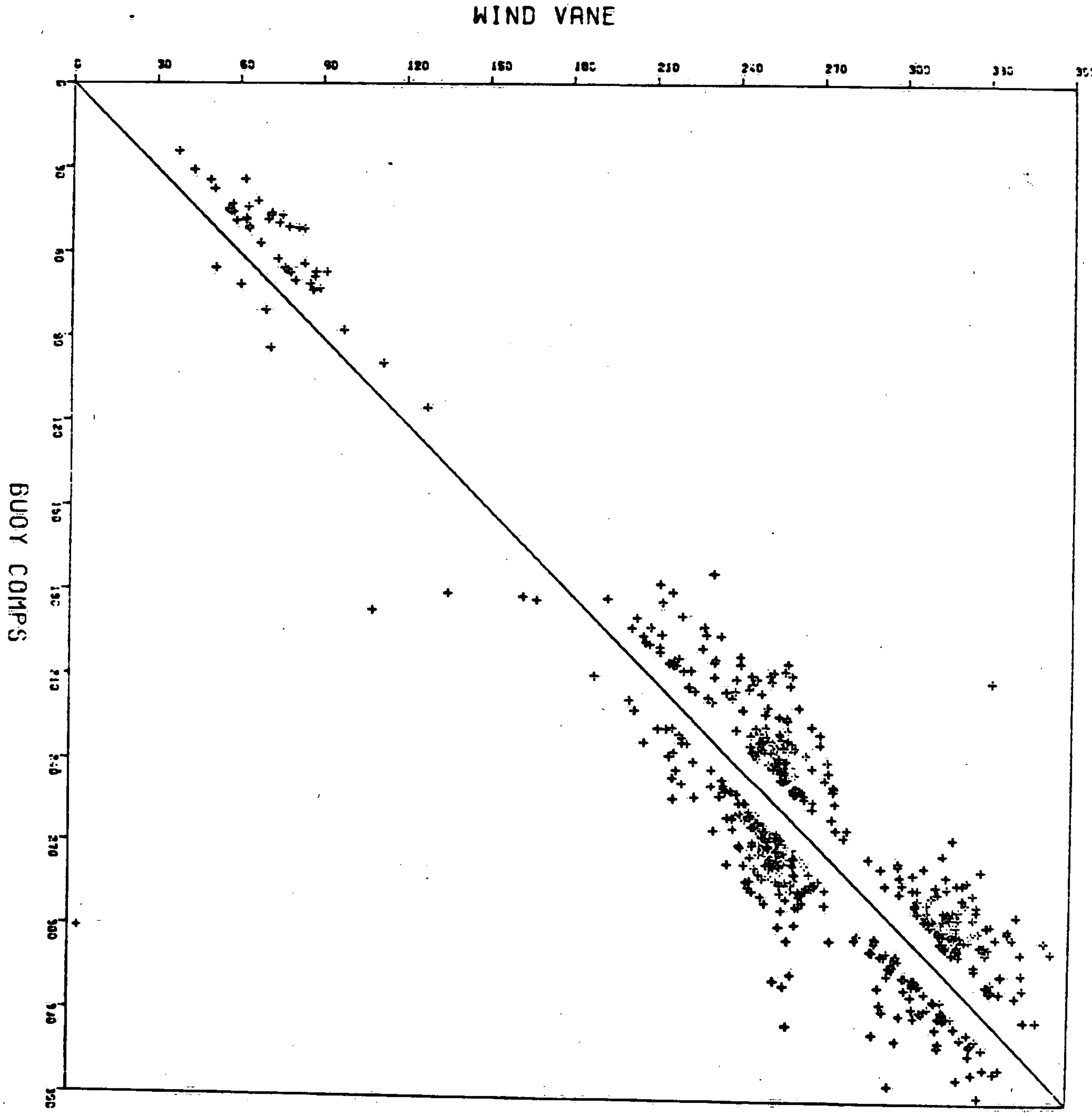


FIGURE 35

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Oct 19, 0000 hrs - Oct 27, 0000 hrs

1153. POINTS READ
474. POINTS PLOTTED
679. POINTS WITHIN 10.0 DEGREES NOT PLOTTED
10 minute data
Selected time period

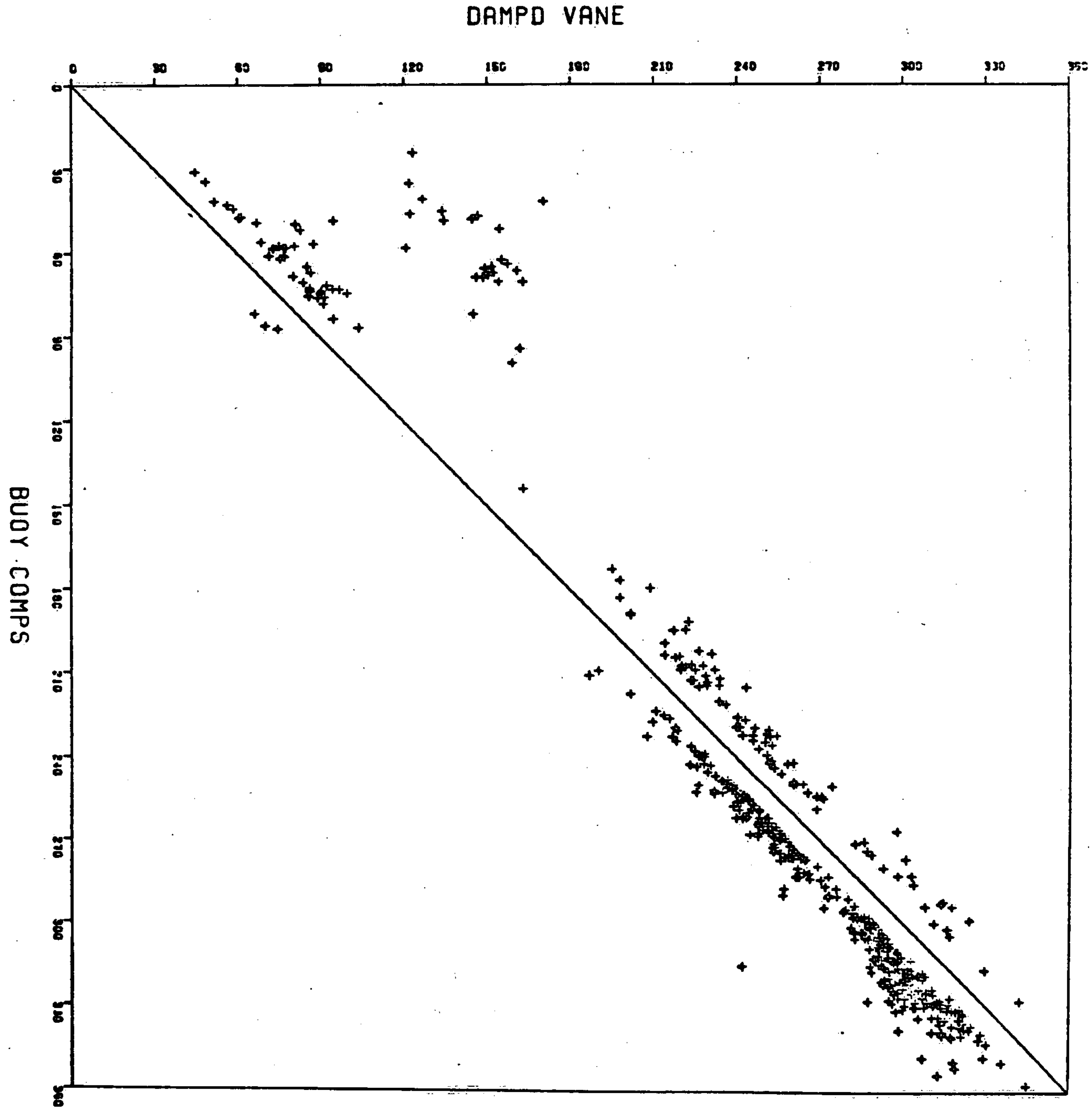


FIGURE 36

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Oct 19, 0000 hrs - Oct 27, 0000 hrs

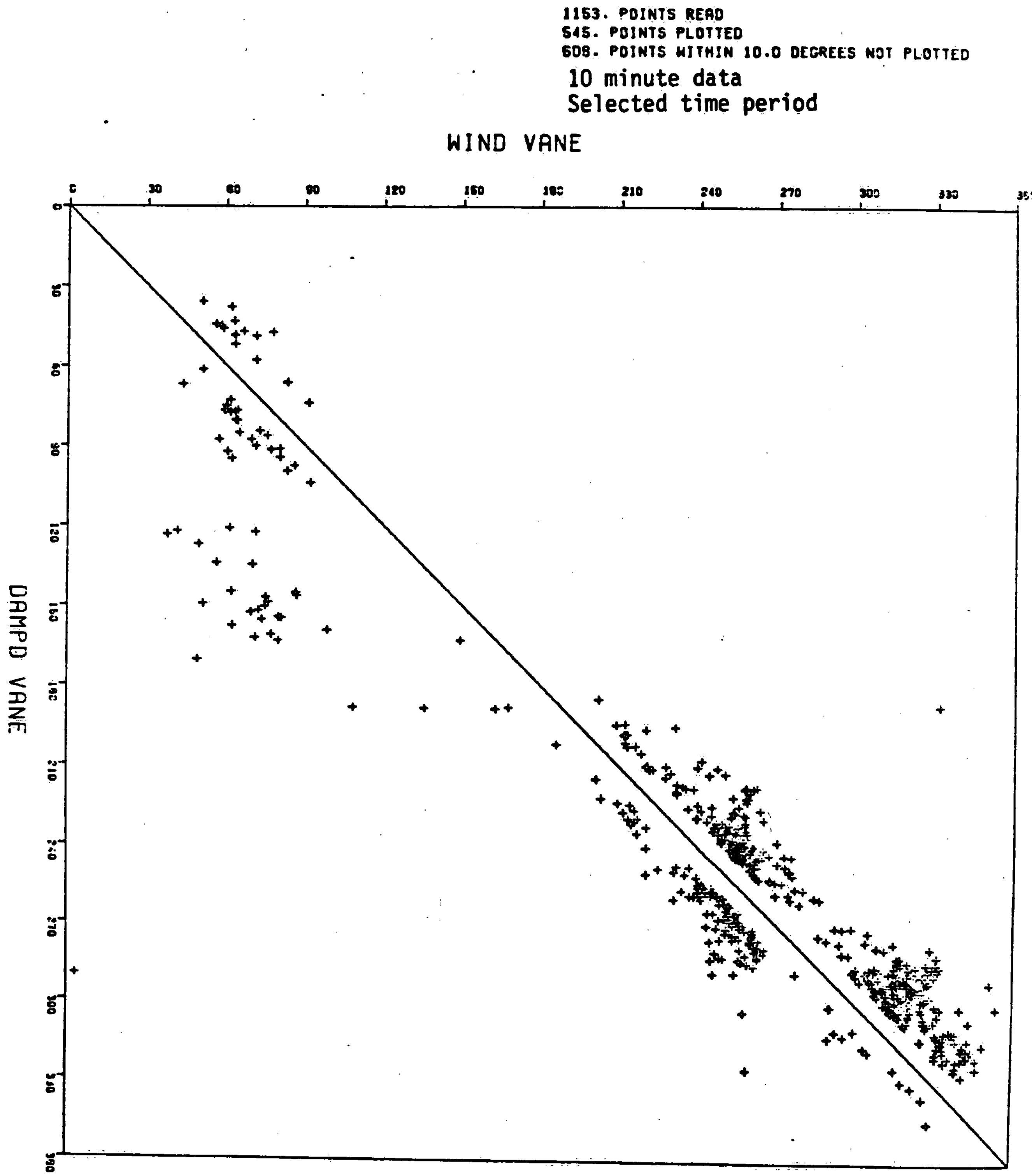


FIGURE 37

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Oct 29, 0000 hrs - Nov 6, 0000 hrs

DIRECTION SCATTER PLOT
START =7910290000.STOP =7911060000.
MINWSP =0.0 MAXWSP =100.0
STATION 79-00M-10A
SCATTER ANGLE =10.0

1153. POINTS READ
369. POINTS PLOTTED
784. POINTS WITHIN 10.0 DEGREES NOT PLOTTED

10 minute data
Selected time period

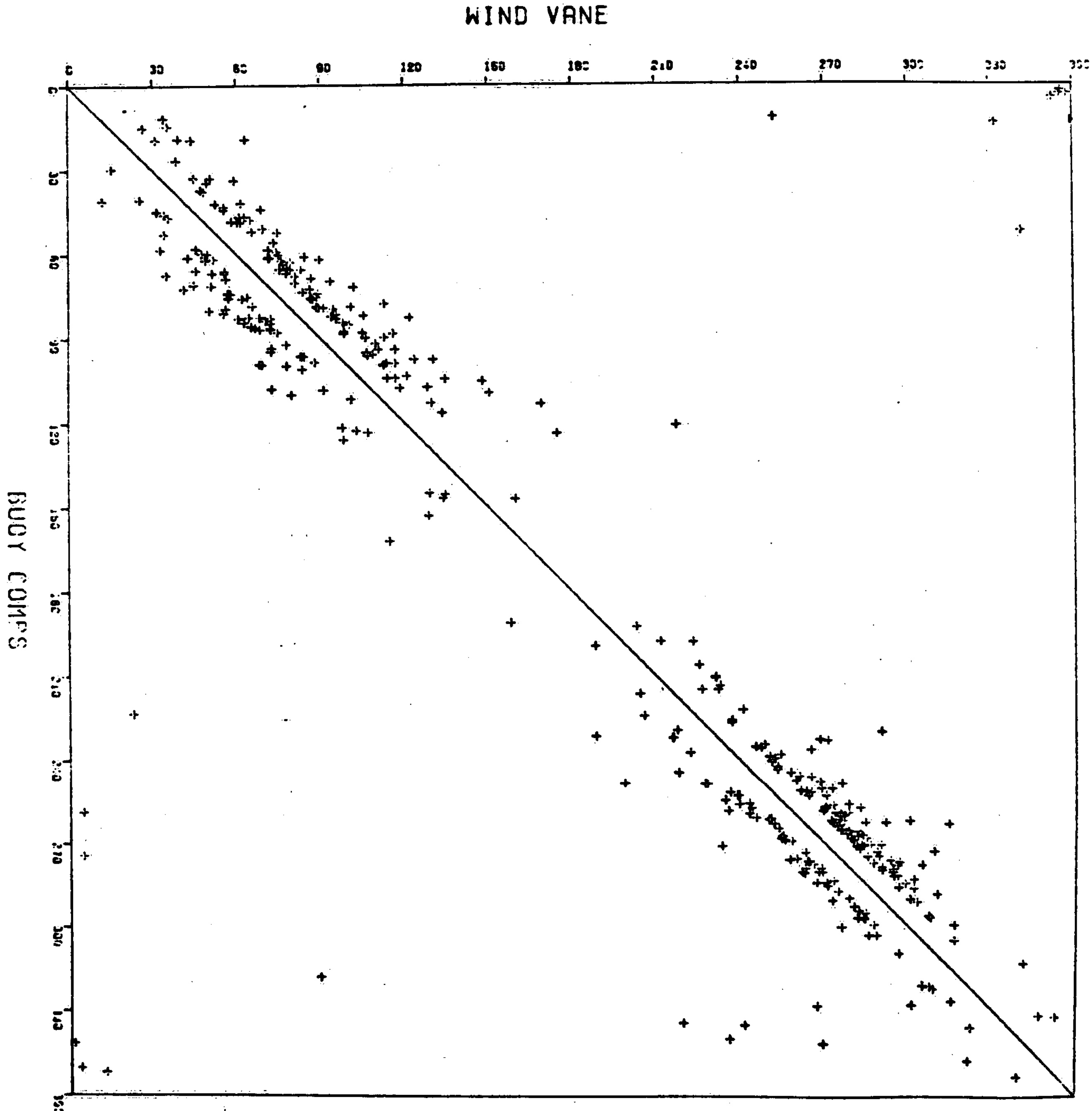


FIGURE 38

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Oct 29, 0000 hrs - Nov 6, 0000 hrs

1153. POINTS READ
458. POINTS PLOTTED
695. POINTS WITHIN 10.0 DEGREES NOT PLOTTED
10 minute data
Selected time period

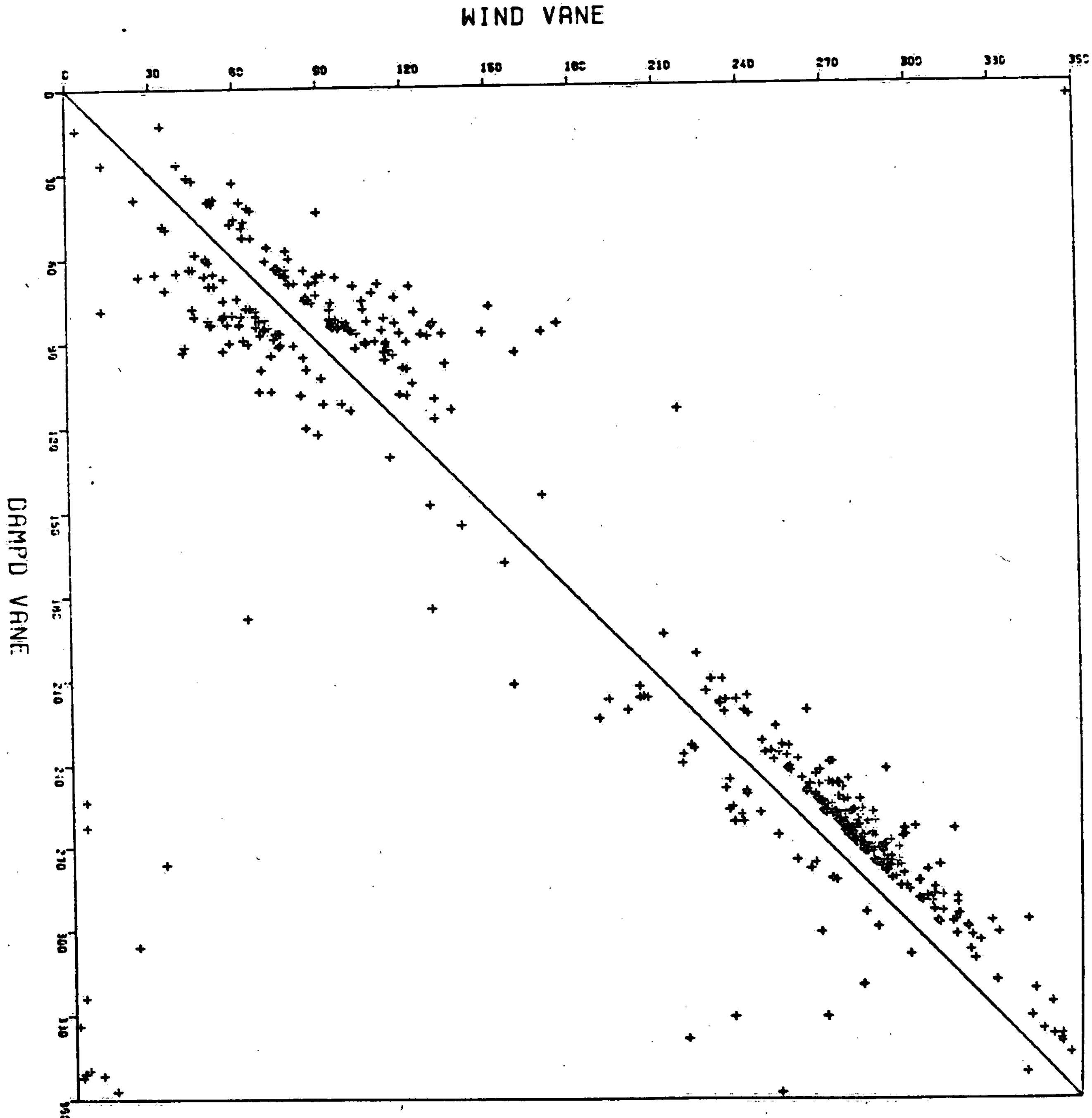


FIGURE 39

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Oct 29, 0000 hrs - Nov 6, 0000 hrs

1153. POINTS READ
417. POINTS PLOTTED
736. POINTS WITHIN 10.0 DEGREES NOT PLOTTED
10 minute data
Selected time period

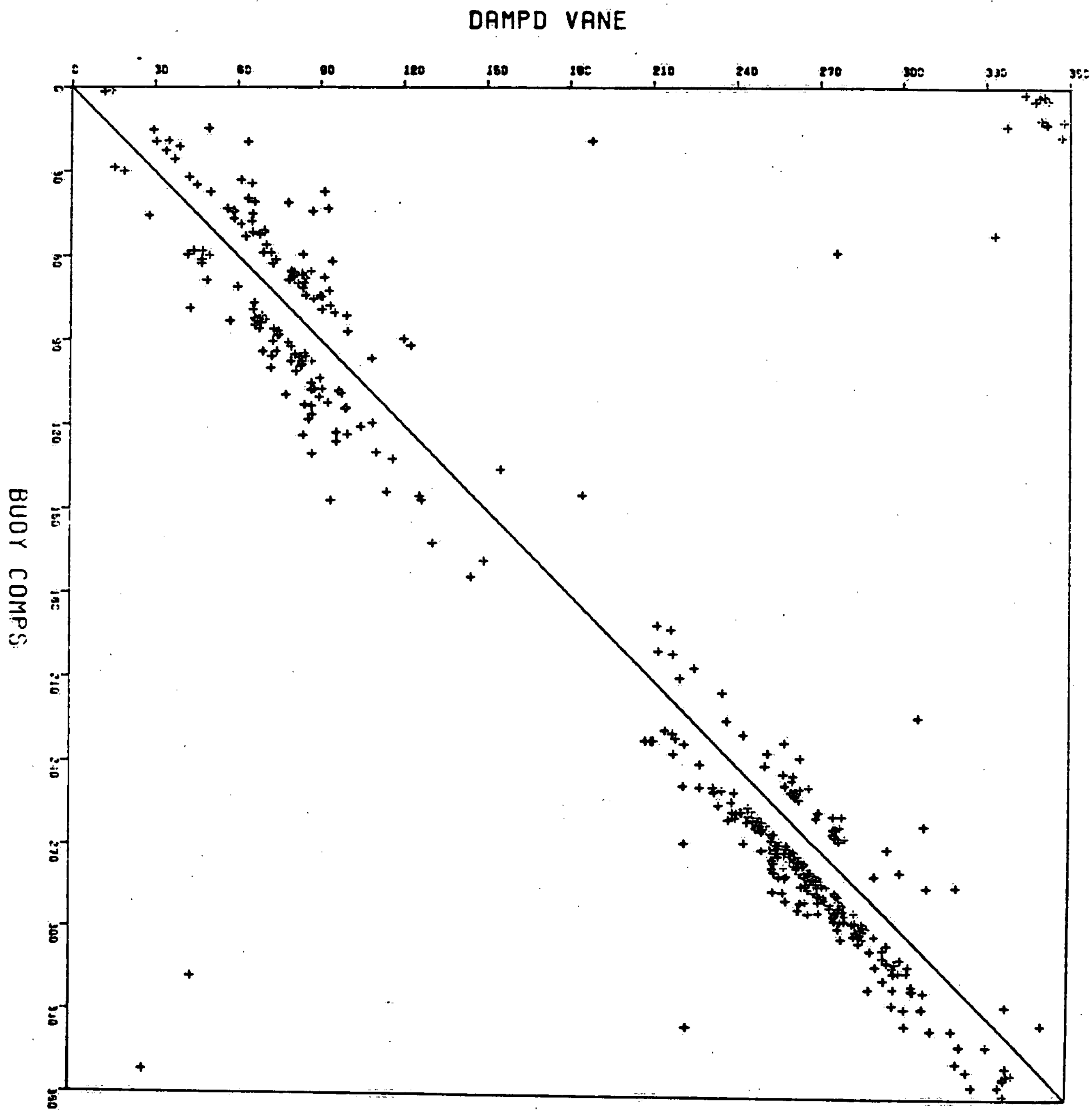


FIGURE 40

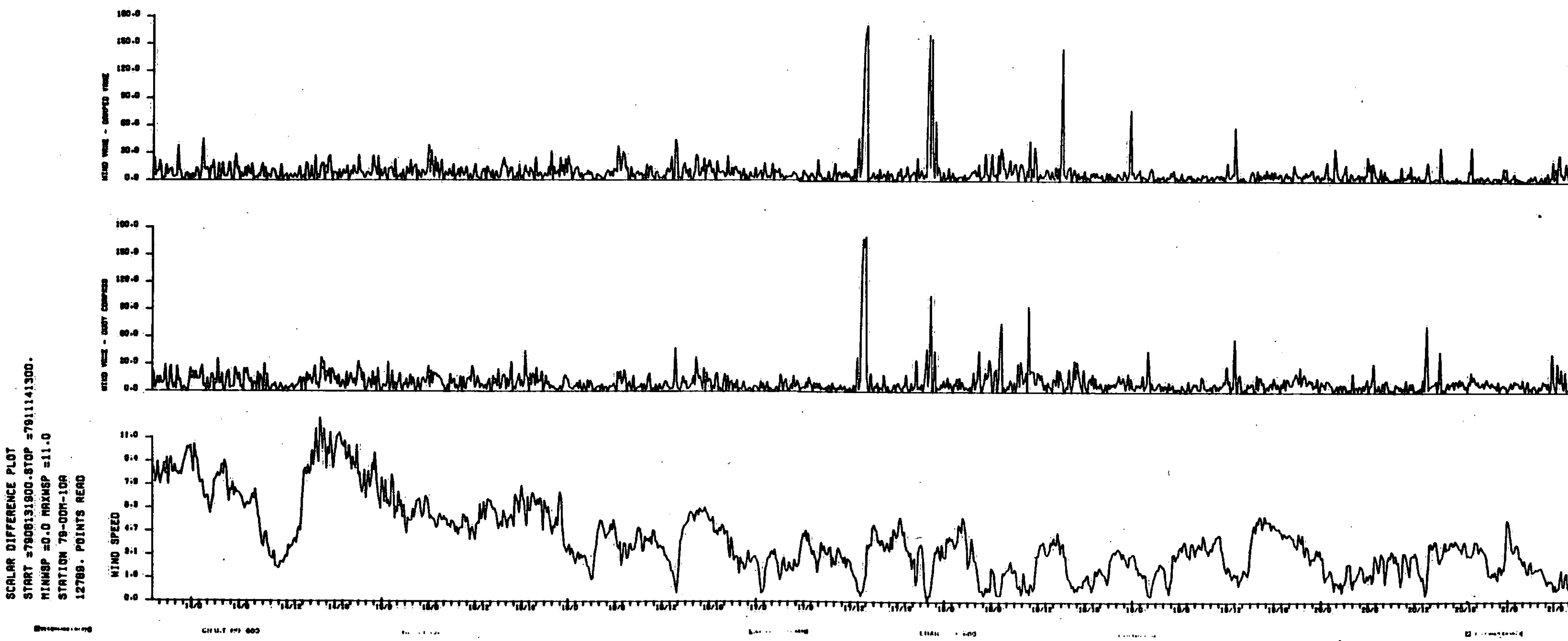


FIGURE 41

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Heading Difference and Wind Speed Time Series
Aug 14 - Aug 21

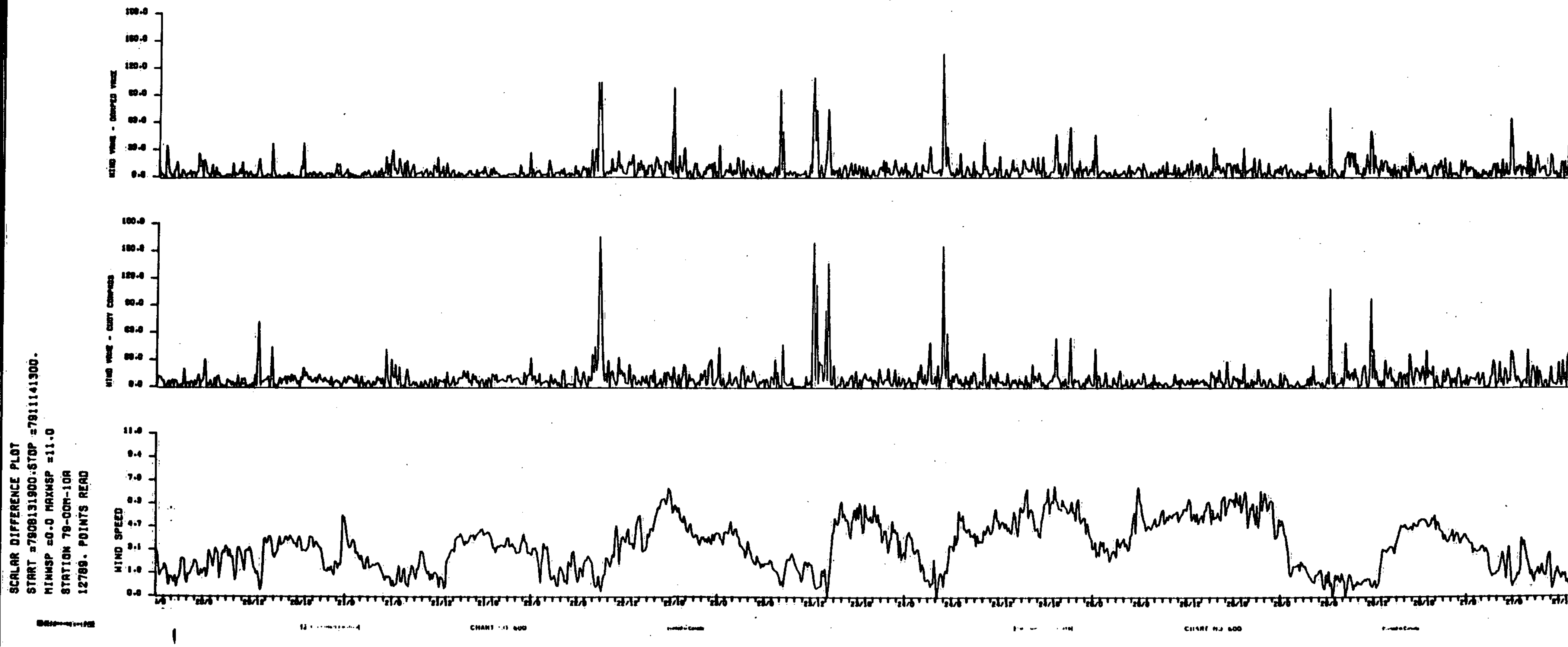


FIGURE 42

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Heading Difference and Wind Speed Time Series
Aug 20 - Aug 27

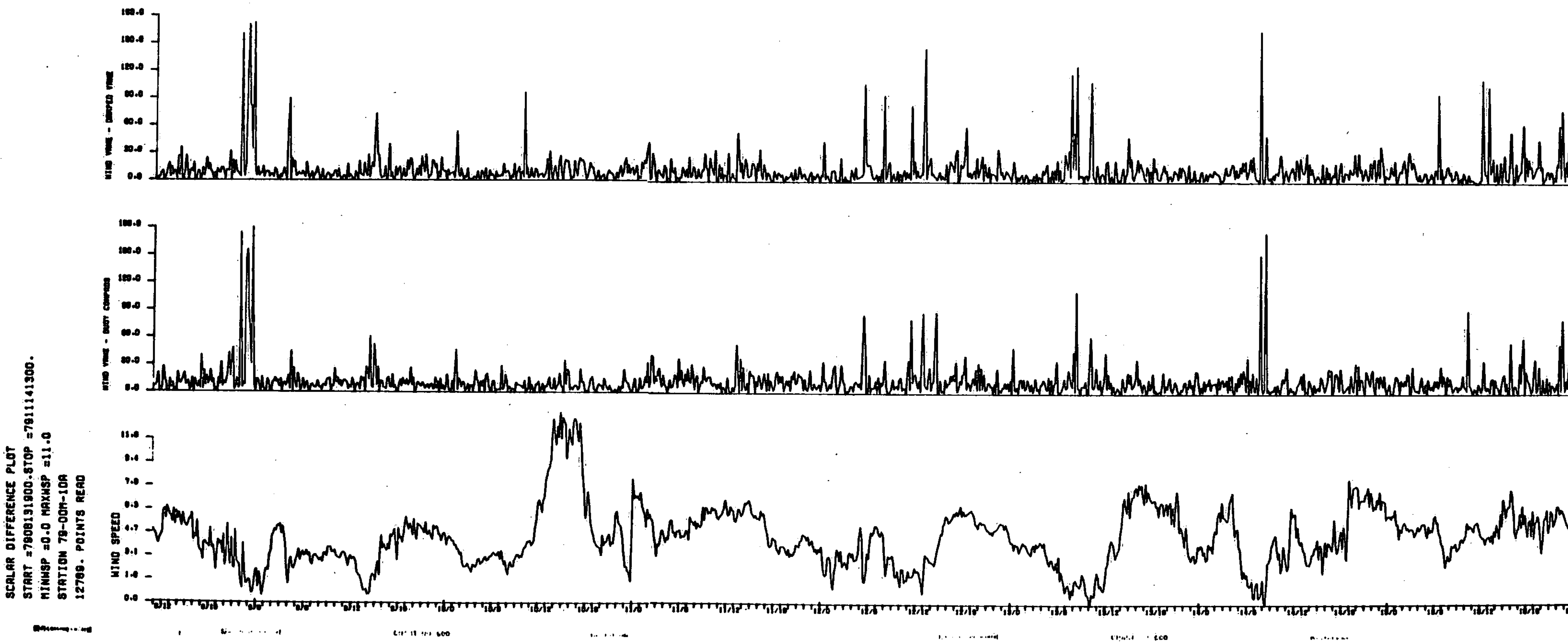


FIGURE 43

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Heading Difference and Wind Speed Time Series
Sept 8 - Sept 16

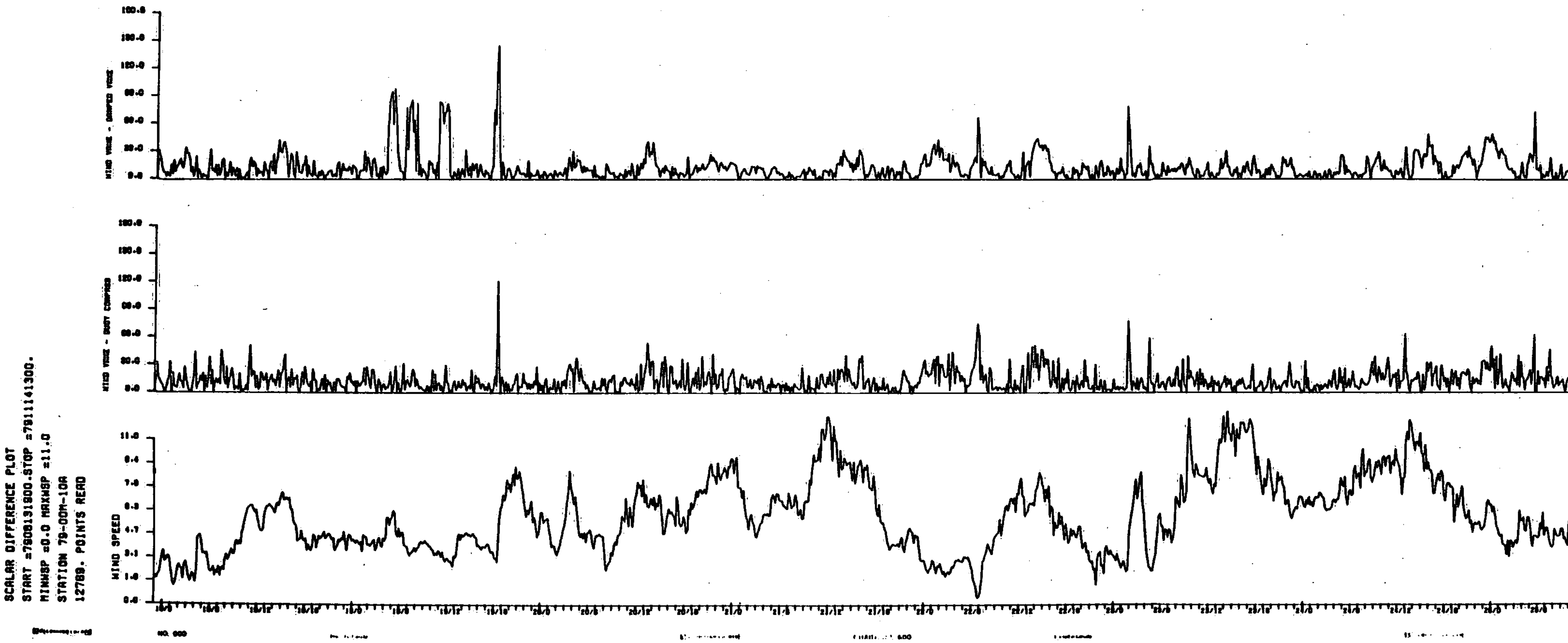


FIGURE 44

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Heading Difference and Wind Speed Time Series
Oct 18 - Oct 25

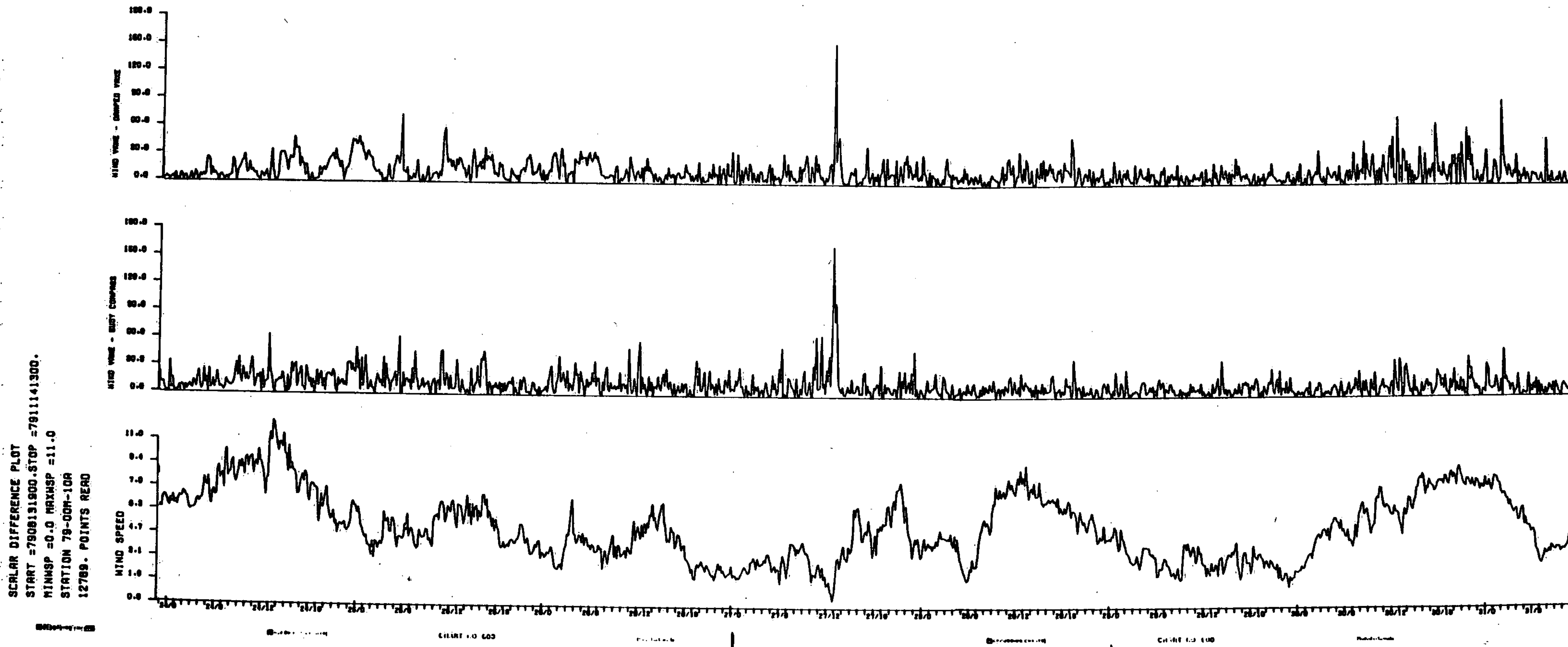


FIGURE 45

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Heading Difference and Wind Speed Time Series
Oct 24 - Oct 31

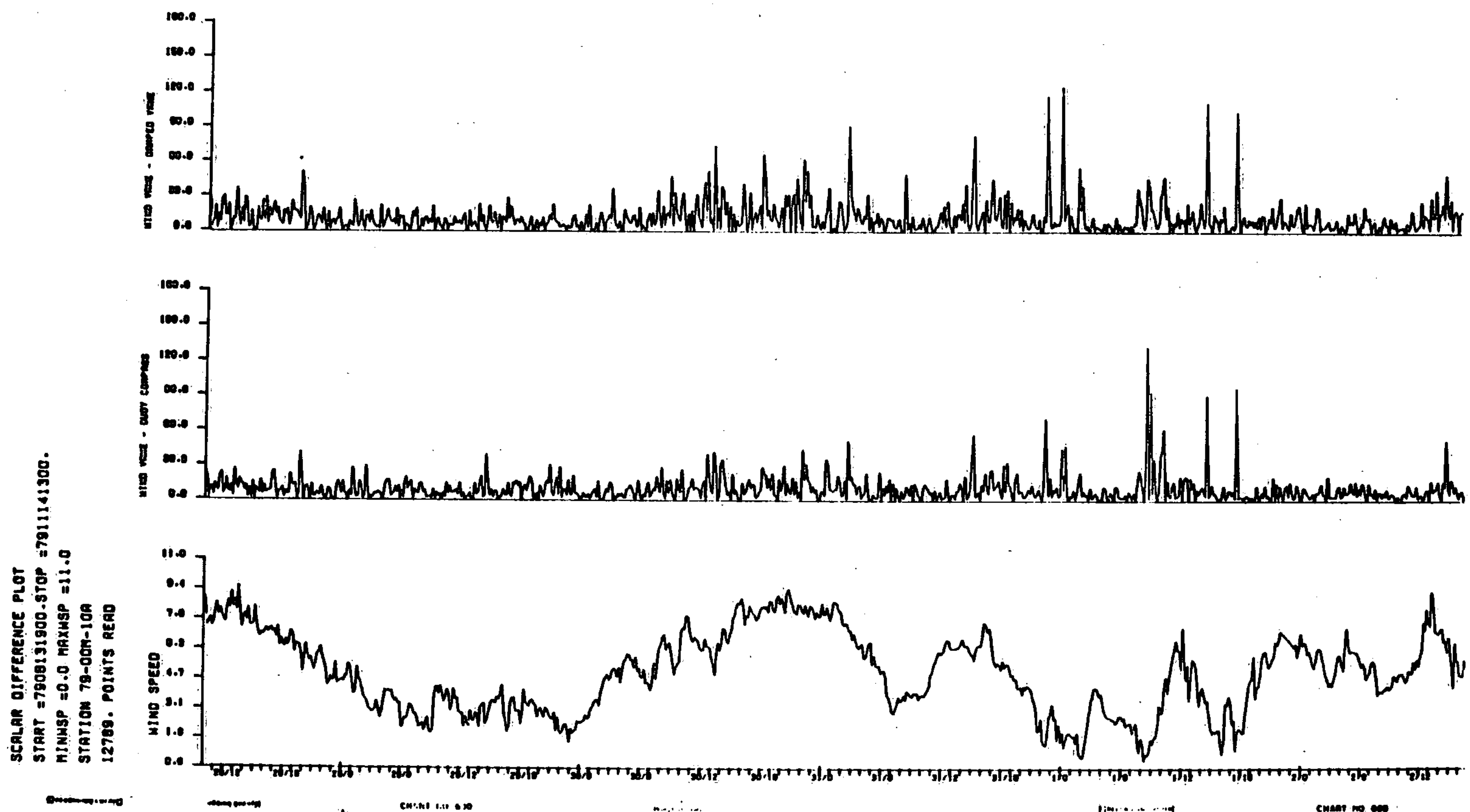


FIGURE 46

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Heading Difference and Wind Speed Time Series
Oct 28 - Nov 2

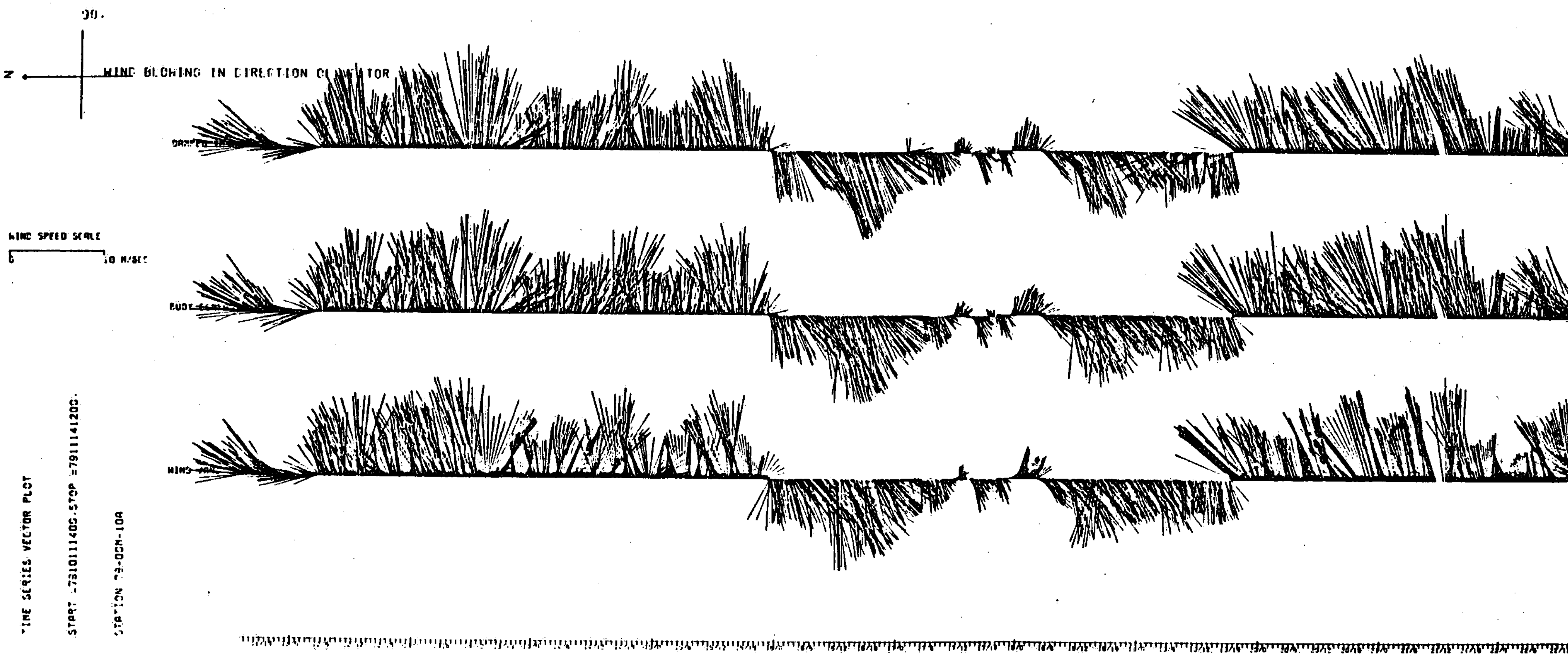


FIGURE 47

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Wind Vector Time Series
Oct 11 - Oct 22

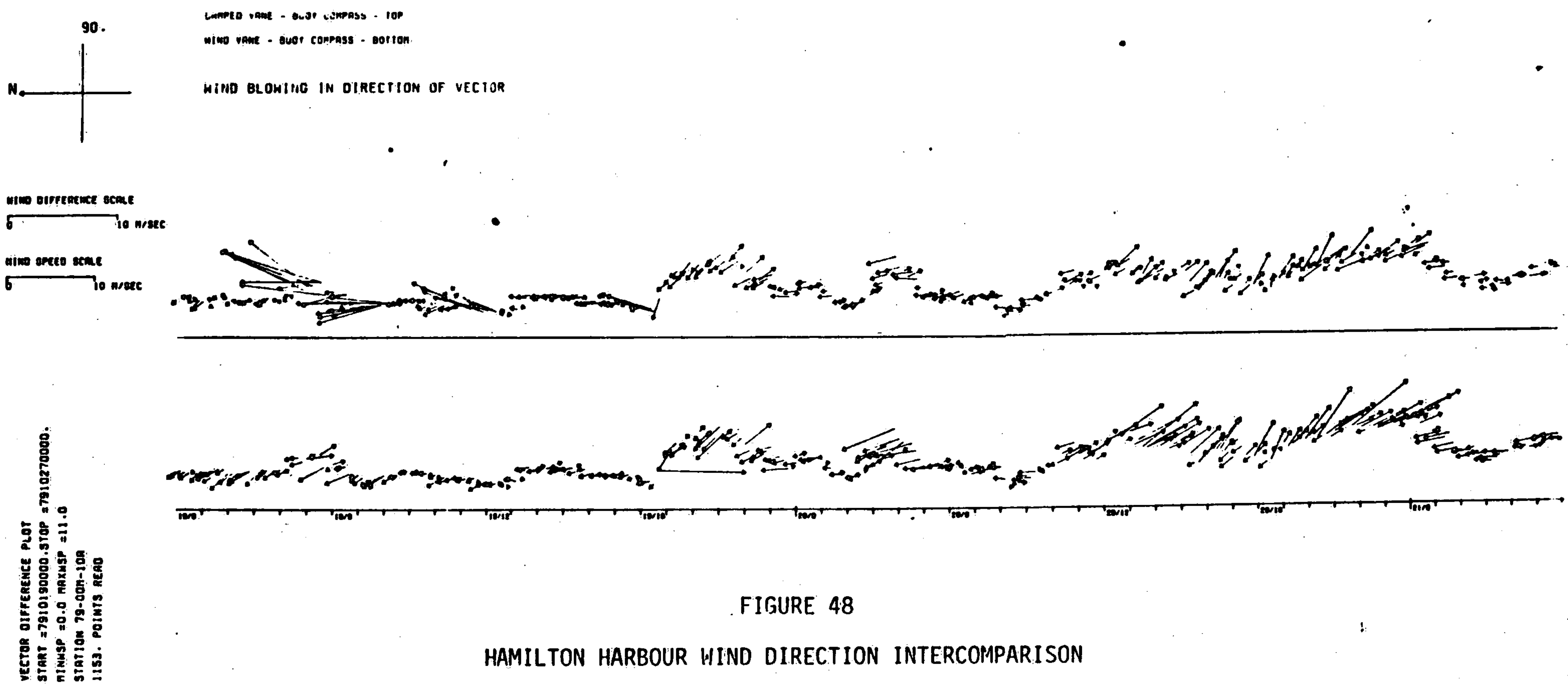


FIGURE 48

HAMILTON HARBOUR WIND DIRECTION INTERCOMPARISON

Wind Vector Difference Time Series
Oct 19 - Oct 21