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Full-scale measurement of environmental wind to compare wind tunnel performance

Dr. A.H. Cusick[1]

and Dr. R.C.F. Dye[2]

(1) Senior Lecturer,
Department of Civil Engineering and Building,
Bolton Institute of Higher Education

(2) Clifton Senior Lecturer in Engineering,
University of Manchester.

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1 Introduction

The main thrust of this work was to investigate the effect of increased sophistication in the simulation of the natural wind in wind tunnels upon the environmental results produced.

A bank of corresponding full scale data was thus vital for comparison with the Wind Tunnel results in each case.

Very little comparison of wind tunnel and corresponding full scale results has been carried-out. The only comprehensive schemes have been in structural loading and hence the data needed had to be specially collected.

The Mathematics Building, on the Manchester University campus, was chosen as the centrepiece of the investigation. It had noticeable ground wind effects, wind speed and direction could be monitored above the roof, and there was good access to the ground surrounding the building to carry out the ground wind speed and direction measurements. There were twenty-six measurement stations and public access to the area meant that neither permanent instruments nor land lines for power supply or data could be used. The roof-top readings were used to classify incident wind direction and to give a ground wind speed ratio normalised relative to the incident wind speed for each ground wind result. A bank of full scale data was collected but this only comprised sufficiently numerous results in incident winds from five of the twelve points of the compass to allow reliable mean wind speed ratios to be established for all ground wind stations.

A model of a section of the Manchester University campus, centred about the Mathematics Tower, was made at a scale of 1 : 250. It extended, at this scale, for a distance of one metre in all directions and was tested in three wind tunnels.

2 Previous Full Scale Work at Manchester

Previous full scale work had been carried out in two successive years by Manchester University Honours Degree students as part of their final year projects. The number of measurement points taken was less than the present work (9 and 11 compared with 26) and measurement was restricted to times when the students could be available during the period October to Easter in their final year. See Ref.1.

Despite these restrictions the two students managed to encounter good conditions on a number of occasions which yielded consistent results and encouraged the present work. A Cassella "Sensitive Cup Anemometer" mounted on a tripod was used for the ground wind measurements.

The wind speed and direction above the Maths. Tower was monitored during ground wind measurement by means of a Meteorological Office Pattern Monroe "In line" Direction and Velocity Head. Details are given in Fig.1. This was placed on top of the Clark Telescopic Mast detailed in Fig.2 and positioned as shown in Fig.3. The latter however had to be erected by successively pushing up sections by hand and pegging them at the lower end in each case. As this was done with the instrument, weighing 16Kg, on top it was not considered safe to extend the top three small diameter sections of the mast and so the instrument was only 8.8m above main roof level (i.e. 2.53m above the roof of the adjacent plant house). However wind tunnel tests indicated that velocities were only affected in the North West (36%) increase) and West (4% increase) directions with deviation from mainstream direction of 45^{o}, and 20^{o} respectively, measurement was by Pitot-Static tube for velocity and trailing thread for direction.

The general method of full scale measurement was to start the recorder on the Maths. Tower and synchronise timing with this record. The Casella instrument was then set up for 5 minutes of measurement at each ground wind measurement point in turn. The start and finish time for each 5 min. period was noted so that mean wind speed above the Maths. Tower could be extracted from the pen trace there for each ground wind measurement period. The Casella instrument gives a count of revolutions which can be converted to a mean velocity over the five minutes.

A measure of the increase (or decrease) in windiness due to the tower was found at each measurement point. The mean ground wind speed with the Maths. Tower present was divided by that without it present. The latter was found by factoring the mean speed from the Maths. Tower Roof measurements, according to the assumed mean velocity profile of the wind, for the appropriate measurement period.

The present Researcher decided to use a simpler non-dimensional ratio for comparison purposes. He merely divided the mean ground wind speed at measurement points by the simultaneous mean free wind speed from the Maths. Tower Roof measurements.

3 Early Conclusions and Improvements to Equipment

On commencement of the present work the equipment available was examined with a view to eliminating as many faults as possible.

The ground wind station, and mode of operation seemed quite satisfactory. It was merely decided to increase the range of the survey, requiring 27 points as shown in Fig. 4.

The point "18" was eventually dispensed with as the wind direction there was difficult to discern and the position became overgrown.

The arrangements on the Maths Tower roof appeared in need of improvement so far as the position of the instrument relative to the adjacent plant house was concerned. The instrument itself was ideal in performance but its weight limited the extension of the mast. Thus provision of a short permanent mast on top of the plant house roof seemed the ideal solution. This was ruled out on safety grounds as it would have meant University personnel working on the plant house roof which is unguarded.

Seemingly restricted to the existing mast and its position the only improvement possible would be to extend the mast fully. The possibility of replacing the instrument with one which was of suitable weight was thus investigated. Price was of essence, but even neglecting this, suitable instruments were negligibly few.

Eventually the Vector Instruments D600 Wind Speed and Direction System was discovered. This instrument was of negligible weight, allowing full extension of the Clark Mast (giving a height of 5.13m above the adjacent Plant House roof).

On receipt the wind speed unit was tested in the Plint Open Jet Wind Tunnel at B.I.H.E., and the sensitivity of the direction meter was checked with a large card dial and a protractor. The results of the tests are included as Figs. 5 and 6. The read-out from the instrument was purely instantaneous, displayed on dials, and thus totally unsuited to the function of recording wind speed and direction, against time, whilst the ground wind measurements were being made. A J.J. (Lloyd) 2 pen plotter was purchased, and the signals were intercepted in the Vector receiving station and cabled out, via variable resistance pots, to the plotter. The Chart Speed was set to give 2 x 1 mm squares per minute which allowed subsequent precise identification of conditions at periods of ground wind measurement.

Samples of chart output, anotated as to speed and direction traces, calibration lines and time scale, are included as Figs. 7 and 8.

The Ground wind instruments gave various running problems which led to some evolutionary development work which is detailed later in section 5. However the greatest problem in measuring effects of the full scale wind is undoubtedly the wind itself. If the wind is weak and the air temperature high, conditions will not accord with the Strong Wind Neutral Stability conditions required for this investigation. Even without thermal effects the possibility of serious lack of correlation in time between the incident wind and its ground wind effects over a 5 minute measuring period is evident if the wind is not strong enough.

Thus for the outer points at least and general 5 minute ground wind measurement sessions 8 m/s would seem to be the minimum mast-top speed acceptable unless the wind was uniform in speed and direction for a little time each side of the synchronised 5 minute sessions. However the most troublesome aspect of the natural wind for the present Authors' purposes, as for Gandemer (Ref.2.) was its continually shifting direction. The variation in velocity with time is less problematic as mast top and ground wind velocity can be averaged and averages compared. However the whole flow pattern about the building is dependent upon the direction of the incident wind to the extent that at certain angles of incidence a small change in this angle can cause a wholesale change in some ground wind strengths and/or directions and it was found that winds with mast speeds of approx. 8 m/s upwards tended to have more directional stability. (See sample copies of charts, Fig.7 mast speed greater than 8m/s Fig.8 mast speed less than 8 m/s).

Thus once these factors had been established ground wind readings were only taken when mast speeds were around 8 m/s and upwards. They were subsequently rejected if the mast direction exceeded $\pm$ 15^{o} of the mean direction of any 5 minute ground wind measuring period.

4 Proposals for Optimised Full Scale Measurement Systems

The above restrictions, when coupled with the part-time availability of the researcher and the need for the Maths. Tower to be open for readings to be taken, severely limited the rate of progress in collecting the full scale data.

The Authors prompted by their experience and the knowledge of the world-wide lack of such a system, submitted a proposal to S.E.R.C. for the provision of a system which would allow continuous monitoring of ground wind speed simultaneously at each of the 26 stations (or subsequently any other 26 stations) but this was not successful.

Subsequently, after consultation with the maintenance and security staff on the Maths. Tower, the Authors suggested a "management" scheme using the existing equipment which would optimise exploitation of suitable wind speed conditions whenever they occurred.

Access was negotiated to the Maths. Tower, outside normal opening hours, at the start of a measurement session (to start up the "Roof System") and at its end (to collect charts and switch off).

The arrangement meant that week-ends and holidays, with suitable weather conditions, could be fully exploited. (The fewer pedestrians and vehicles present gave an added bonus on such occasions).

The Cassella instrument was refurbished and both units, with suitable stands and long term re-chargeable batteries, were used with overlapping 5 minute measuring periods. Thus the rate of taking ground wind readings, during measurement periods, was doubled.

Also by keeping the equipment at his home the Researcher could re-charge the batteries overnight. This meant that the equipment was ready for a full day's measurement on any morning thus removing one possible restriction on working.

This regime was very successful, though short lived, as after some 3 months of operation freak gale conditions broke the top third off the Clark mast. It fractured at the peg holes in the two smallest sections.

The Clark mast had previously always been dismantled before the onset of high winds once a gale warning had been given. Gales are rate in Central Manchester and the system worked well for 10 years. Unfortunately, at the time of damage, four days of strong winds, ideal for measurement, preceded one of gales which became severe. The gale warnings were issued on the fourth day of strong winds and there was no other option open than to let the mast weather the gales.

A new mast was felt necessary, rather than repairing the old and so the opportunity was taken of getting, for less cost than a straight replacement, a more robust, winch operated, folding mast. The Western Electronics ULTIMAST as detailed in Fig.9 was chosen. This mast was to be guy supported as the previous mast but would be stiff enough to avoid damage as sustained by the old mast. It would have the facility of being safely partially or fully lowered, even in high winds.

The erection of the Ultimast has been delayed due to lack of funding as the University Buildings Department insist on works to the guy supports costing five times the initial cost of the new mast on the basis of alleged increased loading on the guys.

5 Developments in Ground Wind Measurement

The Anemometer Units

Two anemometers were used in this work, the Cassella Sensitive Anemometer and the Vector A100R Anemometer.

Both instruments are merely wind driven cup-type windmills connected to a revolution counter. The average speed over a five minute period can be found by counting the revolutions and applying factors to the number.

The circuitry for the former, and a rechargeable Cadmium battery, was enclosed in a weatherproof aluminium case.

The arrangement was compact but in optimum condition the unit would only operate for say 2 hours without a battery recharge.

Current was needed to feed a light source in the revolution sensor unit and an electromechanical counter. The latter was the main culprit in using power and when worn out was replaced by a purely electronic counter with low consumption.

The total consumption of the unit was still too much for the Cadmium battery to cope with reliably all day. Thus to eradicate annoying battery failure, and to facilitate recharging overnight at the Researcher's home, a YUASA, 6.0.Ah, 12 volt, lead acid battery was introduced. This could be easily recharged overnight using a DIY 12 volt trickle charger.

The Vector instrument initially was fitted with the same compact Cadmium battery as above.

It performed better than the original Cassella rig as the revolution sensor took virtually no current but the counter unit was again electro-mechanical and so the instrument would not reliably work all day on a fully charged battery.

The problem was resolved by installing an electronic counter (as the new one on the Cassella instrument) which used much less power thus the Cadmium battery could be kept reliably up to a full day's measurement by a gentle overnight charge. The latest model Vector incorporates an electronic counter as standard.

6 The Anemometer Stands

The original stand for the Cassella instrument was a rigid tripod made of gas conduit Fig.10. It was robust and stable but heavy and awkward to carry.

The Researcher lightened this tripod by substituting aluminium legs, but lost stability in high winds.

When, in the final system of operation two instruments were to be used together at least one new stand was to be provided. Thus the Author reviewed the whole situation and brought in the two new requirements:-

1 That it must be feasible to carry two instruments, in operational state, one in each hand and

2 The stands must be easily demountable and allow the system to be based on the home and car rather than on the Simon Engineering Labs.

These requirements were in addition to the usual ones of stability in high winds and supply with minimum delay at minimum cost.

A plastic parasol base, sold generally for patio use and suitable for filling with ballast, was selected as the base for the new stands. A light, robust, corrosion free, stem was made from a length of 19mm diam. anodised aluminium shower curtain rail. The latter was thickened-up at the lower end by forcing a tight-fitting piece of polythene hose over it. This allowed the chuck of the parasol base to grip the stem firmly without modification, thus preserving the facility of dismantling for car transport.

The instruments could be carried, in full working rig, one in each hand by the Researcher by holding each parasol base by the neck into which the stem fitted. The counter boxes, batteries, etc. could be packed into a plastic carrier bag and threaded onto the latter's arm.

It was important to be able to move both instruments simultaneously because the whole measurement area was open to public access.

This factor meant there was always risk of interference with a deserted instrument.

The ballasting of the parasol bases warranted some development attention as sufficient stability with minimal weight was required because of the mobility requirement.

A prototype base was built with a dummy anemometer on top of the stem and the stability of this tested with varying amounts of water as ballast.

Water is not an ideal ballast, unless the base is full of it, as once the base starts to tip the ballast migrates away from the lifting edge thus increasing the tendency to tip over and reducing the chance of recovery when the wind slackens. Hence once a sufficient weight of ballast had been evaluated by use of water it was replaced by a slightly greater weight of concrete which gave greater stability on both counts.

The only method of testing the prototype available was to use the open jet of the Plint Blower Wind Tunnel at B.I.H.E. as a sudden gust. The tunnel produces uniform air speeds of up to 30 m/s just prior to efflux into the laboratory at a height compatible with the anemometer on the stand.

The method of testing was to leave the tunnel running at full speed and to push the prototype stand, with its dummy anemometer, suddenly into the air flow with a pole.

Two stands were made and ballasted with concrete prior to use. The Vector and Cassella Anemometers were mounted neatly on top of the aluminium stems and are shown in Fig.11.

The stands were highly successful under strong wind conditions and the only problem encountered was on the day of severe gales which broke the mast on the Mathematics Tower. On that day, in conditions of great turbulence, the Cassella instrument blew over at position 7.

The conditions were extreme at the time, the wind gusting severely from at least two distinct directions in rapid alternation with suspected vortex flow.

The stand tilted slightly and then, when the windward edge of the base had risen only a small distance, the whole unit was suddenly and violently thrown up into the air.

It would seem that the wind got underneath the base and exploited its relatively great underside area as a sail.

The development tests had not included the possibility of wind getting under the base but it is doubtful that, with a solid base and vortex flow of such severity, stability could be guaranteed even with maximum ballast. Such ballast would make carrying of two units impracticable and be unnecessary except in gale conditions and at the worst affected points in the vortex flows.

A possible solution, if a purpose-made base was to be provided, would be to use a steel base with holes in it to diffuse any wind pressure on the underside.

7 Local Direction of Ground Winds in Full Scale Measurements

Throughout the collection of ground wind data, the local direction at each measurement station was noted whilst attending the anemometers.

The estimation of direction was based upon its effect upon the observer's eyes, ears and face, or hair and clothing for the strongest cases. Direction was estimated generally in terms of being to or from one of the other measurement stations as these were, of course, known in position with some acuracy both on the ground and on plan.

Some fluctuations in full scale ground wind direction at a station may be purely a product of continuous angular variation of the natural incident wind as it gusts both in speed and direction which would be shown in the records on the Maths Tower Roof.

Results, for which this short time scale angular variation in direction of the incident wind exceeded $\pm 15^{\circ}$ were thus excluded.

7.1 Full Scale Velocity Ratio Results - Introduction

In examining the natural wind speed and direction we have, as Gandemer indicates in Ref.2, a number of modes of variation to consider. We have long term variation in speed and direction, which is simple to make allowance for. We further have short term variation in both these items as the wind continually gusts and shifts its direction.

The speed measurements are generally dealt with by working in terms of mean wind speed over a measurement period. Comparison with wind tunnel results is then best accomplished by comparing ratios of mean speeds in each case. This neatly disposes of problems of reconciling the differing mode of variation, and length of averaging time, in the model and full-scale cases. In each case, values subject to the same mode of variation, amplitude and time scale are used to produce non-dimensional ratios, which are then compared. This, however, excludes consideration of velocity variations which are dependent upon short term fluctuation of incident wind direction. The latter can affect the ground wind velocity reading but not the monitored incident wind velocity reading at any particular time and is thus much harder to deal with than the above velocity variations.

Directional gusting of the incident wind is difficult to simulate in wind tunnels and most workers have been forced back upon use of the mean direction in full scale to compare with the constant direction in the wind tunnel. Here the length of the measuring period can have some influence.

A five minute full scale measuring period has been used in the present work, being the minimum considered viable and within the initial range of the instrumentation used.

To compensate for the shortness of the period, a tolerance limit of gusting angle was introduced and results obtained for winds gusting more than this were discounted.

An alternative mode of operation would be to use a 30 minute measuring period (not so long as to be significantly affected by long term variations) and to assume that a fully representative sample of all short-term variations was present in the ground wind and monitor results, and could thus be legitimately averaged out. (Suggested by Dr. Perrera of BRE in a private communication when the authors were considering a SERC application for a full scale measurement system.)

M. Gandemer (Ref.2) used 15 minute measuring periods for measurements in a wind which was blustery in direction and 5 minute measuring periods for measurements in a wind which was steady in direction. He thus indicates that both the present authors' approach and Dr. Perrera's are equally acceptable, provided the former is not applied when the wind is too blustery in direction.

The option of using a longer measurement period with fewer stations was discounted as it was felt important to maintain enough of these to fully cover the gound wind flow pattern around the Maths. Building as indicated in previous wind tunnel studies. The further alternative of keeping the large number of measurement stations and also using the longer measurement period was not felt a viable method of operation as it would limit the coverage of the ground wind pattern possible per measurement session when only part-day sessions were available. Length of measurement session could be curtailed in this way due to constraints on the availability of the researcher or less predictably deterioration of weather or breakdown of instruments as the session progressed.

Working subject to the conditions and limitations indicated above, it is important to ensure that the final full-scale results considered are each average values correctly derived from a statistically significant population of individual field results before a meaningful comparison with model scale results can be made.

7.2 Initial Screening of Full Scale Velocity Ratio Results

As an initial rough check, the results were tested to see whether any varied too much from the apparent mean value and whether these deviations were due to human errors, or instrument faults, such that they could be re-calculated or discarded as the case might be. The results were also tested for systematic errors or systematic variation with discernible physical causes.

In order to establish a sensible mean value, a reasonable number of full-scale results must be available for any given measurement station. Thus it was only possible with the full-scale results gathered in this work to give serious consideration to these matters for results gathered in the South, South 30° West, West 30° South, West and North 30° East incident wind directions (see Fig.12).

This exhibits some variations from the general Wind Rose for Manchester shown as Fig.13.

However not all winds or weather conditions are suitable. The speed of the wind at Maths. Tower Roof level had to be > 8m/s and < gale force, and the weather dry.

Also the availability of measurement site, usable instrumentation, and the Researcher had overriding influence.

Irrespective of the number of results actually gathered for any station or wind direction, those occurring when the incident wind speed at the Maths Tower Mast was less than 8 m/s were disregarded for the reasons explained in Section 3.

All results were checked for odd abnormal readings in any population, or greatly disparate values in the "low number of results" cases. These could derive from arithmetic mistakes or mis-booking. Thus, the field results and working-out were checked to eliminate these factors. They could also result from instrument fault. For instance, all results from 17-11-1982 were found to be double or more the average for the other corresponding results at each point. The full-scale survey records showed that the anemometer counter had failed later that day and thus these results were eliminated from consideration.

The ground wind speed and direction at each measurement station were expected to vary with incident wind direction. It would, however, have been obviously impractical to only consider full-scale results for incident winds in exactly the directions considered in the wind tunnel tests or vice-versa. The authors decided to take the incident wind from twelve compass points in the model tests and to group the full scale results within ± 15° of each of these.

It was considered that this should give a sufficiently fine division of angular direction for there to be little discernible variation in results with change in angle for any of the winds grouped in any one direction. The truth of this premise was tested when the full scale results had been assembled. It appeared to be corroborated for practically all positions in those incident wind directions in Fig.12. However some systematic variation of ratio of ground wind to Maths Tower Roof Mast instrument velocity reading with angle of incident wind was detected in two cases.

They are both near corners such that a small shift in incident wind angle could produce differing diversionary effects. Bearing the above points in mind, the full-scale result chosen for comparison with the model scale in each of these cases would be that deemed appropriate to the exact direction of the model incident wind.

The full-scale ground wind measurements were made at various times with two different anemometers, each of a different manufacturer. However, there were enough cases of cross-checking at various positions to dispel any suspicions of instrument-dependent bias between the two instruments.

7.3 Statistical Tests on Samples of Full Scale Velocity Ratios and their Means

Statistical tests could only reasonably be applied to sets of results for any measurement position and incident wind direction which were sufficient in number. These generally comprise all stations for the wind directions in Fig.12.

Having initially screened all these results for any sets exhibiting a clearly identifiable bias which could be related to physical causes, those remaining were expected to fit normal distributions about their means.

Despite the fact that these collections of results are large compared with those for the remaining incident wind directions they cannot be considered as large samples from a statistical point of view. Thus statistical methods appropriate to small sample sizes were employed to establish the 95% confidence limits of the means of the full scale wind ratios for each ground wind station in each incident wind direction.

It was found however that the effects of this processing were not rational in as much as where the results for any station in a given wind direction comprised a good number of well conditioned full scale ratios, the 95% confidence limits of the mean were tight and so the corresponding mean from a wind tunnel was less likely to be accommodated within them than in the cases where smaller numbers of ratios or less well conditioned ratio values comprised the full scale results for a station in a given wind direction.

It was thus decided to quote the wind tunnel results as merely lying within ± 10%, ± 20%, ± 30% etc. of the appropriate full scale means and to use a graphical statistical technique on the wind tunnel results to see if they exhibited any consistent bias relative to the full scale results in each incident wind direction included in Fig.12.

7.4 Graphical Comparisons of Wind Tunnel and Full Scale Results

The graphical figures initially produced, comprised a mean and range plot of the full scale data for each wind direction with the results for the three wind tunnels superimposed. They are included as Figs.14 to 18.

These statistical figures were found very useful by the researcher in identifying absolute trends in the wind tunnel mean velocity ratios relative to the range of full scale values at any measurement station but are useful here in demonstrating the spread of full scale results at each station relative to their mean values.

So many factors could affect the full scale values, but there was no way of telling which effects had been included in the full scale results collected for each station. Thus it was assumed that provided the full scale ratios at any station are numerous, and do not display a defined bias with wind angle, that they should be assumed to cover the reasonable range of full scale ratios possible at that station.

The statistical mean and range plots utilised here present useful statistical information, i.e. the range of results at each station and give an immediate identification of the station at which the results were obtained. They allow immediate checking, of likely conditions at the station, the number of contributing full scale results, and comparison with results for the same station in other wind directions.

However the statistical mean and range figures only give a comparison, in absolute terms (i.e. at the same scale at each station without any normalisation with respect to ratio size in each case) of the range of the model scale means compared with that of the full scale results. The comparative overall size of the means is thus lost.

A totally different approach to the graphical presentation of the data is given by Isyumov and Davenport (Ref.3) using ground wind roses at each measurement station. Variation of ground wind speed ratio with direction of incident wind can very clearly be seen at a glance for any station for both wind tunnel and full scale results. However only the mean values of the full scale results are included which loses an aspect of the results felt of great importance by the present Authors, namely the range of the full scale reading. Consequently figures 19 to 22 have been included to display the results of this work in the ground wind rose manner but with the range of full scale ratios, for the directions for which they are available, shown as thick stripes.

The reader is asked to remember that the full scale results are only numerous enough to support such a treatment in the incident wind directions given in Fig.12. The full scale readings represented by circular marks are supported by only one full scale result in each case.

8 Conclusions

1 Having eliminated obvious rogue readings a consistent bank of full scale ground wind data has been collected.

2 Winds with speeds of 8 m/s or more above the influence of the buildings were found to be much more stable in direction than slower winds.

3 The Vector Instruments D600 Wind Speed and Direction system combined with a J.J. (Lloyds) two pen plotter gave an effective economical light weight system for monitoring of wind speed and direction.

4 The Vector Instruments A100 switching anemometer is an excellent, robust instrument for the collection of ground wind data and in the version fitted with an electronic counter will operate for at least a full day on a fully charged battery.

5 An easily carried and dismantled corrosion free anemometer stand can be produced at low cost and effort from readily available lay items.

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2	Gandemer, J.	Aerodynamic Studies of Built-up areas made by CSTB at Nantes, France. Journal of Industrial Aerodynamics, 3 (1978) pp.227-240.
3	Isyumov, N. and Davenport, A.G.	Comparison of full scale and wind tunnel wind speed measurements in the Commerce Court Plaza - Journal of Industrial Aerodynamics Vol.1. 1975 pp.126-137.

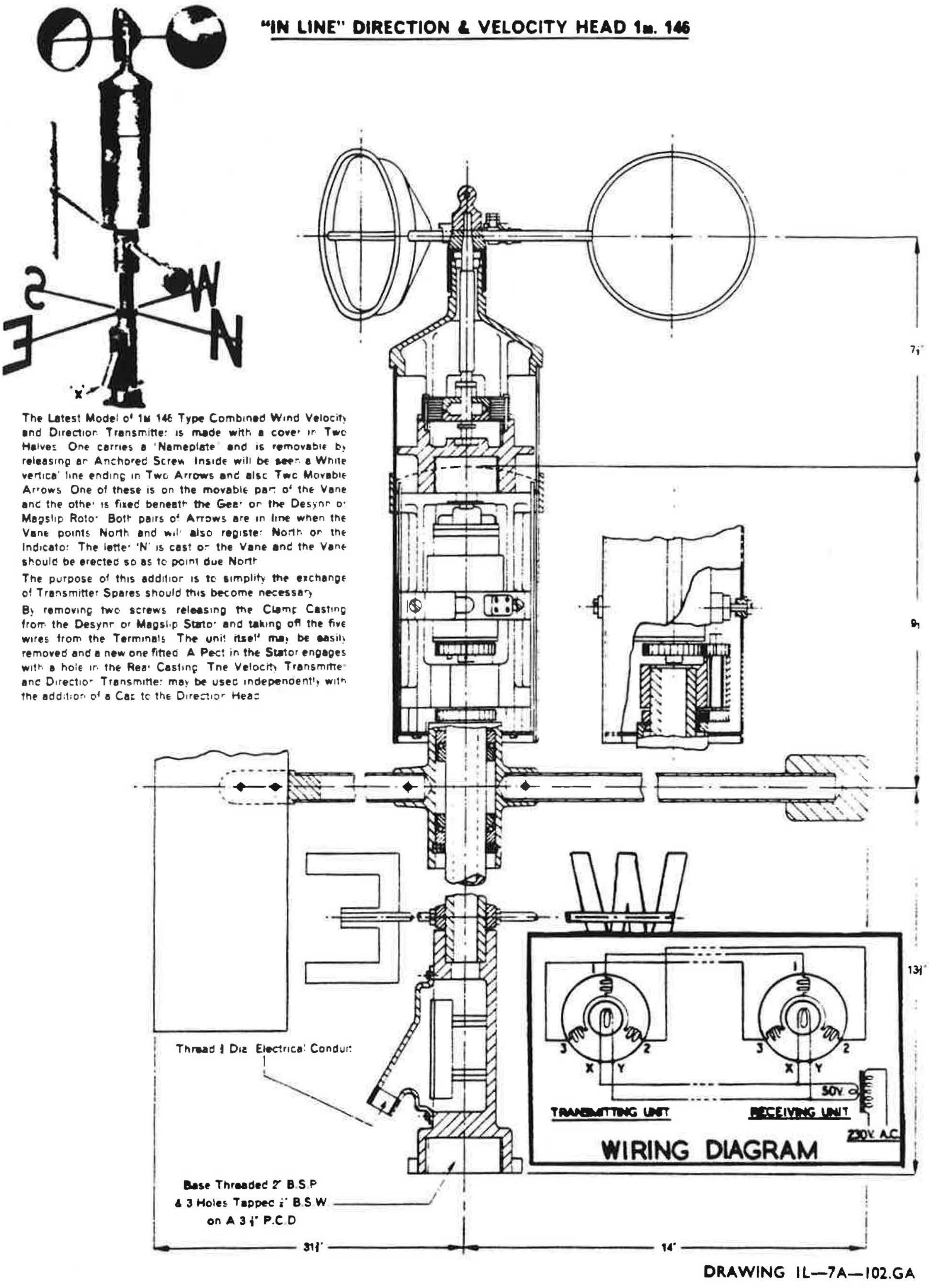
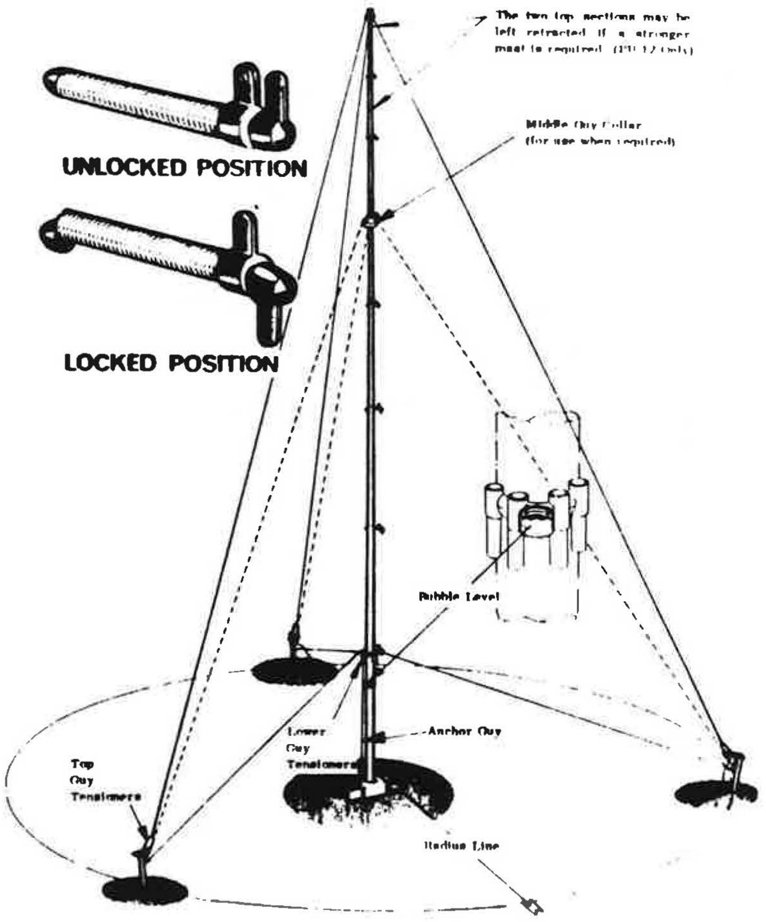


FIG.1. THE MONROE METEOROLOGICAL OFFICE PATTERN WIND SPEED AND DIRECTION SYSTEM

GENERAL LAYOUT OF ERECTED MAST



FIELD ERECTED MAST

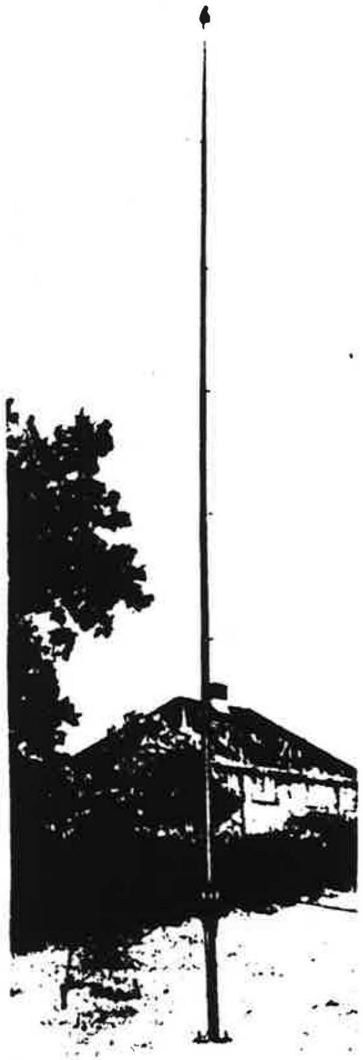


FIG.2. THE CLARK LIGHTWEIGHT TELESCOPIC MAST

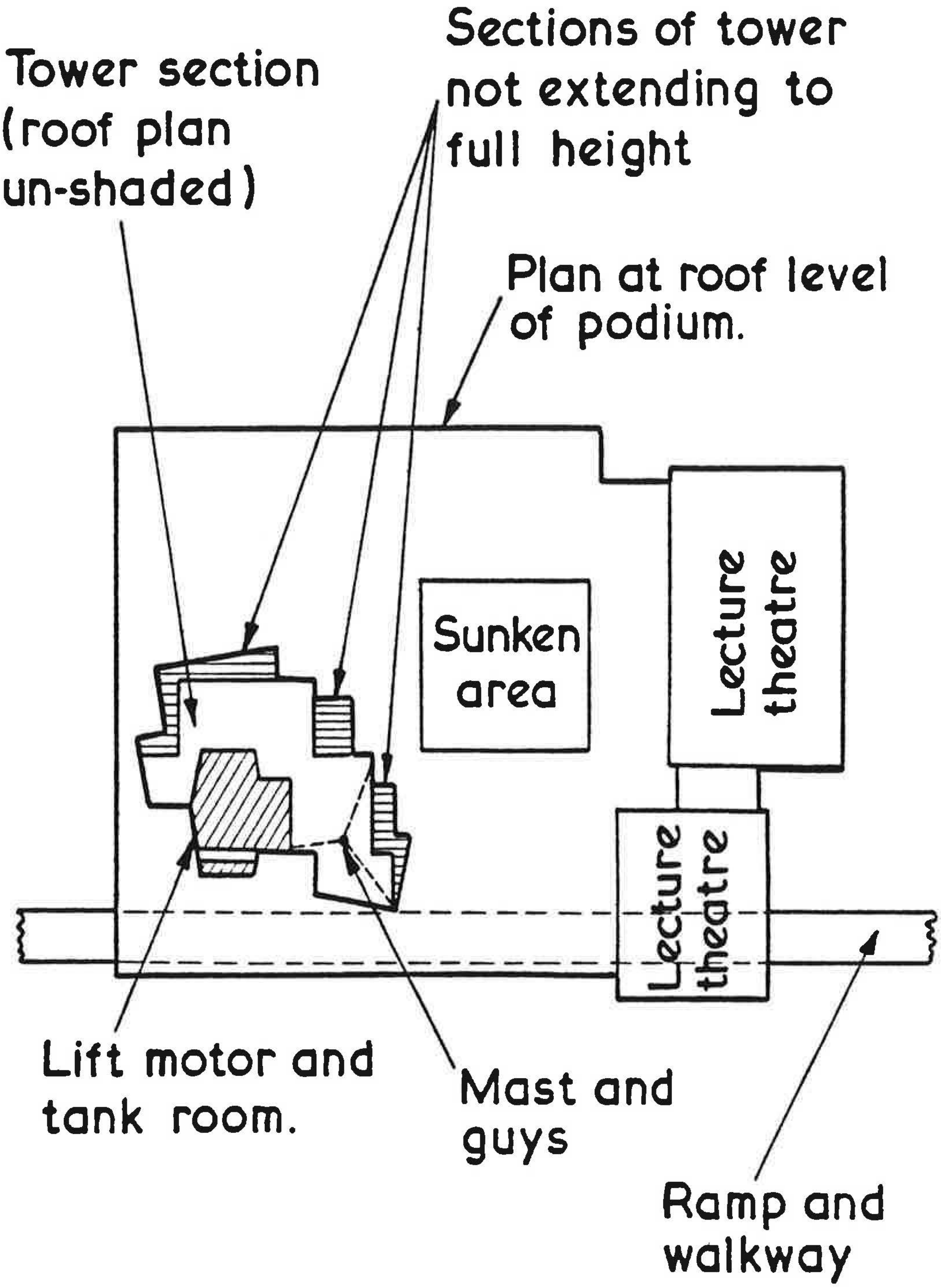


FIG.3. Roof Plan of Mathematics Building at Manchester University. The position of the instrument mast and guys is indicated.

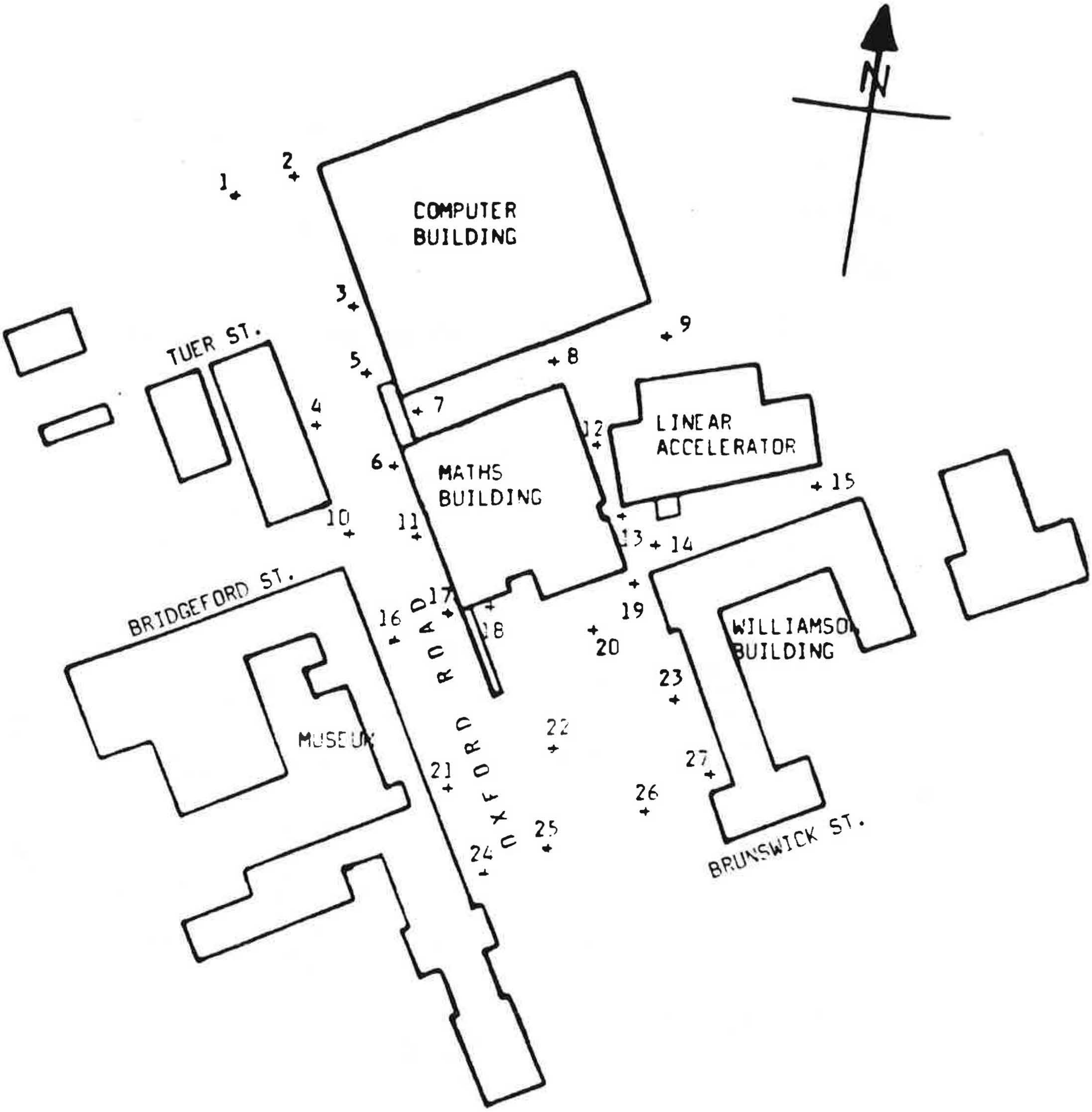


FIG.4. **PLAN OF THE AREA AROUND THE MATHEMATICS BUILDING SHOWING THE GROUND WIND SPEED MEASUREMENT STATIONS**

FIG.5. CHECK CALIBRATION OF PORTON WINDVANE VIA J.J.PLOTTER IN THE PLINT WIND TUNNEL AT BOLTON INSTITUTE OF HIGHER EDUCATION

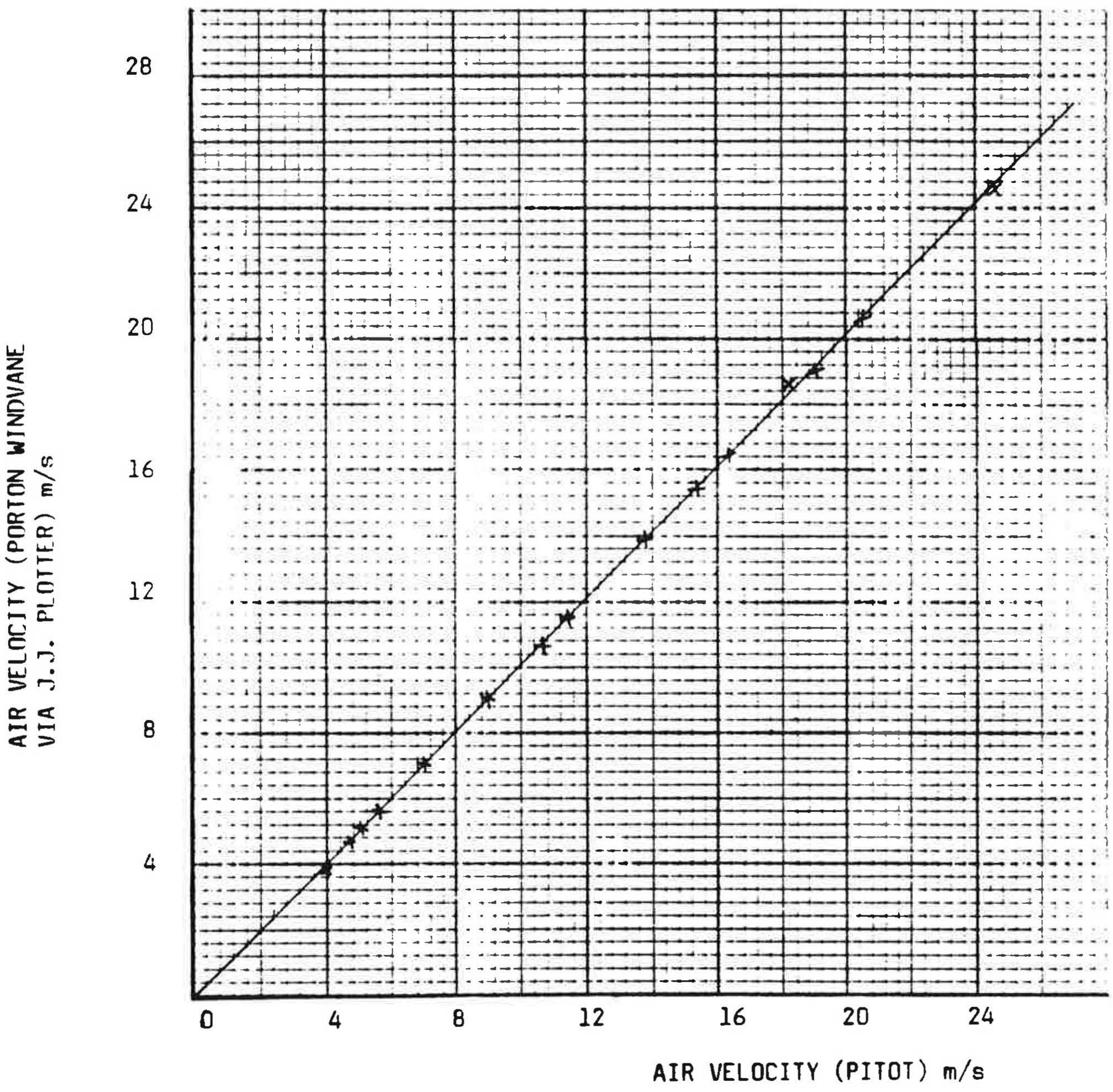
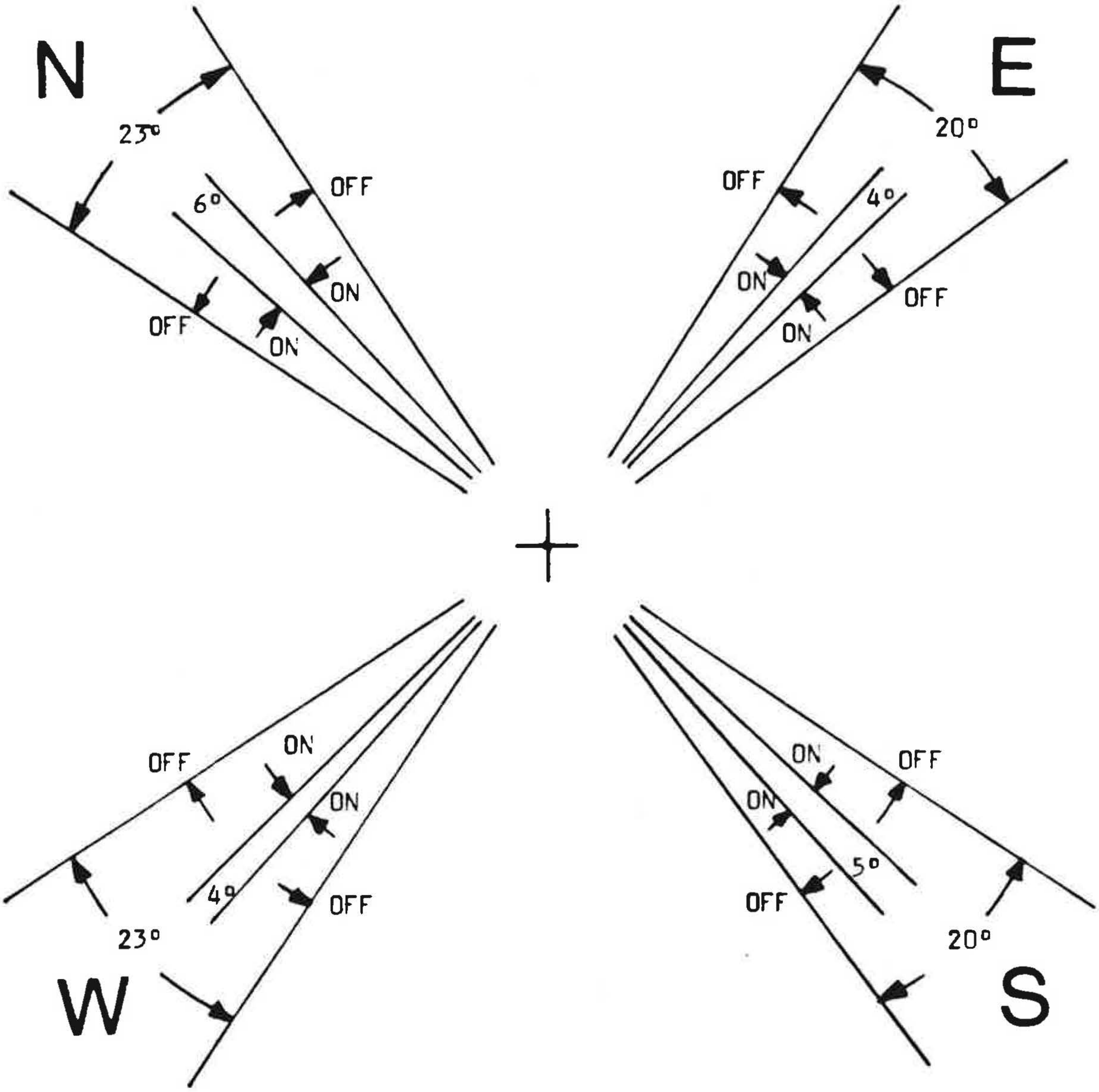


FIG.6. **Sensitivity Test on the Porton Wind Vane**



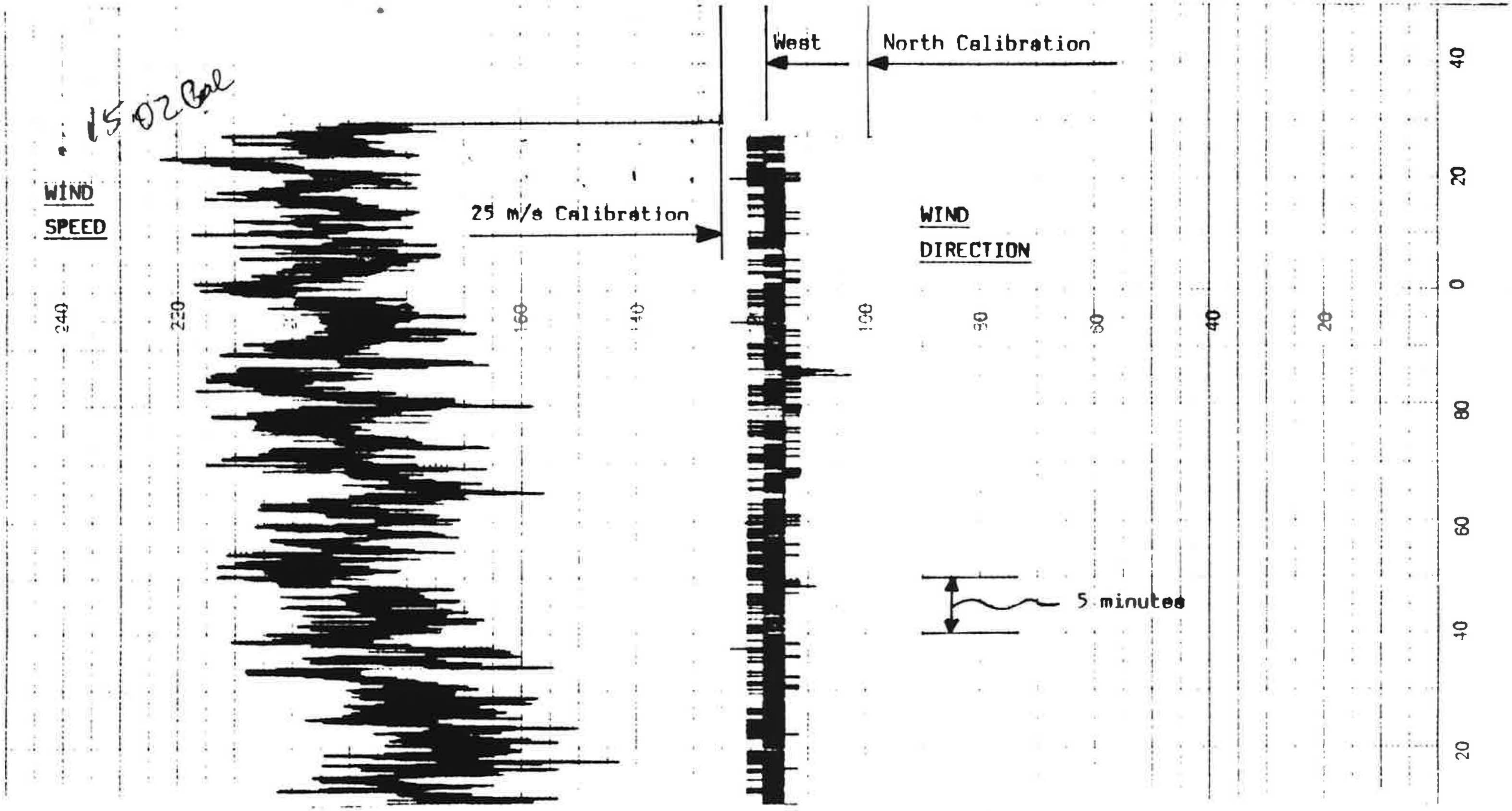


FIG.7. TYPICAL SAMPLE CHART OUTPUT FOR
MAST SPEED GREATER THAN 8 m/s - DIRECTION STEADY

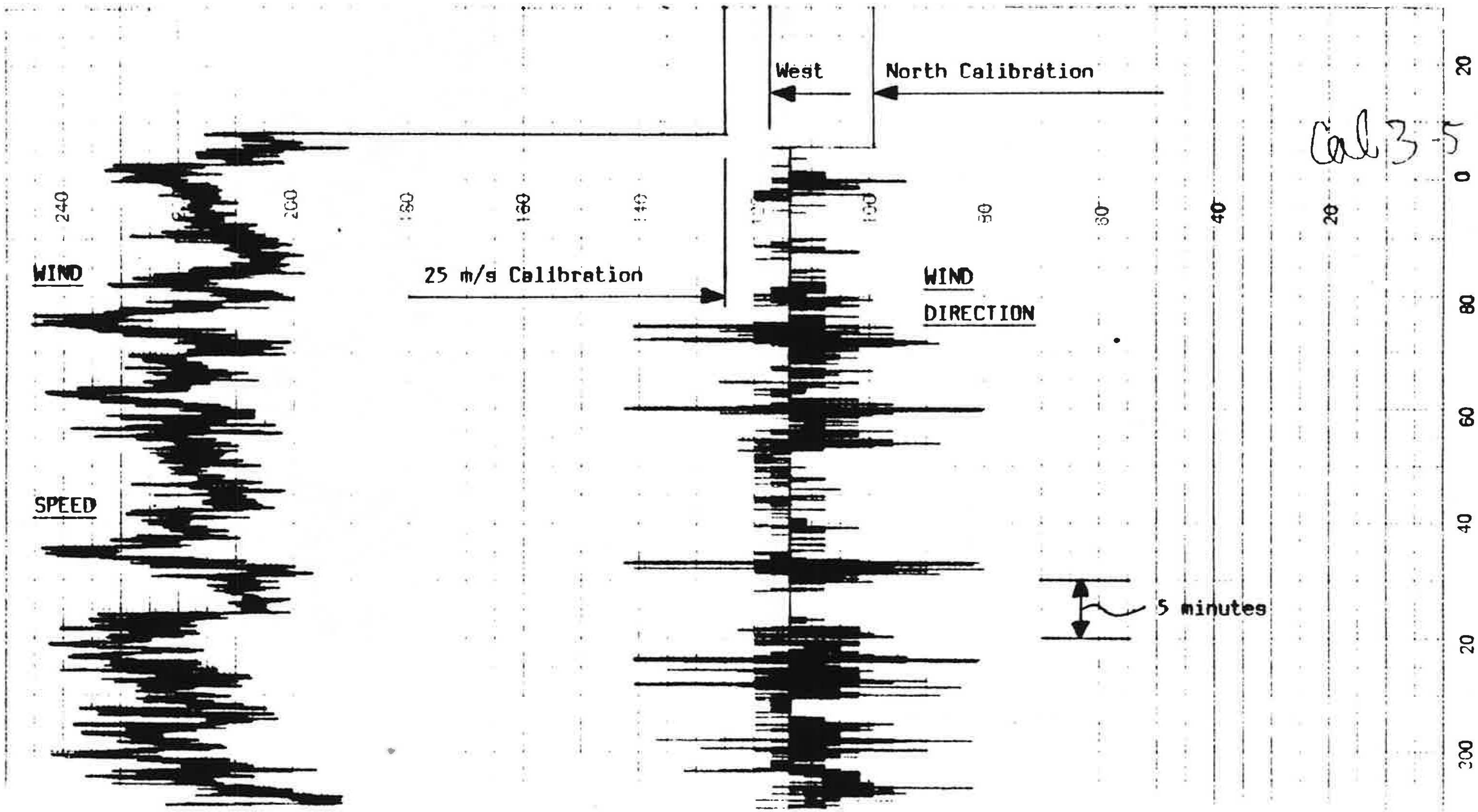


FIG.8. TYPICAL SAMPLE CHART OUTPUT FOR MAST SPEED LESS THAN 8 m/s
- DIRECTION UNSTEADY

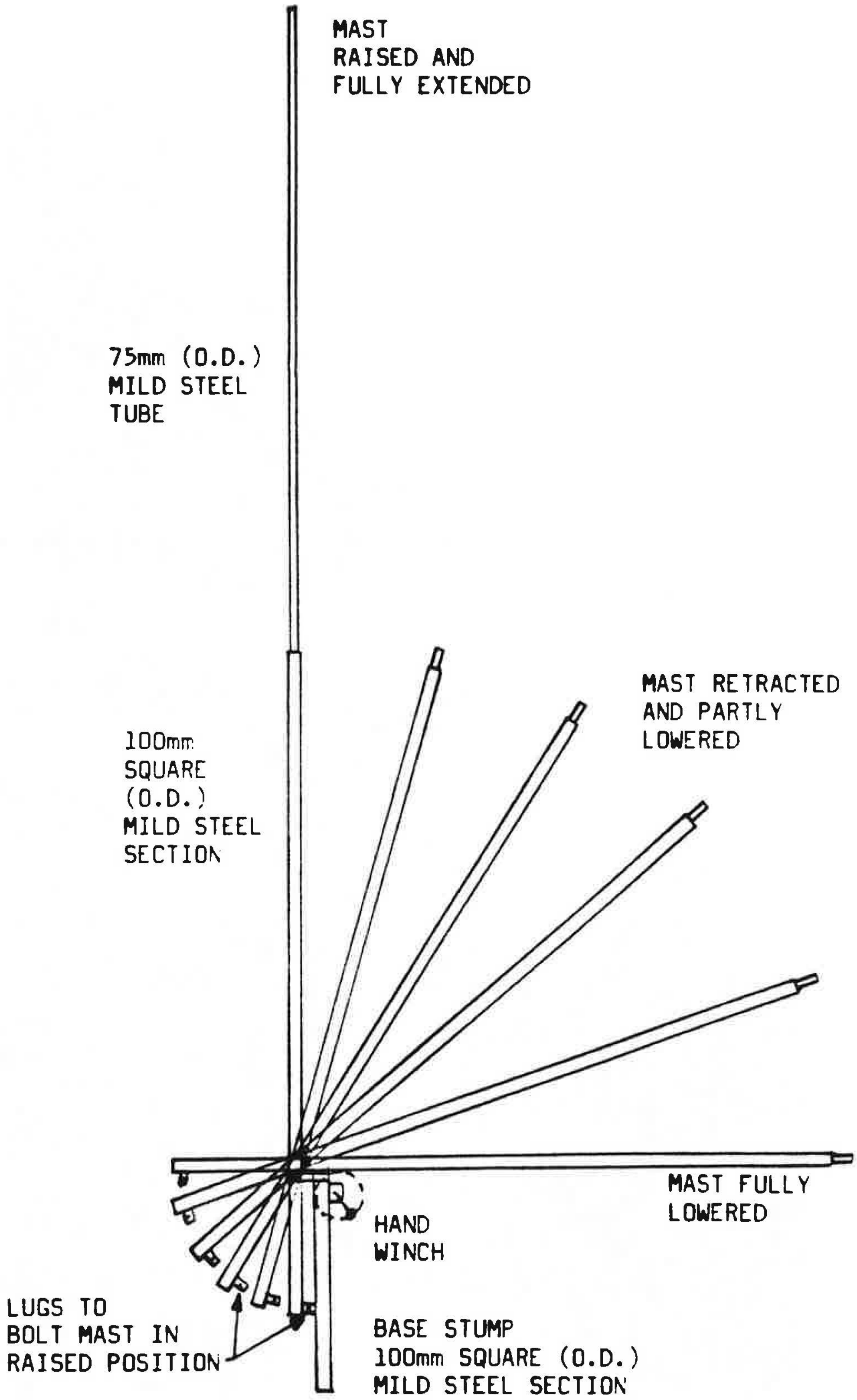


FIG.9. **THE WESTERN ELECTRONICS ULTIMAST**

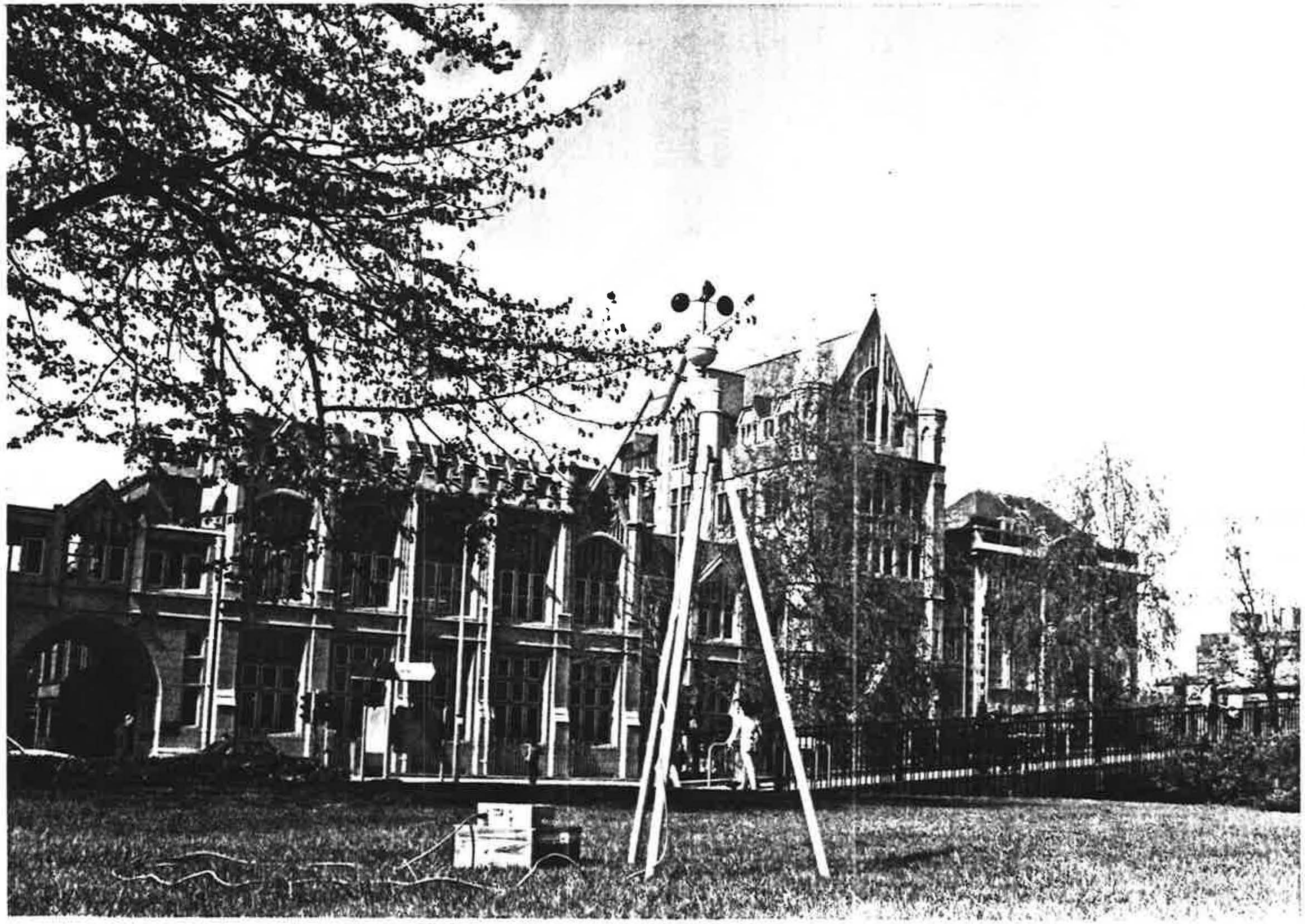


FIG.10. THE CASSELLA SENSITIVE CUP ANEMOMETER ON ITS ORIGINAL RIGID TRIPOD

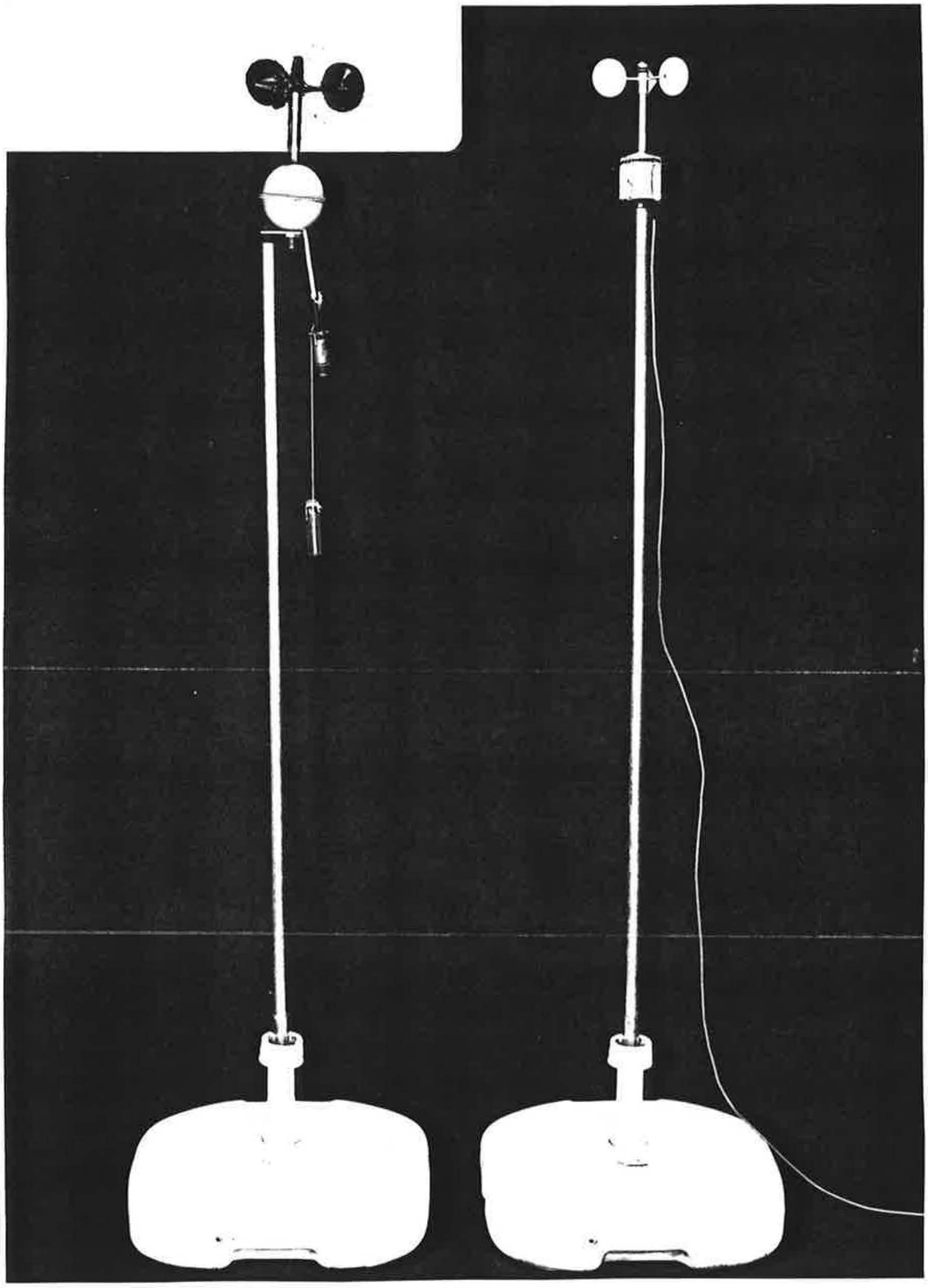


FIG.11. THE CASSELLA (LEFT) AND VECTOR (RIGHT) ANEMOMETERS MOUNTED ON THEIR NEW STANDS

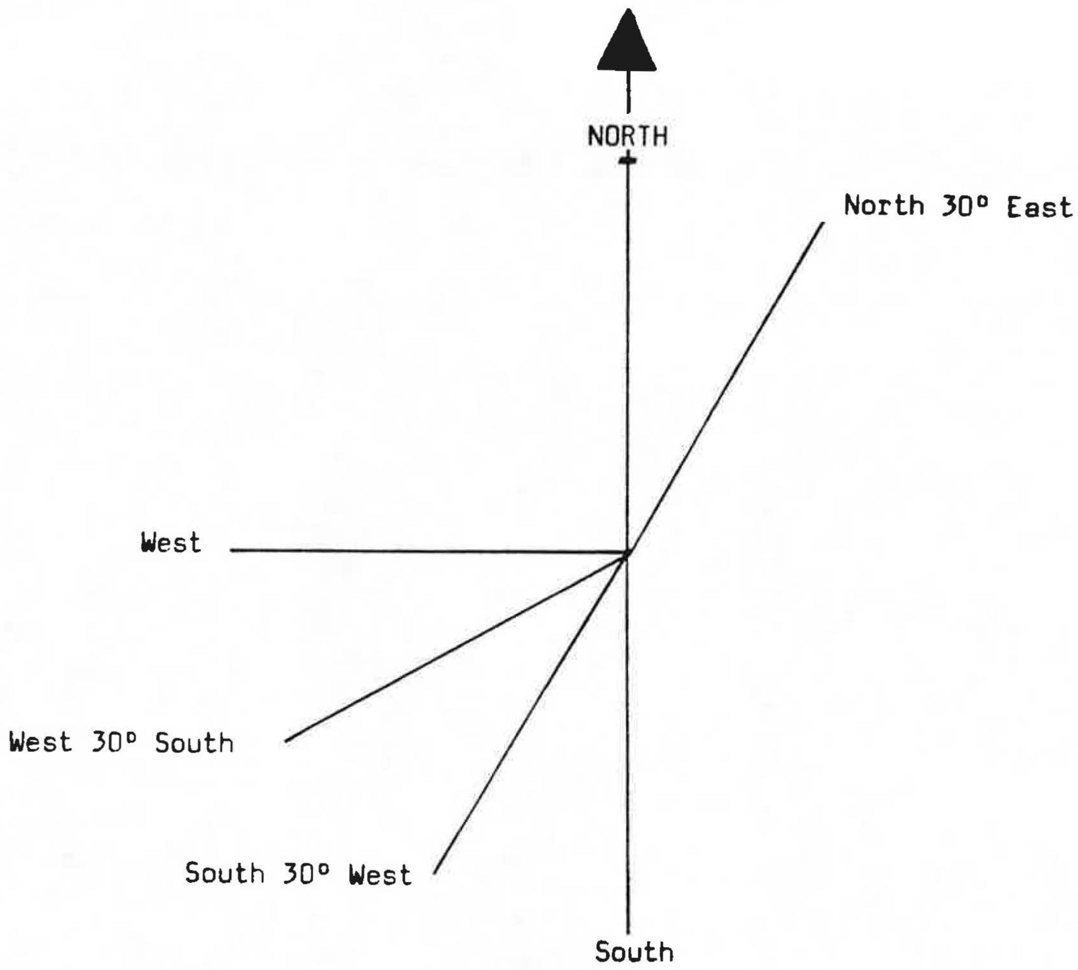


FIG.12. The Five Incident Wind Directions in which sufficient Full Scale Results were obtained to allow serious consideration as to their consistency.

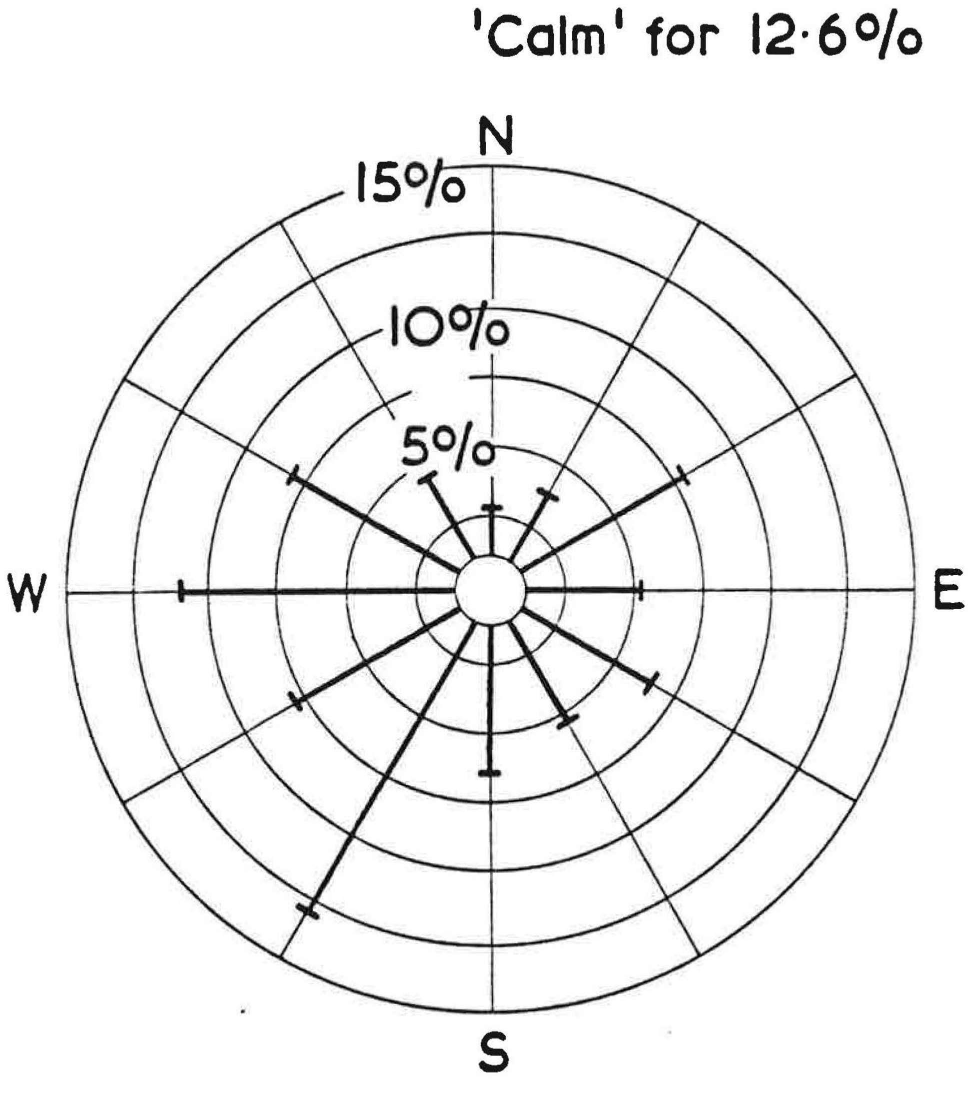


FIG.13. **Wind-rose Manchester (annual percentage frequency of wind direction)**

MEAN AND RANGE PLOTS

OF GROUND WIND RATIOS

(FIGS. 14 TO 18)

Points plotted above the full scale mean ratio lines represent full scale or wind tunnel ground wind ratios which are less than the full scale mean. Those below the mean lines represent ratios greater than the full scale mean. The vertical scale represents the relative magnitude of ratios at a rate of 2mm to 0.01 of ratio.

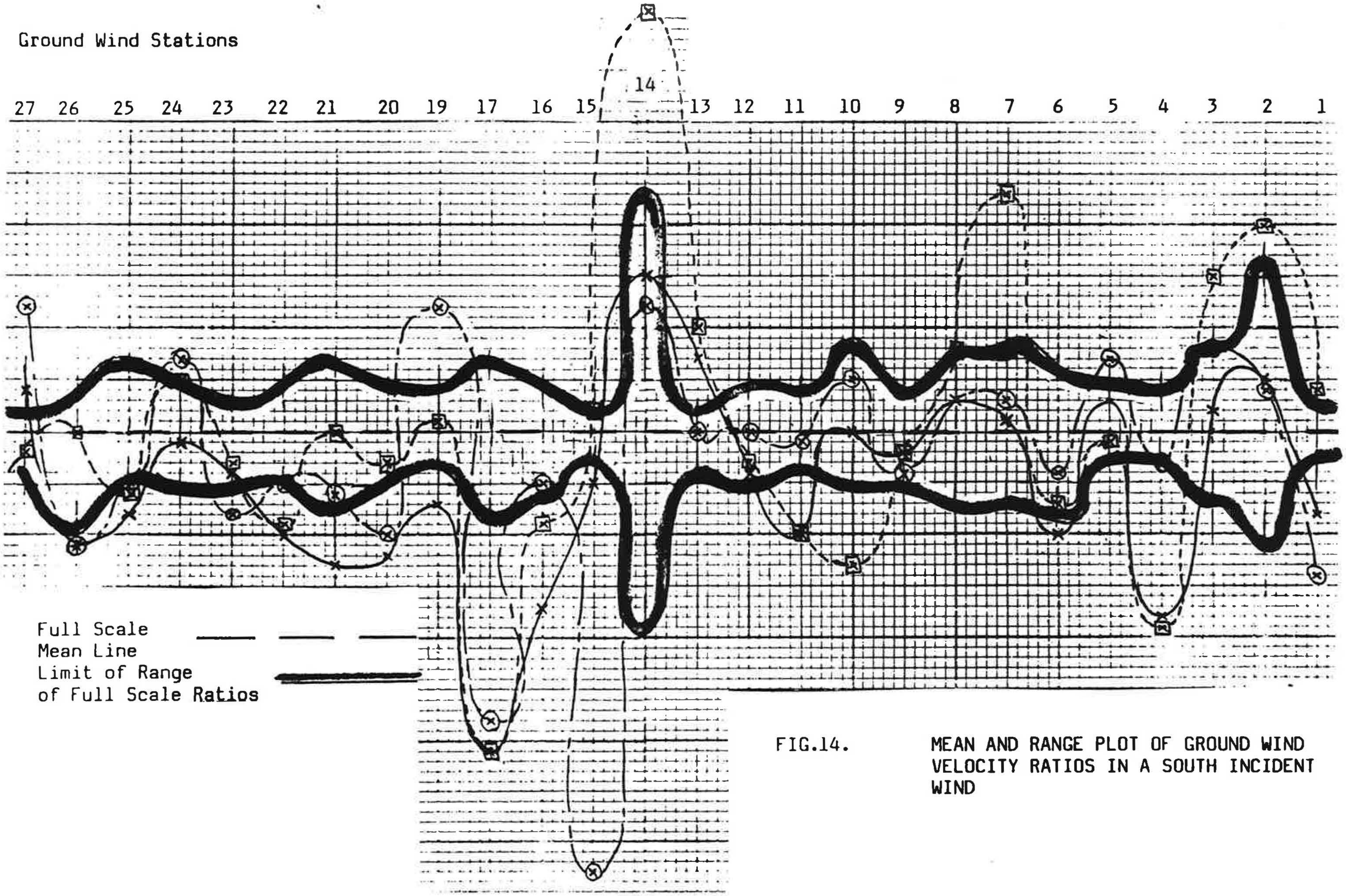


FIG.14. MEAN AND RANGE PLOT OF GROUND WIND VELOCITY RATIOS IN A SOUTH INCIDENT WIND

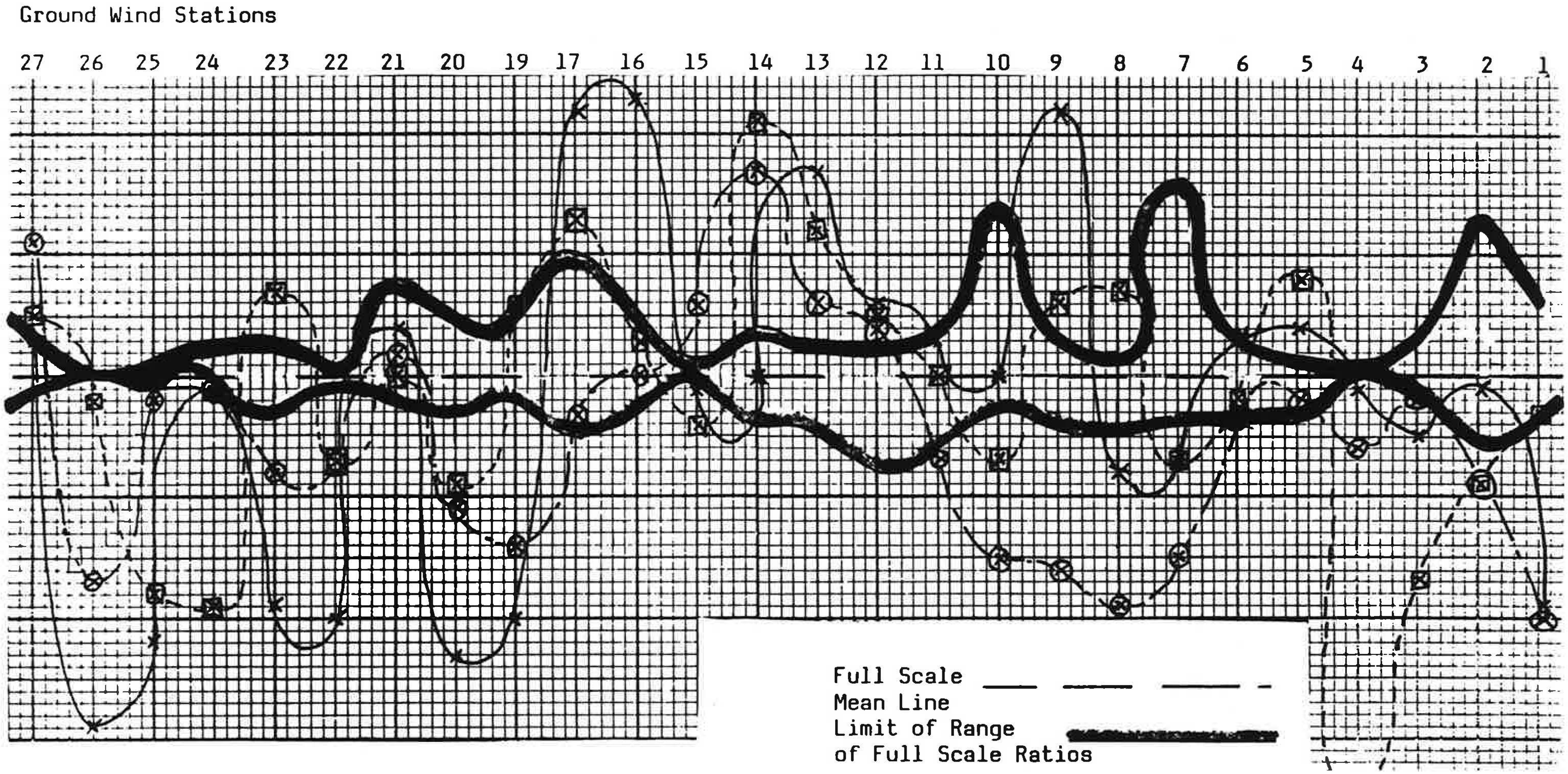
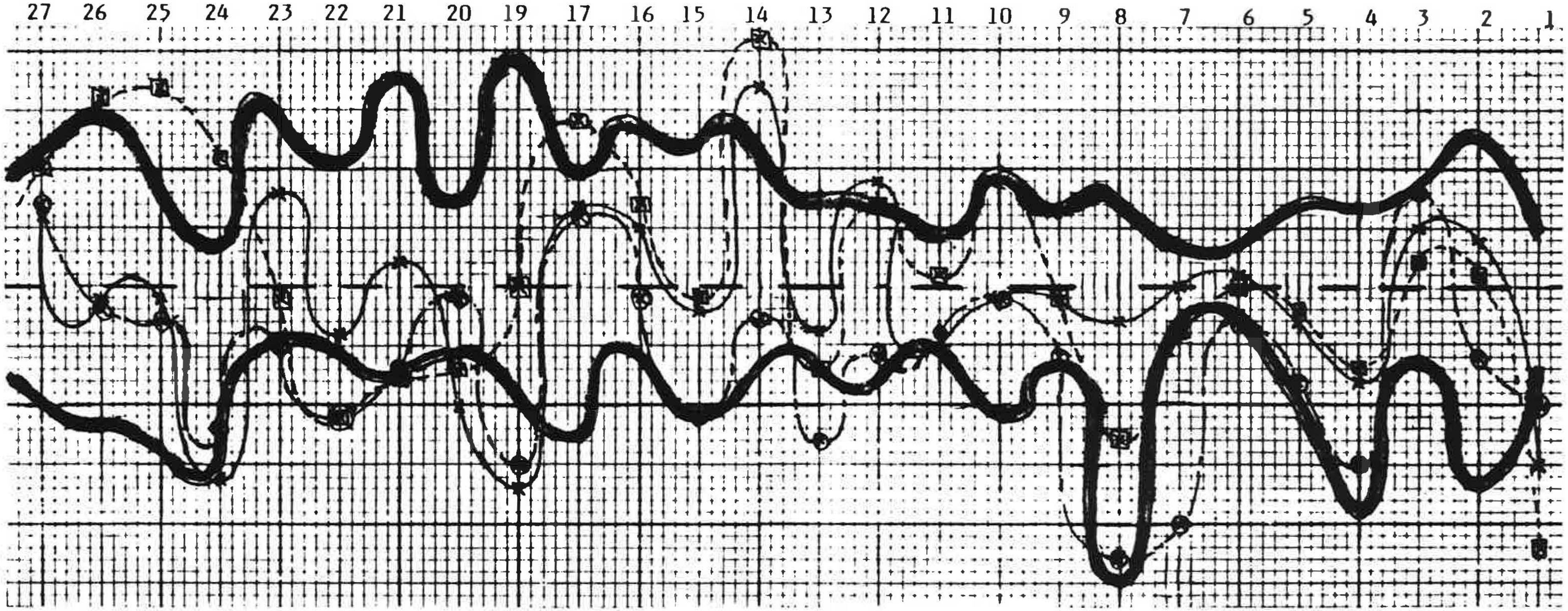


FIG. 15. MEAN AND RANGE PLOT OF GROUND WIND VELOCITY RATIOS IN A SOUTH 30° WEST INCIDENT WIND

Ground Wind Stations



Full Scale
Mean Line
Limit of Range
of Full Scale Ratios

FIG.16 MEAN AND RANGE PLOT OF GROUND WIND VELOCITY RATIOS IN A WEST 30° SOUTH INCIDENT WIND

35

Ground Wind Stations

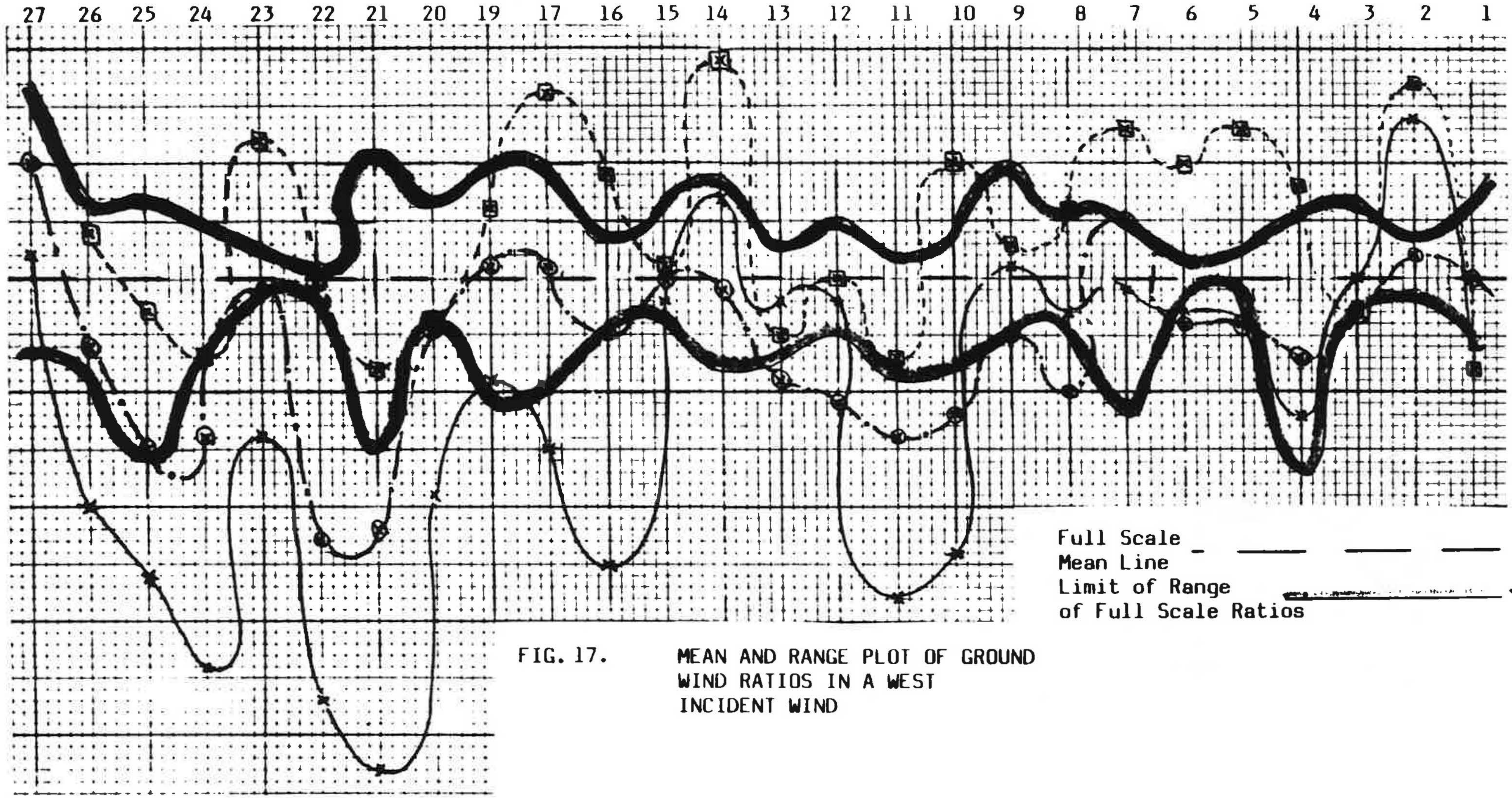
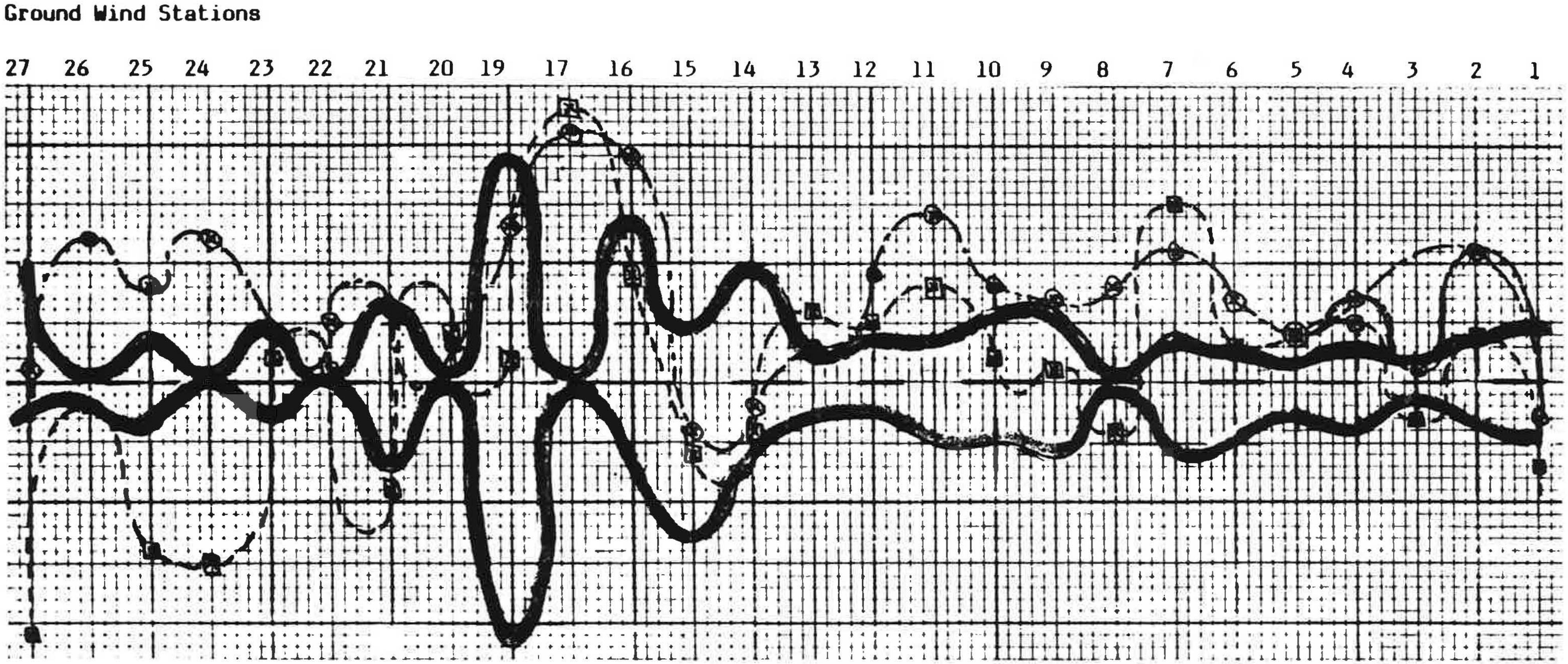


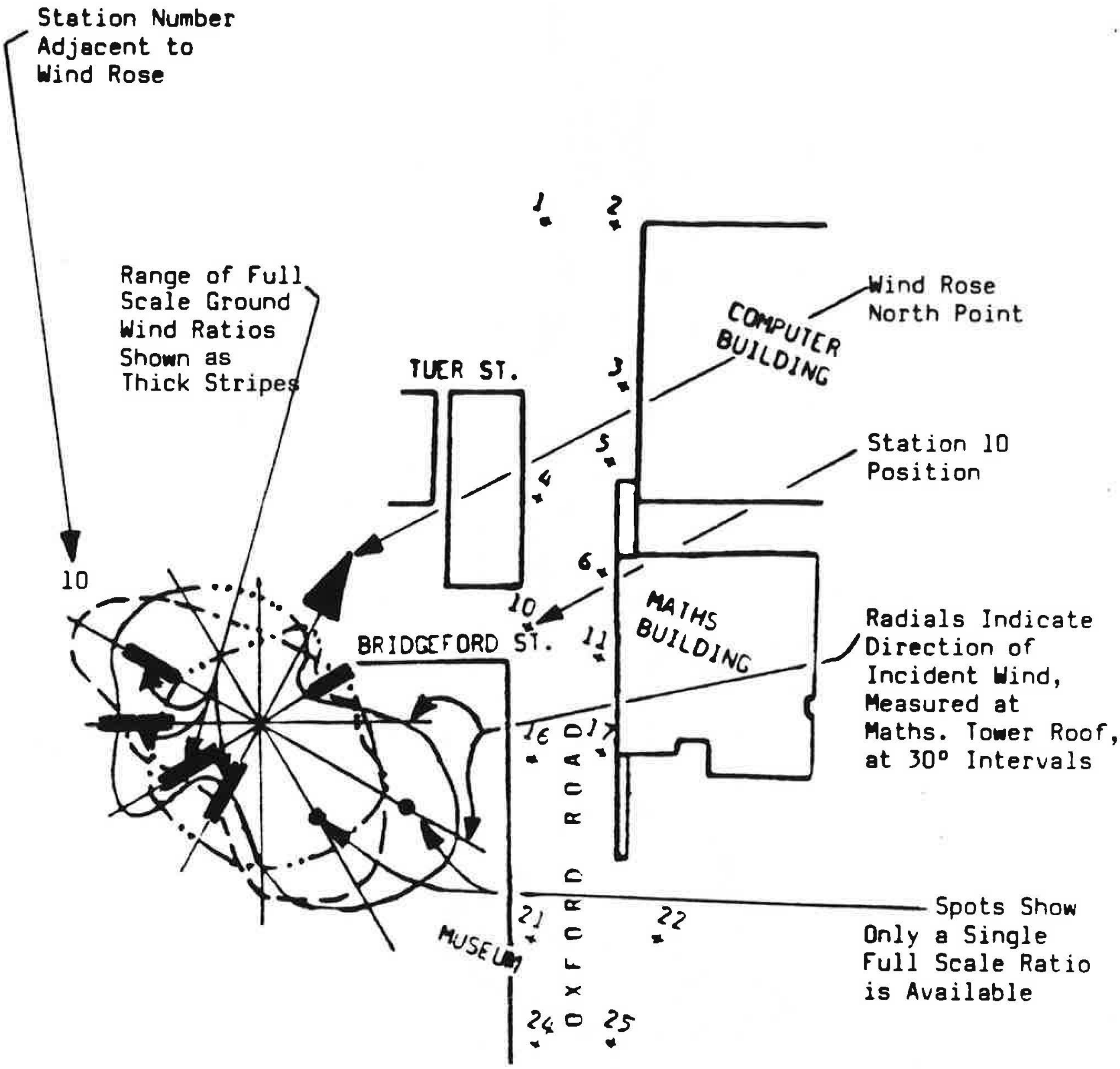
FIG. 17. MEAN AND RANGE PLOT OF GROUND WIND RATIOS IN A WEST INCIDENT WIND



Full Scale Mean Line — — — —

Limit of Range of Full Scale Ratios ———

FIG. 18. MEAN AND RANGE PLOT OF GROUND WIND RATIOS IN A NORTH 30° EAST INCIDENT WIND



Distance from the Wind Rose centre represents the Ground Wind Ratios at the rate of 1mm to 0.02 of Ratio.

FIG.19. KEY TO WIND ROSE FIGURES

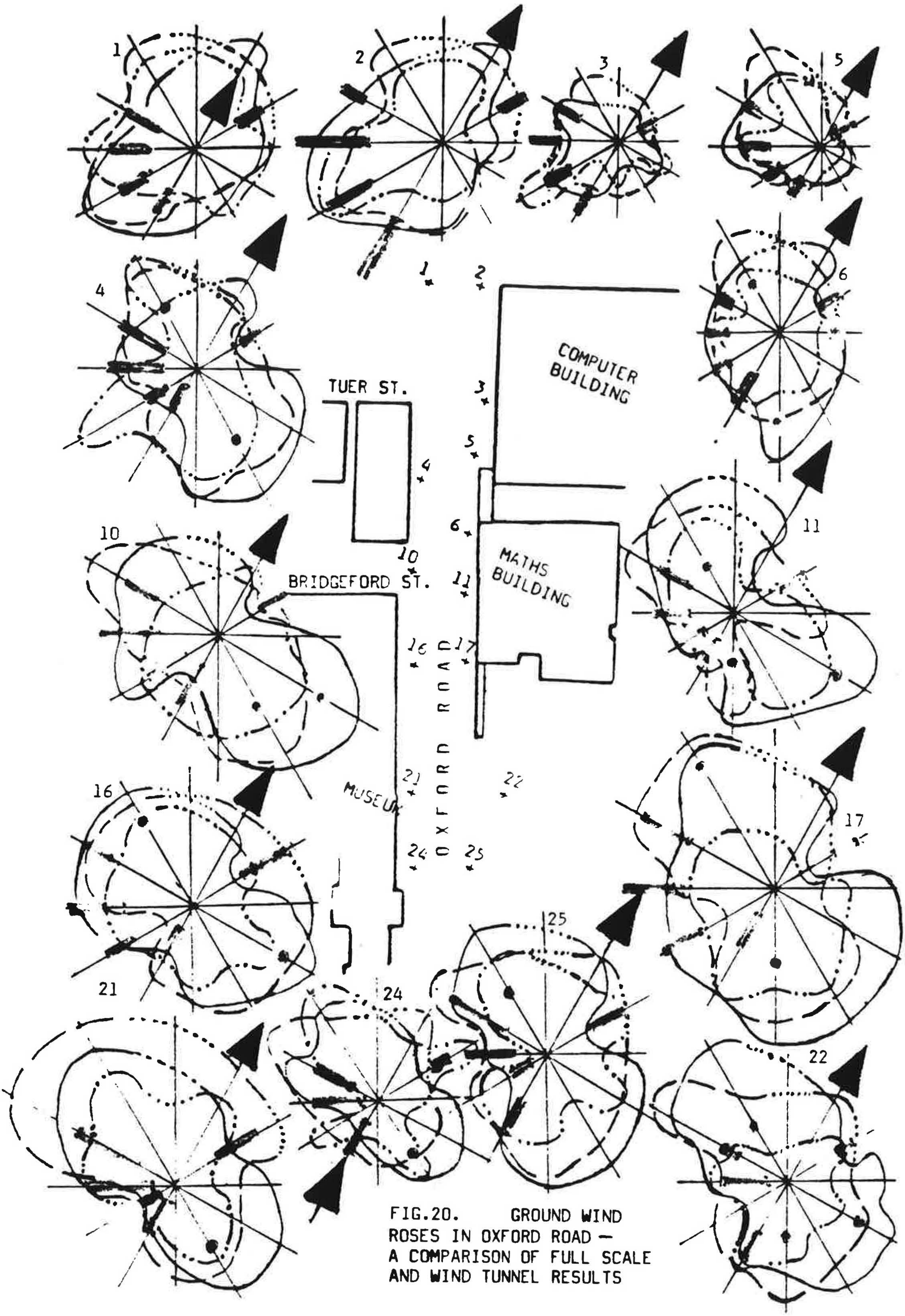


FIG.20. GROUND WIND ROSES IN OXFORD ROAD — A COMPARISON OF FULL SCALE AND WIND TUNNEL RESULTS

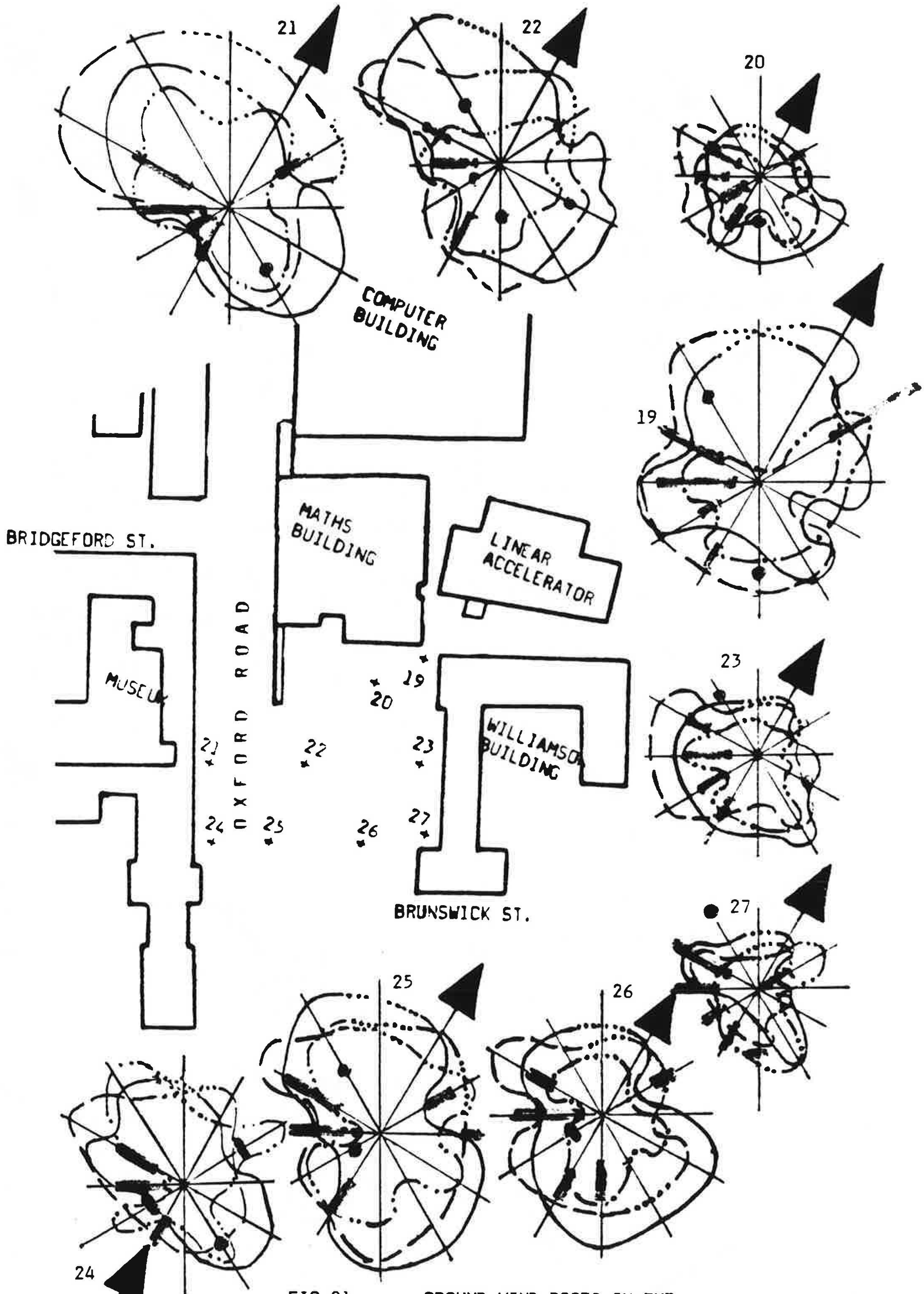


FIG.21. GROUND WIND ROSES IN THE MATHS BUILDING SOUTHERN FOREGROUND - A COMPARISON OF FULL SCALE AND WIND TUNNEL RESULTS

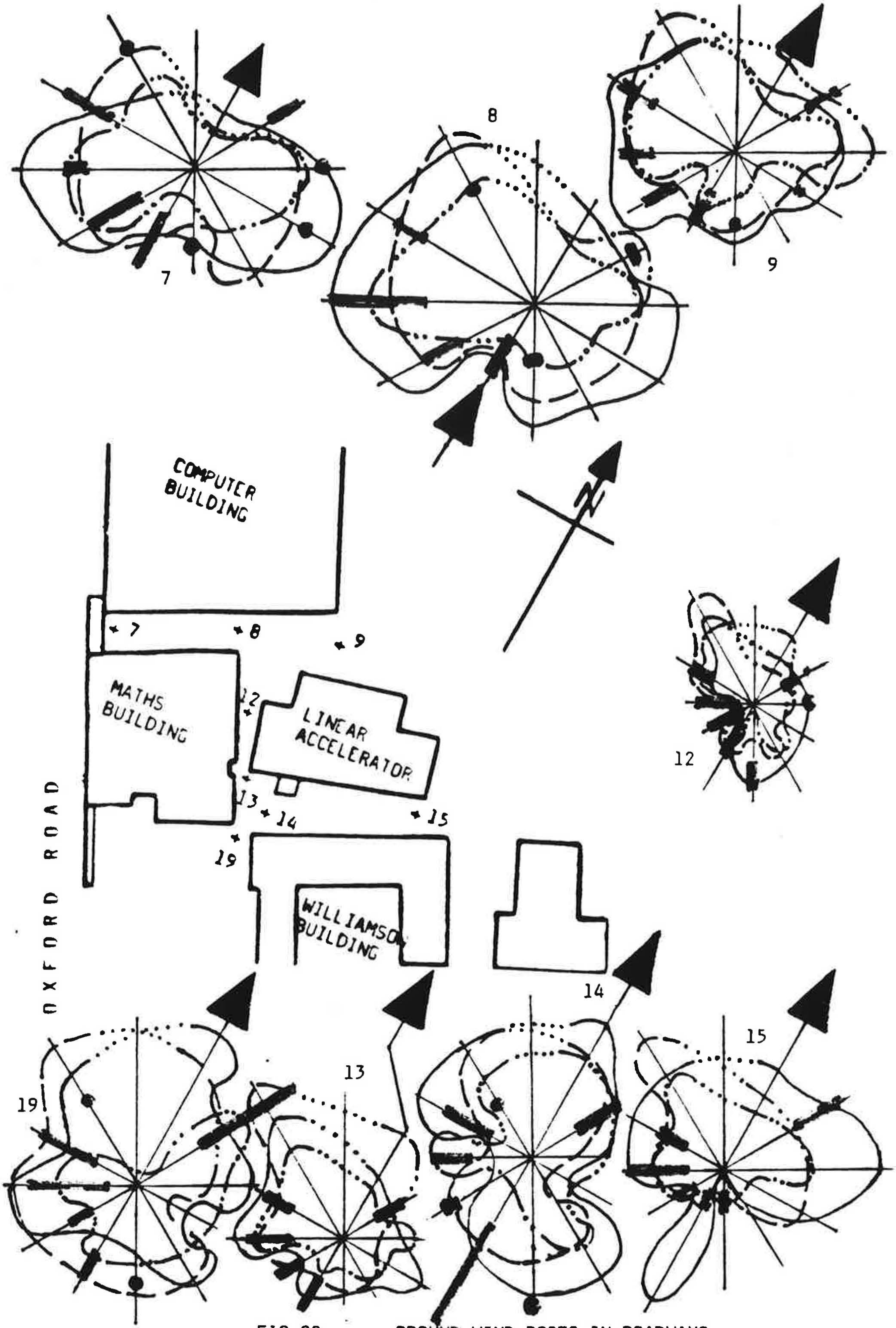


FIG.22. GROUND WIND ROSES IN ROADWAYS TO NORTH AND EAST OF THE MATHS BUILDING - A COMPARISON OF FULL SCALE AND WIND TUNNEL RESULTS