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J. C. Doran
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Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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SUMMARY

A series of wind velocity measurements upwind and downwind of the MOD-OA wind turbine at Clayton, New Mexico, was used to determine some of the characteristics of wakes within approximately two blade diameters of the machine. The magnitudes and shapes of the velocity profiles downwind of the turbine were compared with results obtained from a model described by Lissaman et al. (1982). Generally good agreement was obtained at speeds well below the rated speed of the MOD-OA, but the results were not as satisfactory for higher values.

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1. INTRODUCTION

While the use of single wind turbines may be sufficient for a number of applications, it is also likely that clusters of turbines will be required in many cases, particularly where relatively large amounts of electrical energy are required. The possibility of one machine interfering with the operation of another has led to the consideration of the characteristics of the wakes behind a turbine. Perhaps the principal questions are those concerning the magnitude of the velocity deficit behind a turbine and the distance required for the ambient wind to "recover" to some given percentage of its initial value.

Lissaman (1977) has developed a model describing some of the mean features of wakes behind turbines; wake fluctuations were not treated in his approach. A number of experimental studies have been carried out to test various aspects of this model, and a number of revisions have been incorporated based on these studies. Lissaman et al. (1982) give a good list of much of the experimental work in this area. One feature that is apparent is that there is a dearth of experimental tests of the model in actual field conditions such as might be encountered by a working turbine.

A MOD-OA turbine has been operated at Clayton, New Mexico, by the National Aeronautics and Space Administration (NASA) for the Department of Energy (DOE) since 1977. As part of their study of wind characteristics affecting turbine operation, Connell and George (1982) presented a study of a case in which a wake was measured at an array of towers downstream of the turbine. The emphasis in that report was on the structure of the wind field in the wake rather than on a comparison with wake models. In this report additional data are presented for a number of cases with a variety of wind conditions that resulted in wakes measured at the tower array or at two additional towers located on the other side of the MOD-OA, opposite the tower array. These data are compared with the model predictions, and an evaluation of the model's performance is given.

2. SITE AND INSTRUMENTATION

The MOD-OA turbine used in these studies is located on the outskirts of Clayton, New Mexico. The predominant strong winds at this site are from the southwest; in that direction the fetch is generally open desert with sparse vegetation consisting primarily of grasses. While the terrain is not perfectly level, elevation changes are generally quite gentle and small (<20 m in 3 km), and the topography would be described as simple by most observers. A plane array of seven towers, known as the vertical plane array or VPA, is located 76 m (4 rotor radii) to the southwest of the turbine; some of its features are described elsewhere (Connell and George, 1982). A line from the center tower of this array through the turbine lies on an azimuth of 205 degrees. The towers are placed to each side of this center tower at distances of 9.5, 16.4 and 19.1 m, corresponding to 0.5, 0.86 and 1.0 blade radii of the MOD-OA.

On the other side of the turbine, lying 76 m to the northeast on the same azimuth, is another tower. A final tower lies 19.1 m to the northwest of that, on an azimuth of 115 degrees. This pair of towers will be referred to simply as "the two towers" to distinguish them from the VPA. Figure 1 shows a diagram of the layout of the turbine, the towers and the VPA.

For winds coming from the northeast, such that the towers are upwind of the turbine, the fetch is not nearly as simple as that southwest of the VPA. A mixture of trees and houses in Clayton lies within a few hundred meters or less to the north and northeast. Although these obstacles are generally less than 15 m high, they could conceivably have some influence on the wind characteristics measured at the towers and even the turbine and VPA.

The instruments relevant to this study consist of Gill[a] propeller anemometers located at a height of 30.5 m on the VPA towers and the two towers to the northeast. This height corresponded to that of the nacelle of the

(a) R.M. Young Company, 2801 Aero-park Drive, Traverse City, MI 49684

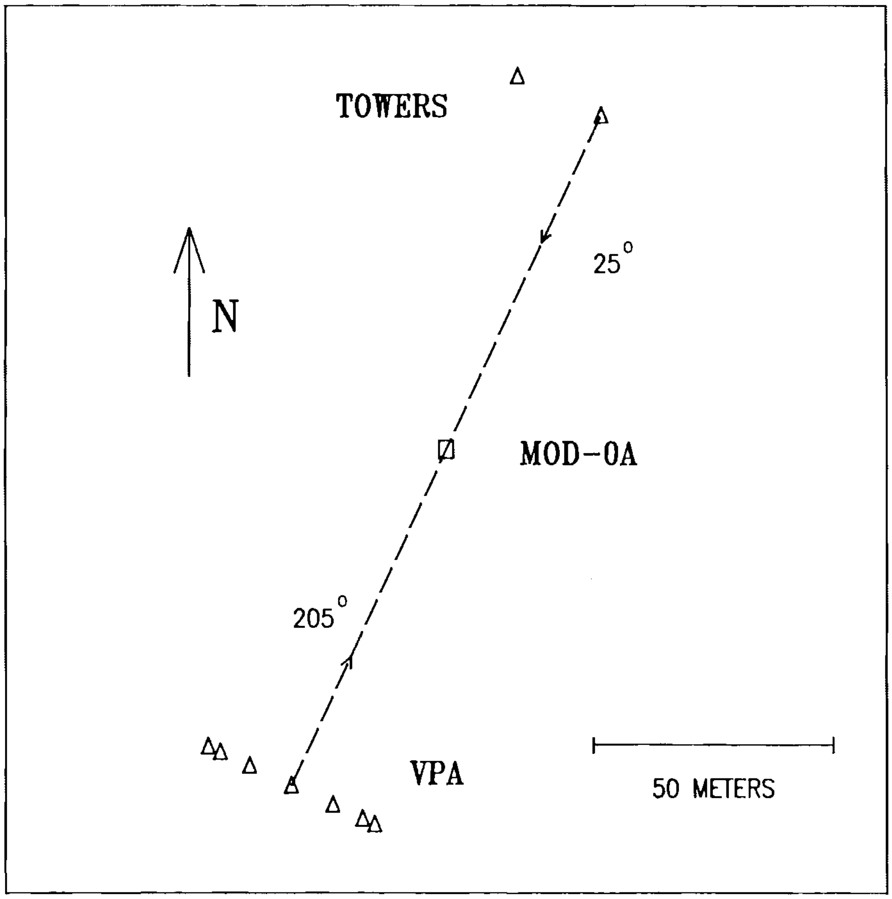

FIGURE 1. Schematic Diagram of Two Towers, Turbine and VPA at Clayton, New Mexico

MOD-0A. The anemometers were equipped with polypropylene propellers with a distance constant of 3 meters. Data were recorded on magnetic tape at a rate of four scans per second. In data processing, two successive scans were averaged, the recorded wind components were corrected for non-cosine response using the approach of Horst (1973), the mean wind direction was found at each anemometer location and the data series was then resolved into components along and perpendicular to the mean wind direction. Means were defined for 20-min periods. Fluctuations of the crosswind component were used to compute σ_v, the square root of the variance of the v component. The ratio $\sigma_v/\overline{U}$, where $\overline{U}$ is the mean wind speed, is called the turbulent intensity in this report. This differs from the more usual definition, $\sigma_u/\overline{U}$, but is justified by noting that it is the parameter describing the ambient turbulence structure required by the Lissaman model.

In some applications of the model, the turbulent intensity is not known. It may be inferred from a measurement or estimate of the atmospheric stability, but such an approach introduces an additional source of uncertainty. For the measurements reported here, no stability estimates were available, but the direct determination of σ_v made such estimates unnecessary.

The wind directions derived from the "upwind" instruments and the instruments in the wake of the turbine differed by less than 4 degrees on the average. This is about the estimated accuracy to which the arms of the anemometers were aligned, and should not be a source of significant difficulty in the succeeding data analysis. Connell and George (1982) have noted the possibility of tower shadow effects influencing the results for certain wind directions. Such effects are not obvious for the directions chosen in this report, but there is no way of ensuring that such effects are totally absent.

Several calibration runs were made during which the turbine was not operating for one reason or another. These measurements provided an opportunity to test whether the anemometers at the various towers gave comparable values of speed in the absence of wake effects. The results were generally quite good, and provide an estimate of the relative accuracy that can be expected between various instruments. It is well known, however, that Gill anemometers are susceptible to performance degradation after prolonged operation in dusty or extreme environments. In a number of instances one or more components on the anemometers failed. It is believed that the data finally chosen were not obtained with defective instruments, but no simple tests are available to assess anemometer performance <u>in situ</u>. By noting the dates of the various calibration runs given in Section 4, however, some confidence can be obtained that the wake cases presented were chosen from periods when reliable data were being recorded.

3. WAKE MODEL

A computer code called WAKEWIND was used to model the wake behind the Clayton, New Mexico, wind turbine using the approach reported by Lissaman et al. (1982). This model is based on observations of co-flowing jets in fluids as reported by Abramovich (1963). Abramovich's results were obtained in a non-turbulent fluid, and Lissaman's principal contribution has been to include the effects of ambient turbulence in an ad hoc fashion. Later modifications introduced additional effects arising from the profile drag of the turbine, and WAKEWIND incorporates all of these features. Details of the wake model can be found in Lissaman et al. (1982) and Eberle (1981). Eberle arrived at a somewhat different formulation from that used by Lissaman, but the effects incorporated are essentially the same, with one exception that will be noted later.

The model treats three different regions of the wake: near, far and a transition region connecting the two. The near wake includes a core region with a constant velocity equal to that immediately behind the turbine. The radius of this core decreases linearly with downstream distance and the downwind extent of the near wake is defined by that distance at which the core vanishes. The growth of the wake is determined by both ambient and machine-generated turbulence. The velocity profile in the near wake is an empirical function of radial distance from the center of the wake normalized by the local wake radius. A different velocity profile is observed further downstream in the far wake, but it is also a function of the normalized radial coordinate. In the far wake, the wake growth is controlled by turbulence alone. A transition region connects the near and far wakes.

A principal input to the model is the ratio m of the upstream wind speed to that immediately behind the turbine. All of the empirical results reported by Abramovich depend on this ratio. The velocity ratio m is uniquely related to the axial induction factor, which depends, in turn, on the aerodynamic efficiency of the wind turbine.

The initial wake radius is found by assuming that the wind speed at the turbine is the mean of the upstream and downstream values and by conserving mass as air passes the turbine. The downstream value is defined here as the wind speed immediately behind the turbine. The wake radius at the end of the near wake is determined by a momentum balance, using the empirical velocity profile with no core region and a centerline wind speed equal to that immediately behind the turbine.

The rate of growth of the near wake, from its initial to its final radius, determines its downwind extent. Abramovich's data only include the growth due to mechanical turbulence generated by the shear in the wake itself. Lissaman added the growth due to ambient turbulence and turbulence produced by the profile drag of the turbine blades. The resultant growth rate is assumed to be the Pythagorean sum of the individual growth rates.

The growth of the far wake is assumed to be dominated by the effects of ambient turbulence. By equating the mass flux for the co-flowing jet velocity profile observed by Abramovich with that for a Gaussian profile as observed for turbulent diffusion of a passive substance, Lissaman finds the growth rate dr/dx due to ambient turbulence to be equal to 2.8 times the turbulence intensity; r is the wake radius while x is the downstream distance. Although the wake model uses the Abramovich profile for the far wake, the two profiles are quite similar.

A transition region connects the near and far wakes. The wake radius at the far end of the transition region is determined by a momentum balance in the same manner as the radius at the end of the near wake, again assuming a centerline velocity equal to that immediately behind the turbine but using the velocity profile observed in the far wake. The downwind extent of the transition region then follows from the assumption that the growth rate is equal to that of the near wake. The velocity profile in the transition region is a linear combination of those in the near and far wakes.

In summary, WAKEWIND predicts three principal features: magnitude, shape, and dimensions. The magnitude of the velocity deficit depends solely of the velocity ratio m and the conservation of momentum. The shape of the velocity profile is determined by the co-flowing jet observations reported by Abramovich. The dimensions of the wake are determined by Lissaman's *ad hoc* extension of Abramovich's data for a non-turbulent fluid to include the effects of ambient turbulence and turbulence produced by the turbine blades.

Lissaman et al. (1982) note that in an earlier version of their model the effect of viscous drag caused by the rotor was neglected, and Eberle's model (1981) leaves out this effect as well. Figures 2 and 3 show some comparisons of the Eberle model, and the Lissaman model with and without viscous drag. Eberle's model shows a somewhat more extended potential core region with correspondingly greater velocity deficits close to the turbine in the transition region. The models all show generally similar behavior well downstream of the machine.

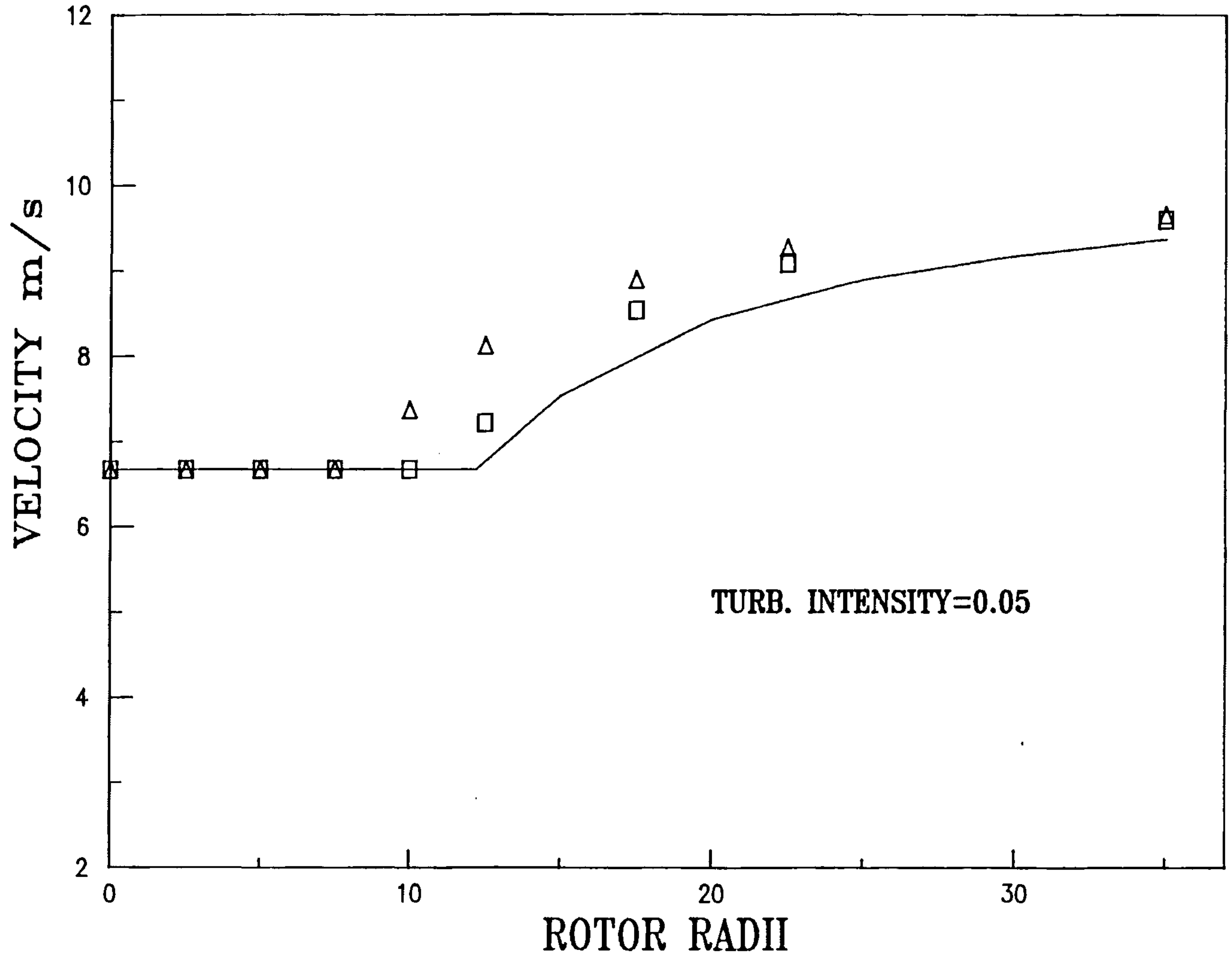

FIGURE 2. Comparison of Eberle's Model (—) and Lissaman's Models: With Viscous Drag (Δ), Without (□). Turbulent intensity = 0.05.

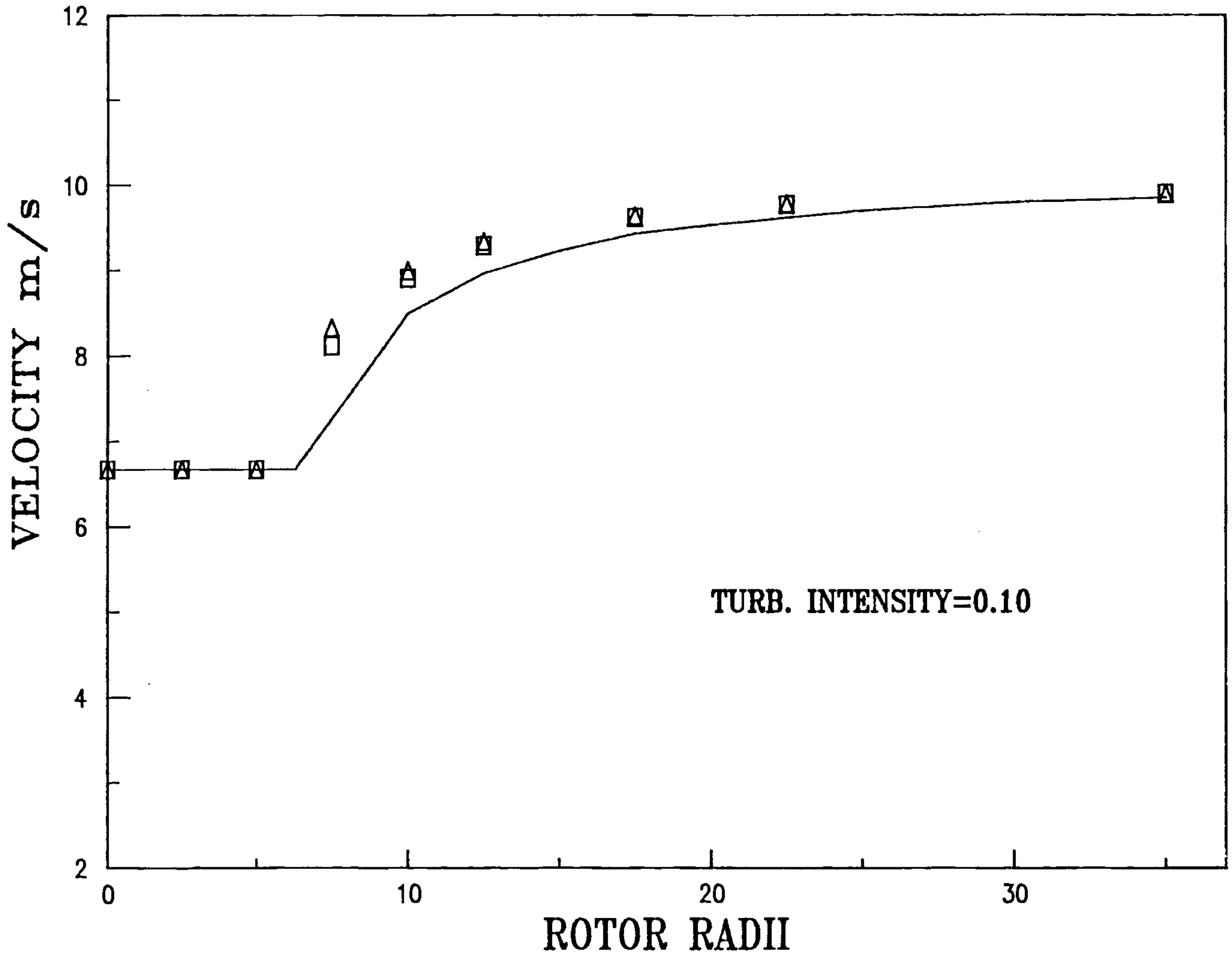

FIGURE 3. Comparison of Eberle's Model (—) and Lissaman's Models: With Viscous Drag (Δ), Without (□). Turbulent intensity = 0.10.

4. RESULTS

For the cases discussed in this report, the velocity profiles were computed along a horizontal line containing the downwind anemometers, i.e., along a line running through the VPA for winds from the northeast and along a line containing the two towers for southwesterly winds. The input parameters were the incident wind speed, direction, and turbulent intensity, obtained from one or more of the upwind anemometers. The axial induction factor was obtained from a tabulation provided by T. Richards of NASA/Lewis Research Center, as were the profile drag coefficient and blade solidity. No attempts have been made to adjust the model to produce a best fit to the data, nor have any "corrections" been applied to the data.

Several criteria were used in selecting data periods to be analyzed. The primary one, of course, was that the wind blew in a direction such that a wake could be observed at the downstream towers. A second criterion was relative stationarity of the wind speed during the 20-min averaging periods. Some effort was also made to choose times that provided a range of operating conditions for the MOD-OA.

Table 1 gives a summary of the cases studied. The wake regions given in the last column are determined from the model calculations and not the measurements. The times shown are the starting times of the 20-min averaging periods. Those cases with zero power were used as calibrations to evaluate the performance of the anemometers by comparing the indicated speeds at the upwind and downwind towers. Their behavior is shown in Figures 4 through 8. In each figure the solid line is the speed determined from one or more upstream anemometers, while the squares are the speeds recorded by the downstream instruments. Figures 9 through 20 give the behavior observed during wake periods. In these figures the solid line corresponds to the predictions of the Lissaman model, while the squares denote the observations. Each model prediction shows a region of constant speed at the edges of the wake; this speed is simply the value obtained from the upwind anemometer(s) and is one of the input variables in the model. The abscissas have units of rotor radii. They are measured either along the line joining the two towers to the northeast of the turbine or the line passing through the VPA towers. The zero point is located either at the more eastern of the two towers or at the center tower of the VPA, respectively. In all cases, the values depicted in the figures are shown as an observer would see them if looking from the southwest toward the northeast.

A few general features are apparent. For northeasterly winds the model predictions are quite good, both in the predictions of the velocity deficit and in the shape of the profile. The agreement for southwesterly winds is not quite as satisfactory, although the general features of the wake are reproduced reasonably well. The latter cases correspond to higher wind speeds than do the former cases, and it is possible that the axial induction factor is not as well-known for this range. For the case of May 10, 1982, it is also possible that the data from the downwind anemometers were beginning to deteriorate; some problems in their circuitry were discovered a few weeks later. However, similar discrepancies between model and measurements were seen on April 23, 1982, and May 3, 1982. On this second date, a temporary shutdown of the turbine permitted a calibration to be made, and the calibration showed very good agreement among the anemometers.

Unfortunately, the VPA and tower instrumentation were not functioning properly during those rare occasions when northeasterly winds in the range of 10 m/s or higher occurred. There was an opportunity on May 30, 1982, but the anemometers on the upwind towers were not functioning properly. Attempts to use one of the VPA towers at the edge of the wake to obtain ambient wind conditions were not satisfactory. The two anemometers presumed to be outside the wake gave slightly different wind speeds and direction, and the resultant wake predictions using each in turn were sufficiently different as to preclude confidence in either. Moreover, the shape of the wake profile differed significantly from the predicted shape, the only cases in which such behavior was observed to occur. In view of this, further analysis of this case was dropped.

For northeasterly winds, the discrepancies that do exist show a slight tendency for the modeled wake to overestimate the velocity deficit derived from the actual measurements. For the higher, southwesterly winds the tendency is reversed, with the model generally giving underestimates of the velocity deficit. It is difficult to evaluate the relative merits of the Eberle model and the two Lissaman models (with and without viscous drag) using such a limited data base. From a practical standpoint there is relatively little difference between them, since a machine is unlikely to be located closer than several blade diameters downwind from another machine. Within the experimental accuracy obtained in these measurements, the Lissaman model seems to provide a reasonable representation of the measured wake behavior. However, further study of wake characteristics at the higher wind speeds, as well as studies at larger downstream distances, is indicated.

TABLE 1. Summary Description of Some Features of the Cases Selected for Wake or Calibration Measurements

Date	Time	Incident Speed (m/s)	Incident Angle (deg)	Turbulent Intensity	Power (kW)	Nacelle Angle (deg)	Wake Region[a]
12/23/81	12:17:55	4.22	21	0.18	0	0	9
12/23/81	12:39:55	4.14	34	0.17	0	0	9
01/06/82	17:19:48	5.67	23	0.13	62	20	4
01/06/82	17:41:48	6.43	21	0.13	105	16	3,4
01/06/82	18:47:48	5.76	21	0.12	53	15	3
01/12/82	15:11:56	5.83	37	0.15	64	31	4
01/12/82	15:55:57	6.74	38	0.11	103	31	3
03/22/82	11:12:42	7.44	206	0.18	89	194	4
03/22/82	16:32:49	9.66	192	0.12	162	184	3
03/29/82	12:08:44	15.25	191	0.12	0	175	9
03/29/82	13:14:45	16.48	202	0.16	0	195	9
04/23/82	15:20:40	10.28	202	0.15	156	184	4
04/23/82	16:48:40	12.26	190	0.087	197	186	3,2
05/03/82	10:44:38	8.17	193	0.21	111	193	4
05/03/82	14:02:40	9.71	209	0.28	0	0	9
05/10/82	15:55:23	11.93	202	0.20	196	212	4
05/10/82	18:07:24	11.23	200	0.095	198	209	3

(a) Key
- 9 = outside wake
- 1 = potential core
- 2 = near wake, outside potential core
- 3 = transition region
- 4 = far wake

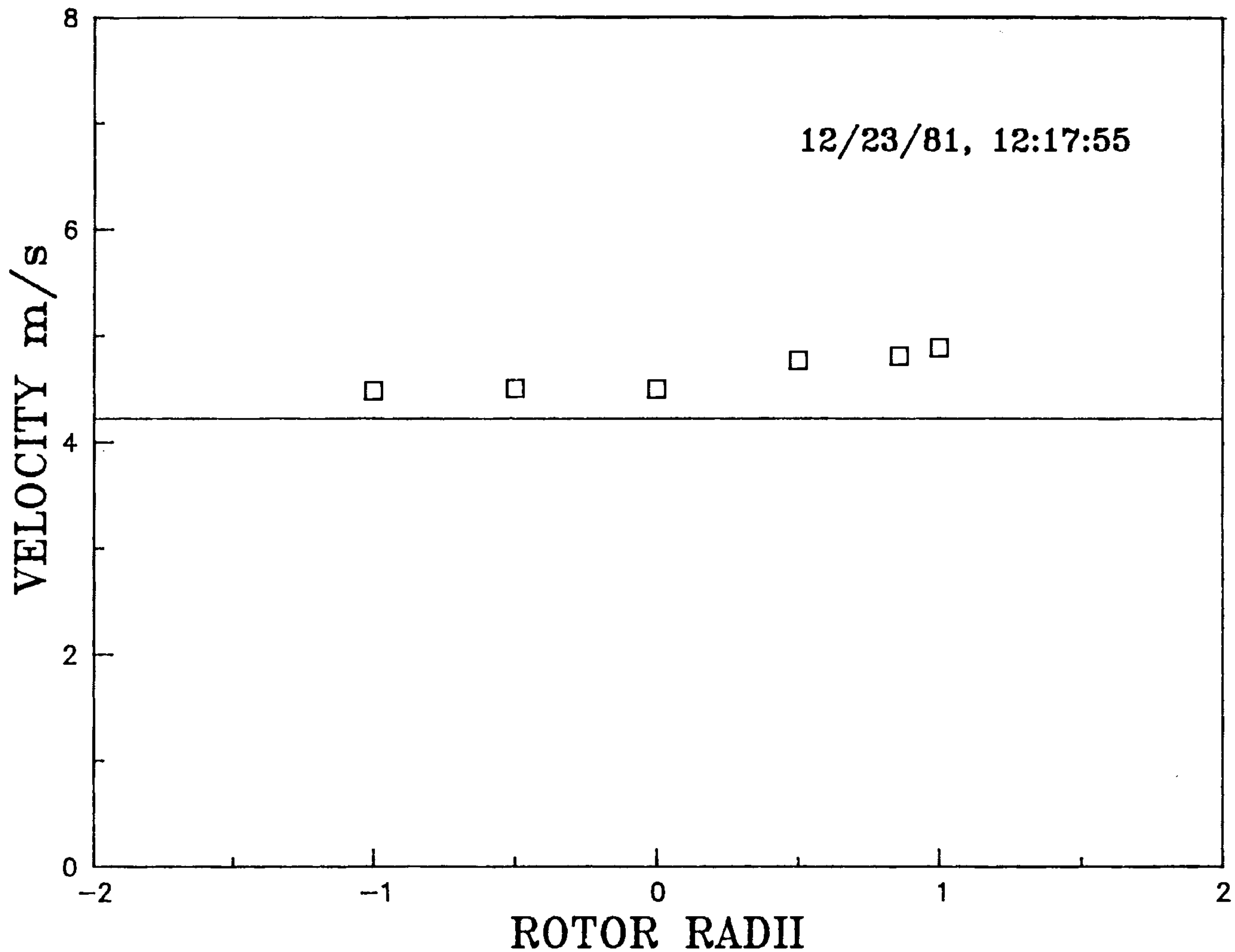

FIGURE 4. Calibration of Anemometers Showing Upwind Speed (—) and Downwind Speeds (□), 12/23/81, 12:17:55

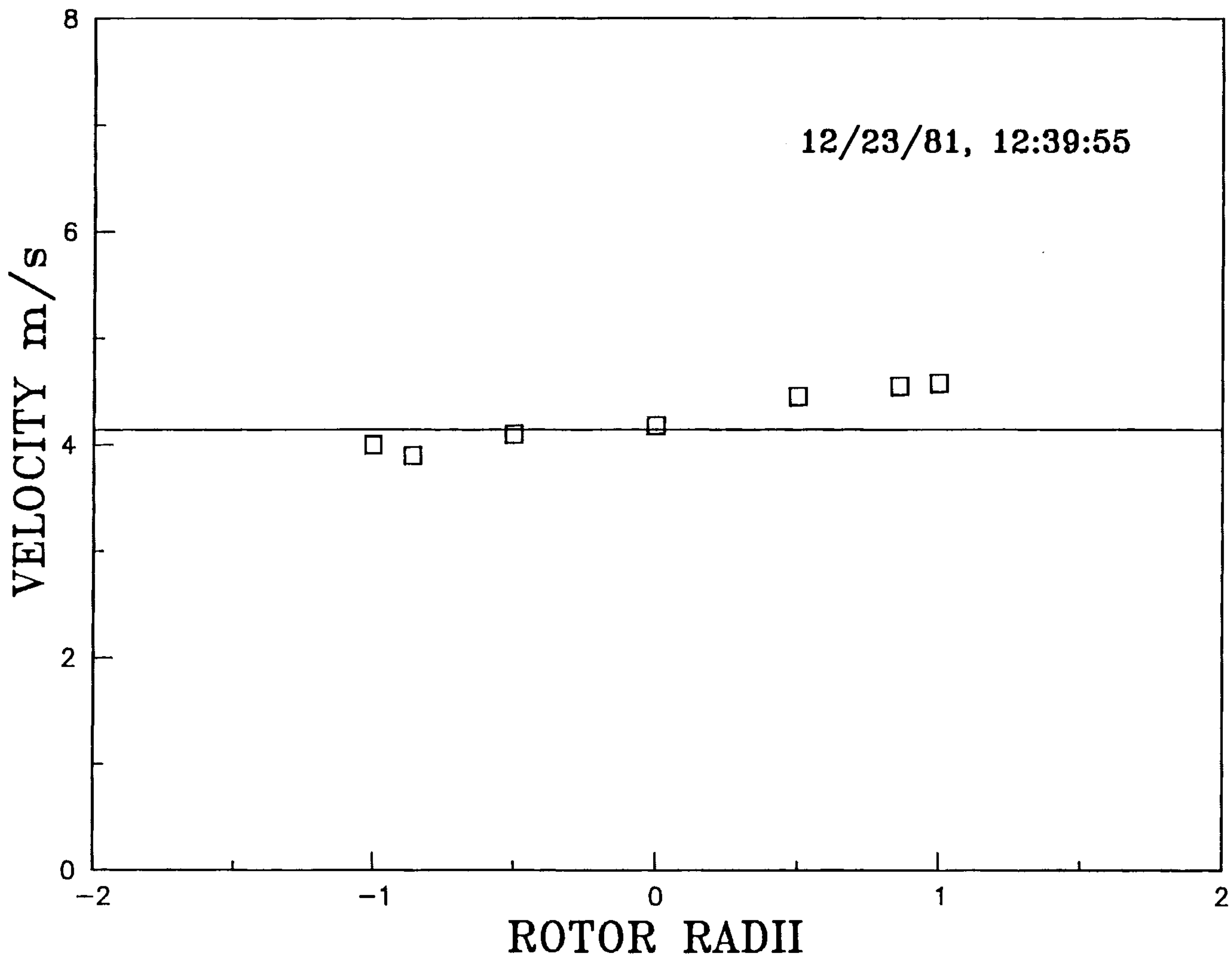

FIGURE 5. Calibration of Anemometers Showing Upwind Speed (—) and Downwind Speeds (□), 12/23/81, 12:39:55

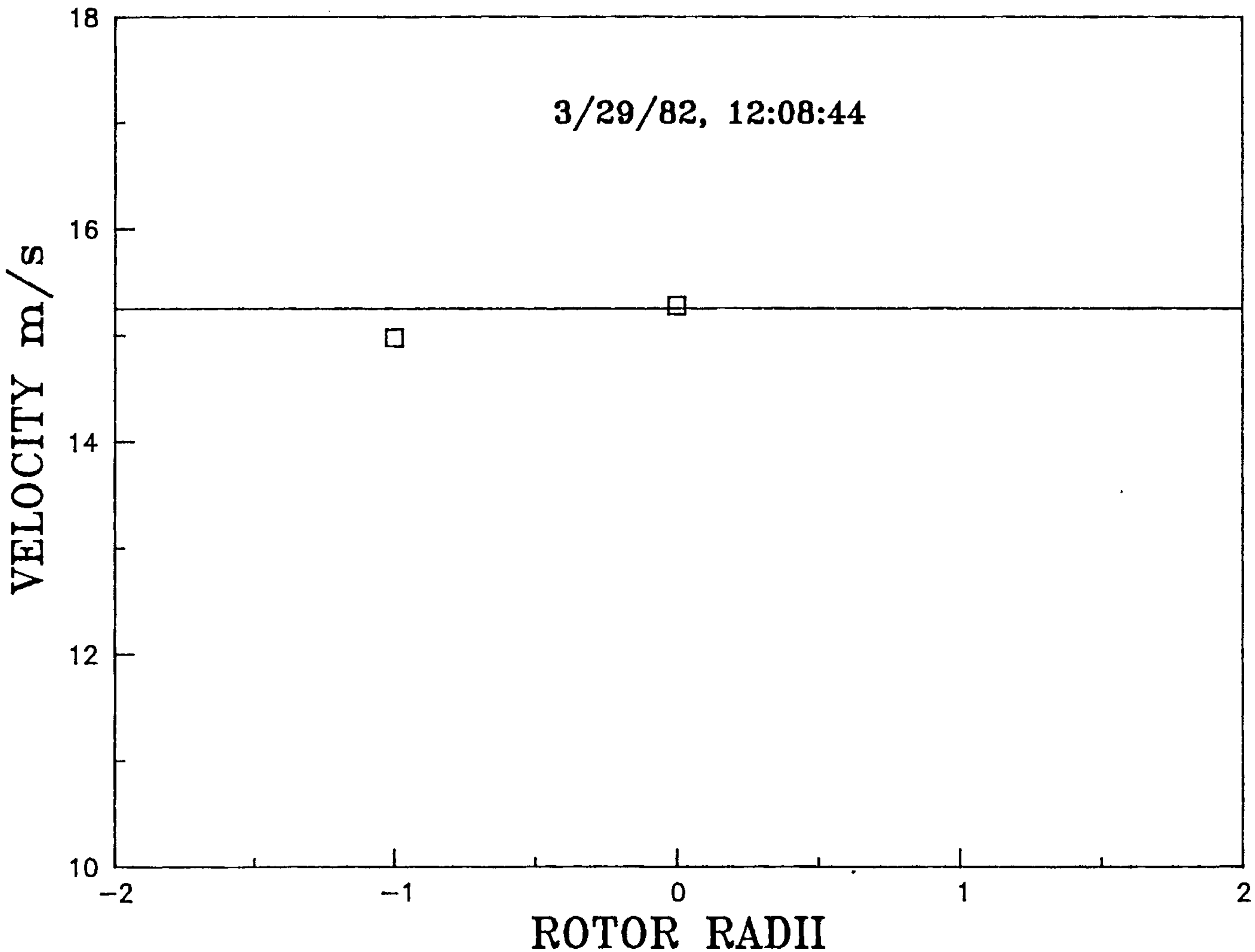

FIGURE 6. Calibration of Anemometers Showing Upwind Speed (—) and Downwind Speeds (□), 3/29/82, 12:08:44

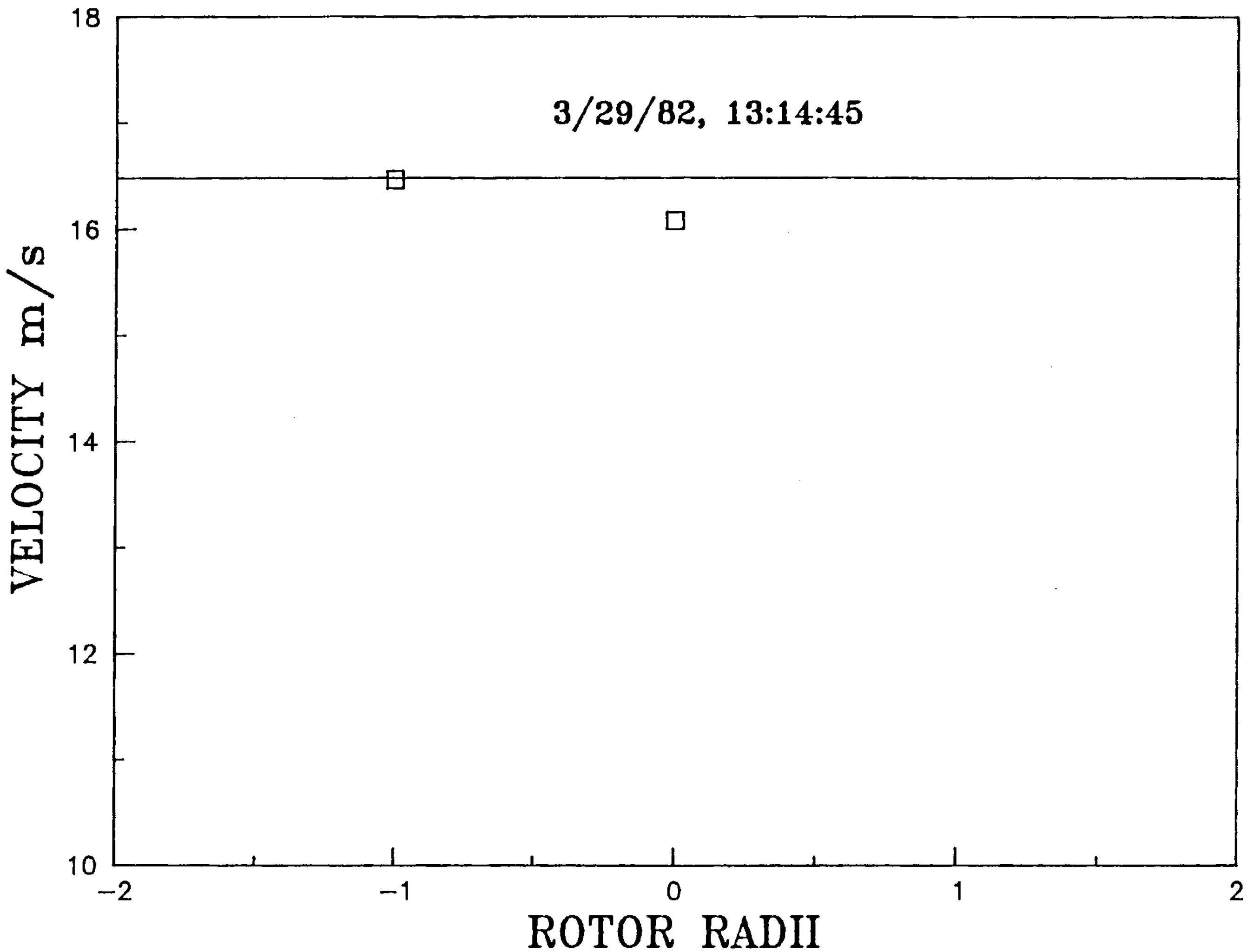

FIGURE 7. Calibration of Anemometers Showing Upwind Speed (—) and Downwind Speeds (□), 3/29/82, 13:14:45

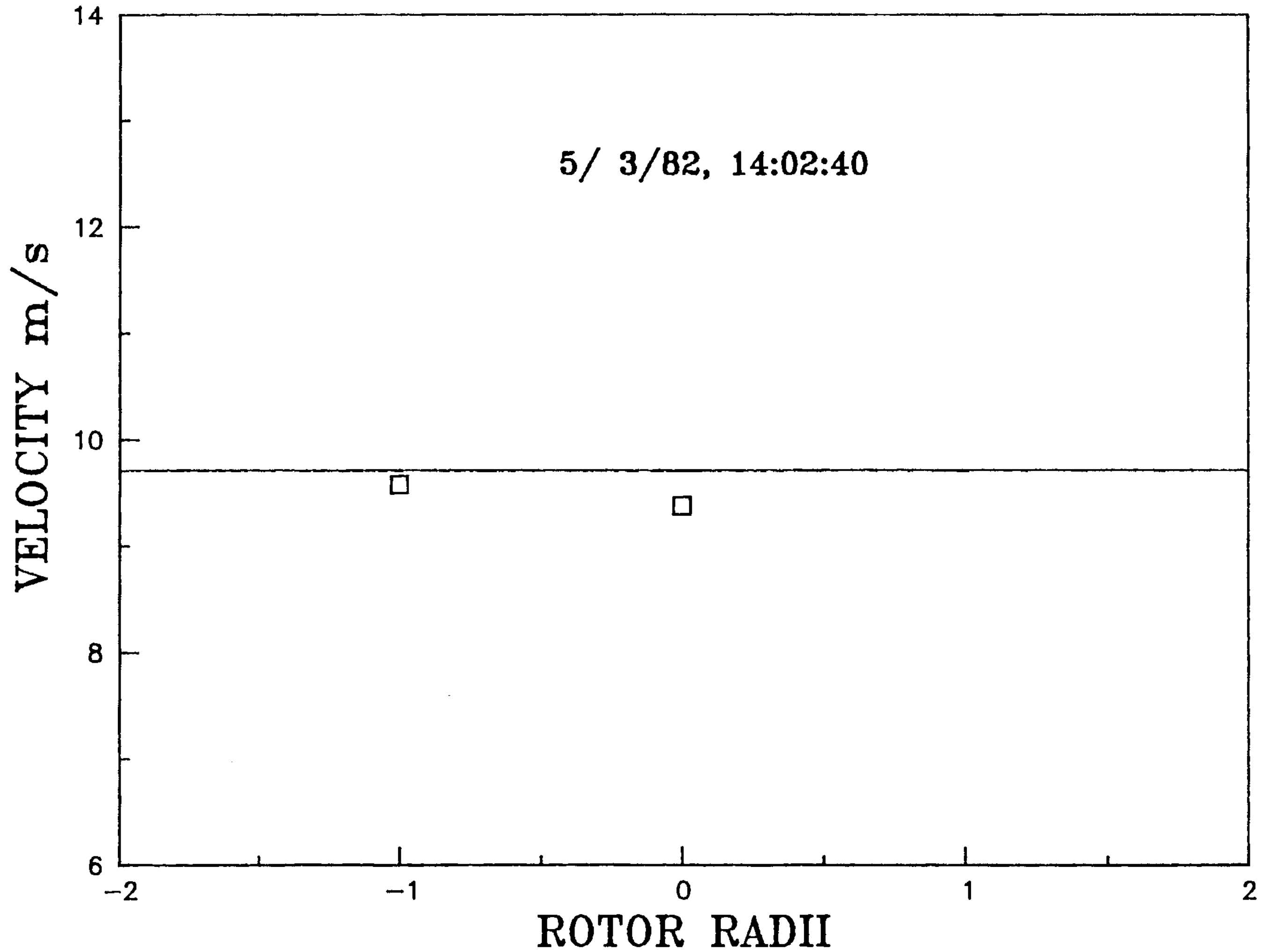

FIGURE 8. Calibration of Anemometers Showing Upwind Speed (—) and Downwind Speeds (□), 5/3/82, 14:02:40

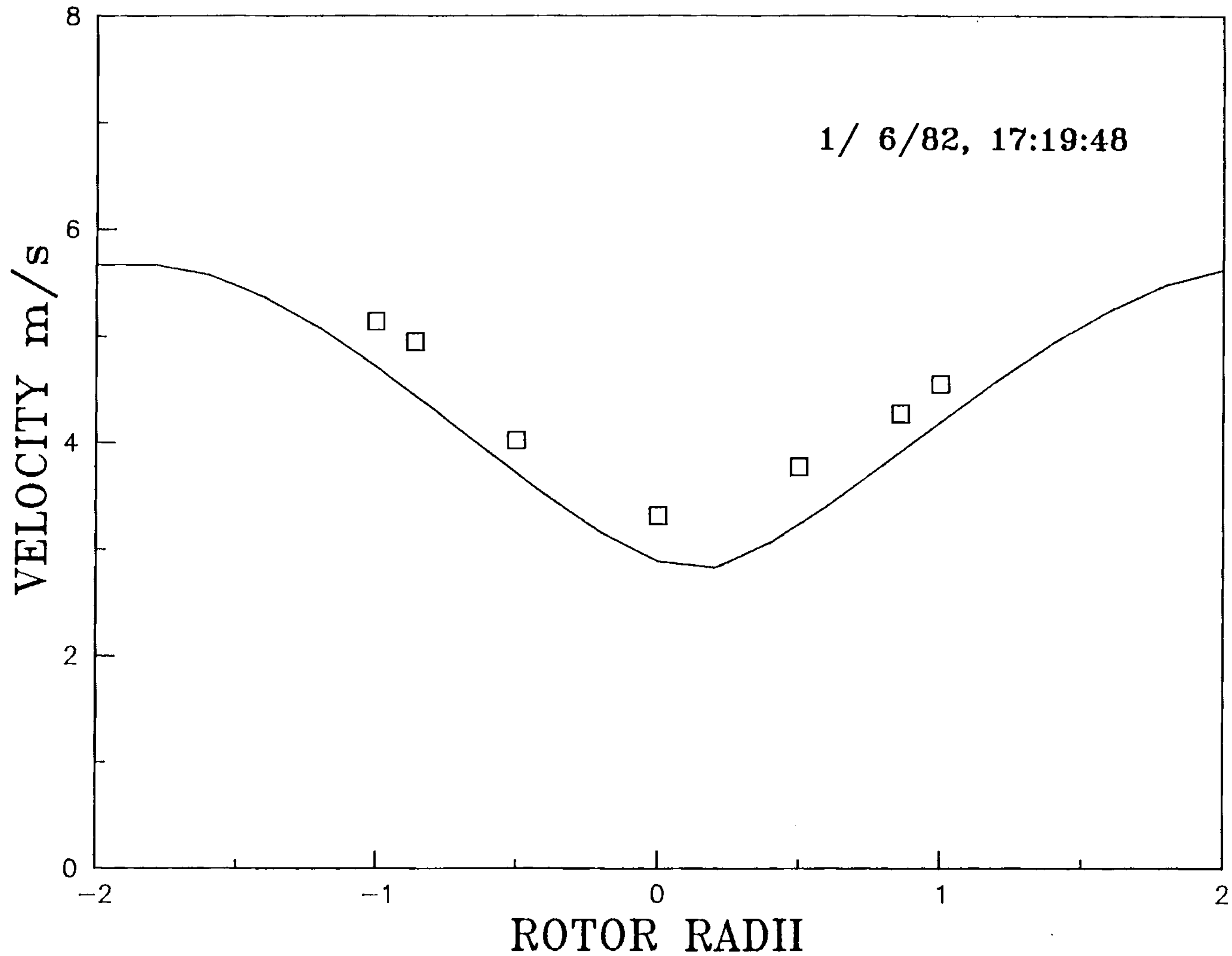

FIGURE 9. Comparison of Lissaman's Model Results (—) With Observed Speeds (□), 1/6/82, 17:19:48

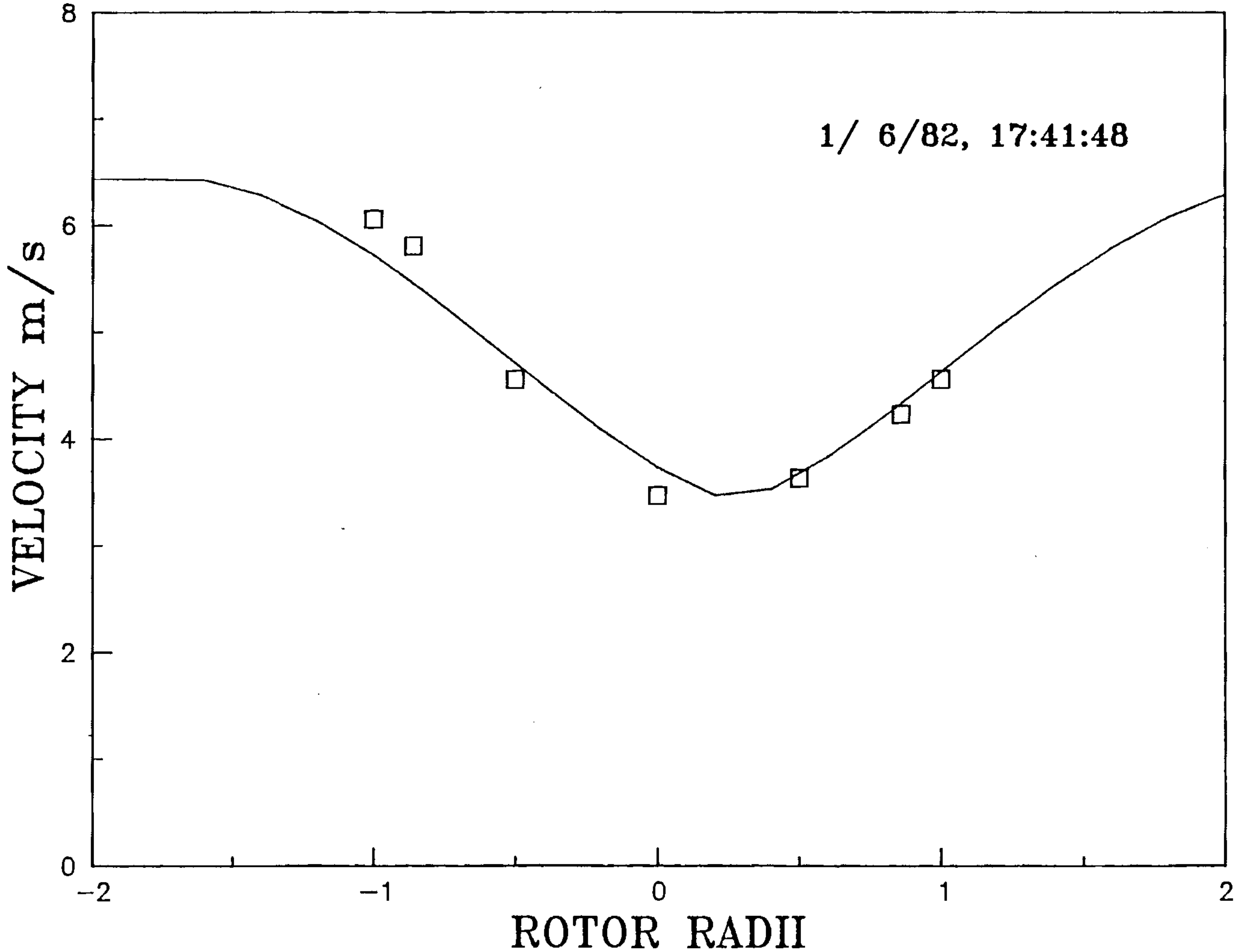

FIGURE 10. Comparison of Lissaman's Model Results (—) With Observed Speeds (□), 1/6/82, 17:41:48

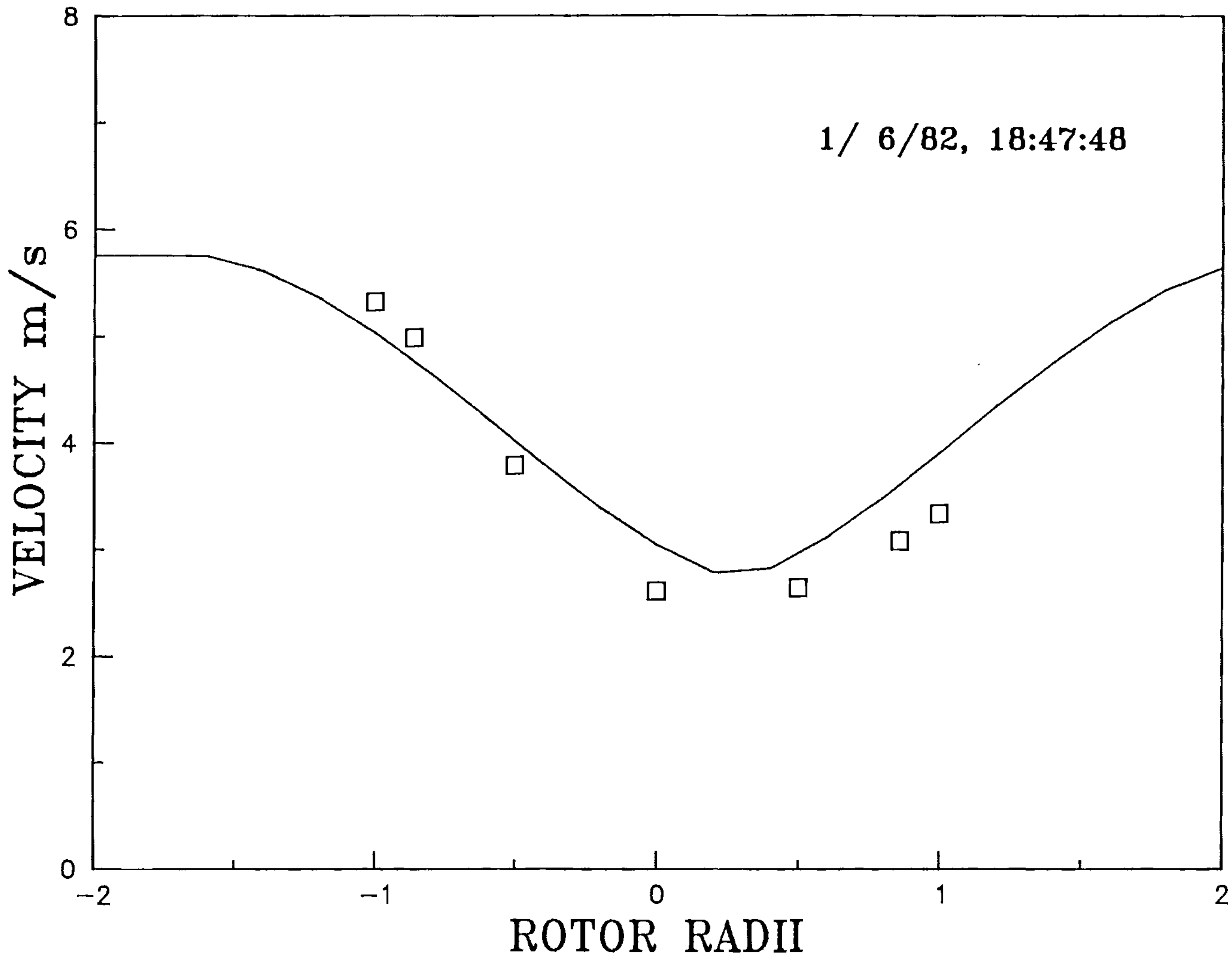

FIGURE 11. Comparison of Lissaman's Model Results (—) With Observed Speeds (□), 1/6/82, 18:47:48

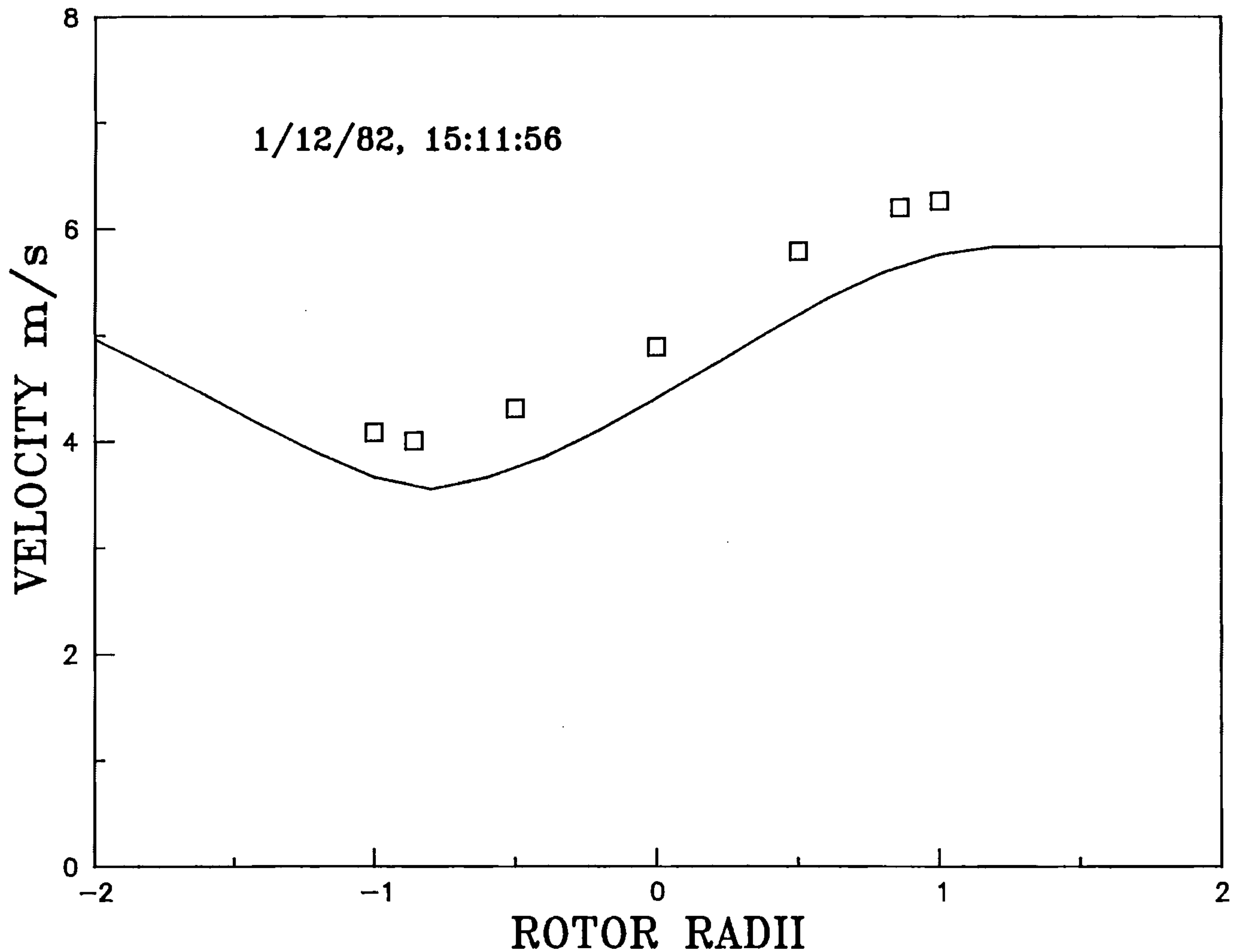

FIGURE 12. Comparison of Lissaman's Model Results (—) With Observed Speeds (□), 1/12/82, 15:11:56

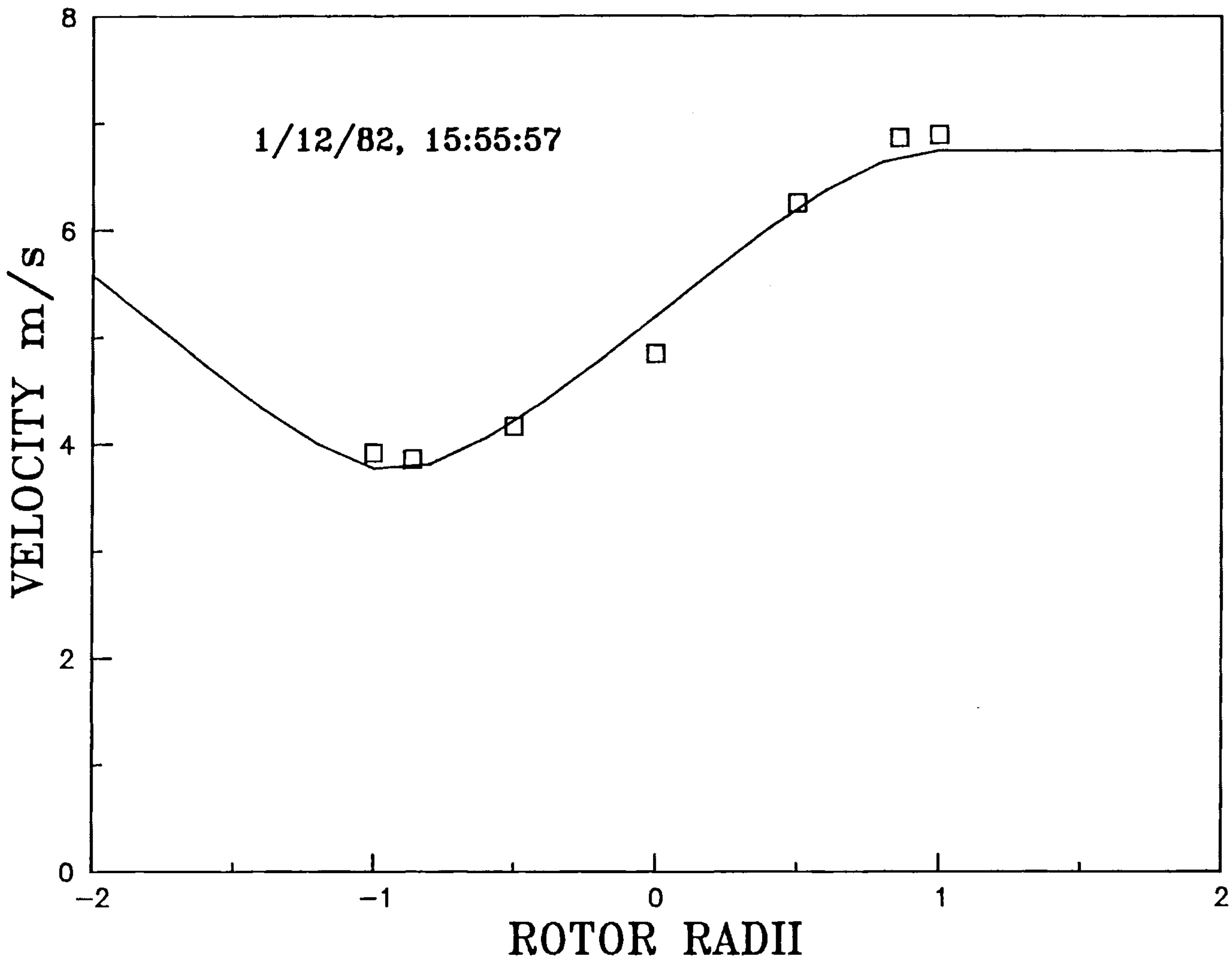

FIGURE 13. Comparison of Lissaman's Model Results (—) With Observed Speeds (□), 1/12/82, 15:55:57

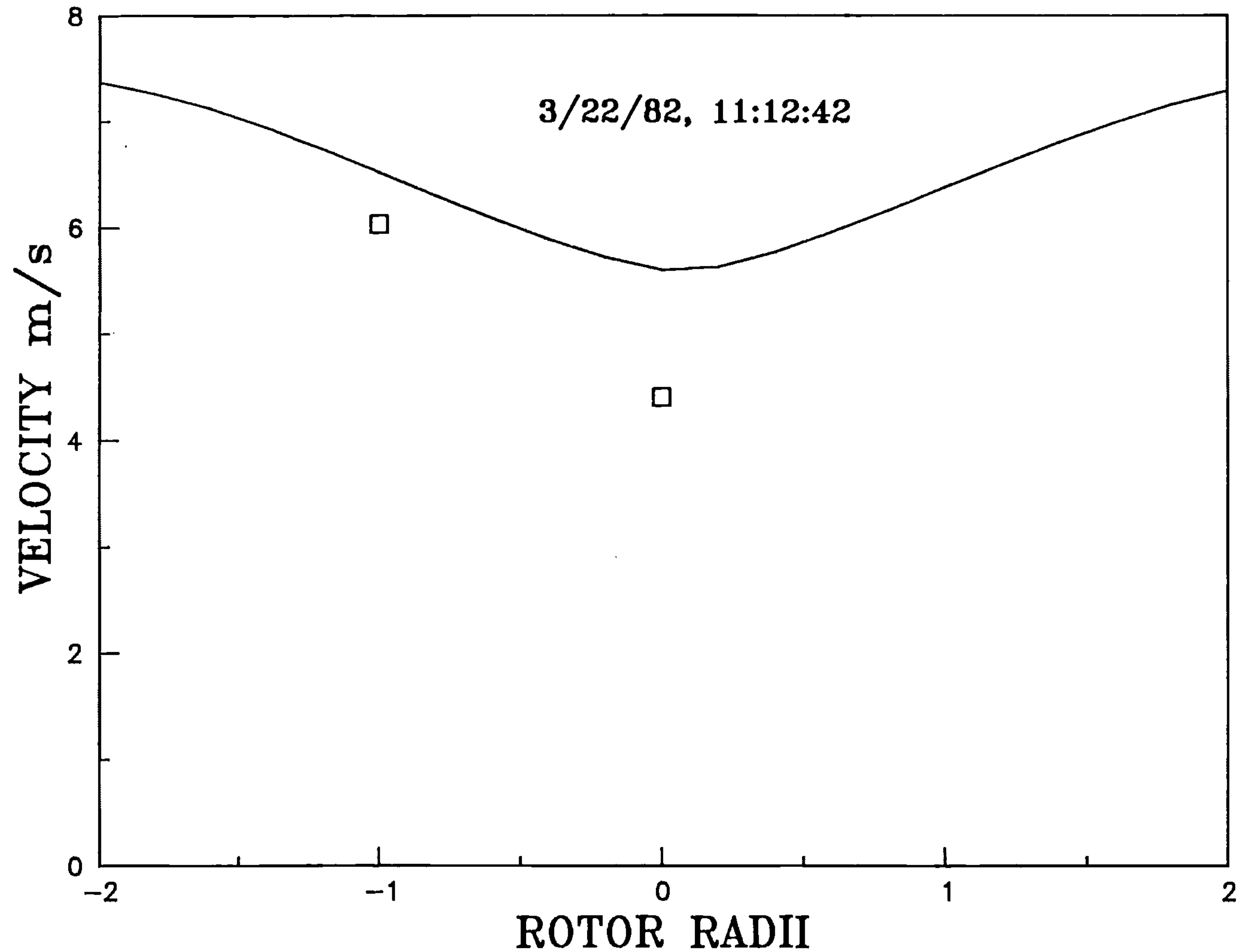

FIGURE 14. Comparison of Lissaman's Model Results (—) With Observed Speeds (□), 3/22/82, 11:12:42

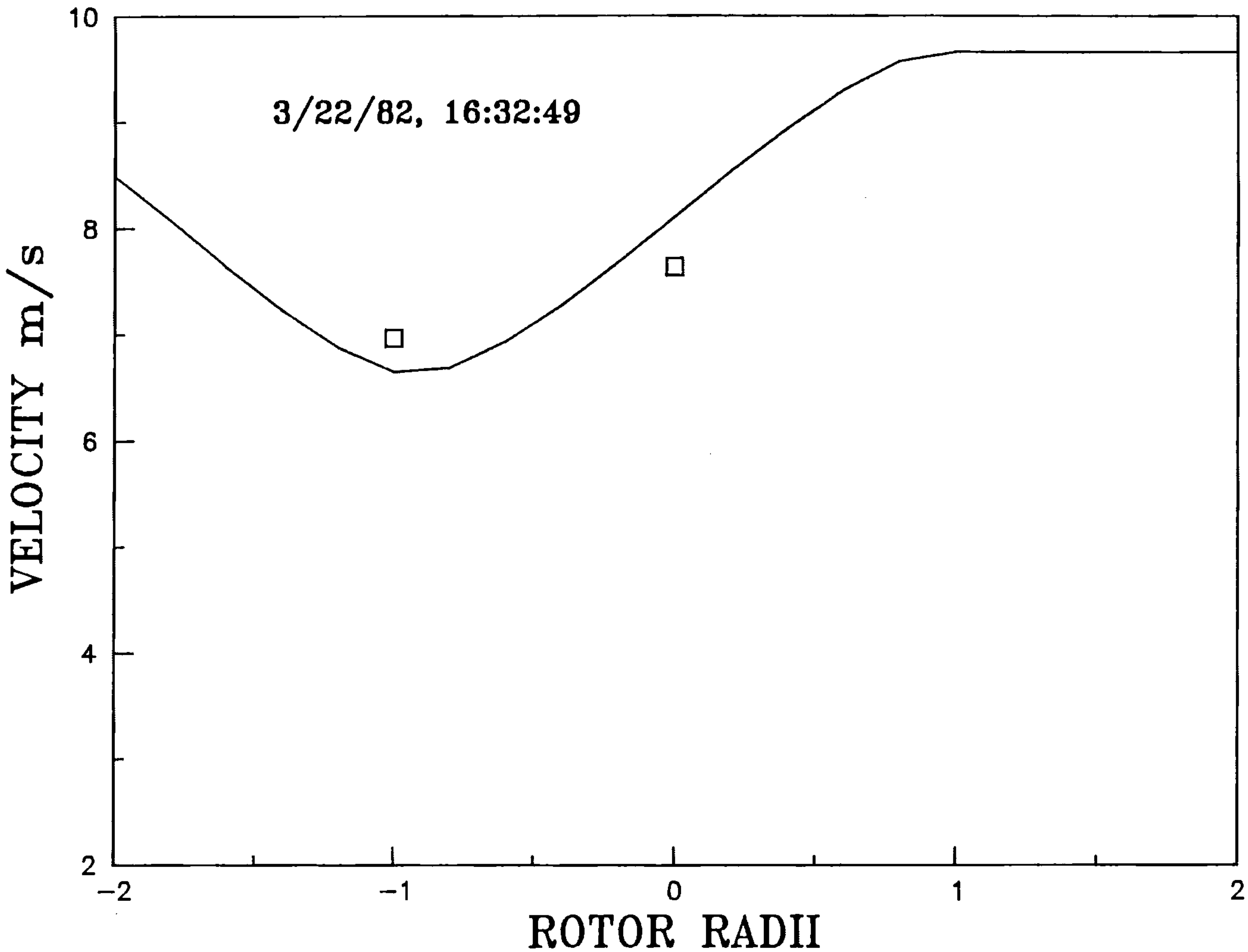

FIGURE 15. Comparison of Lissaman's Model Results (—) With Observed Speeds (□), 3/22/82, 16:32:49

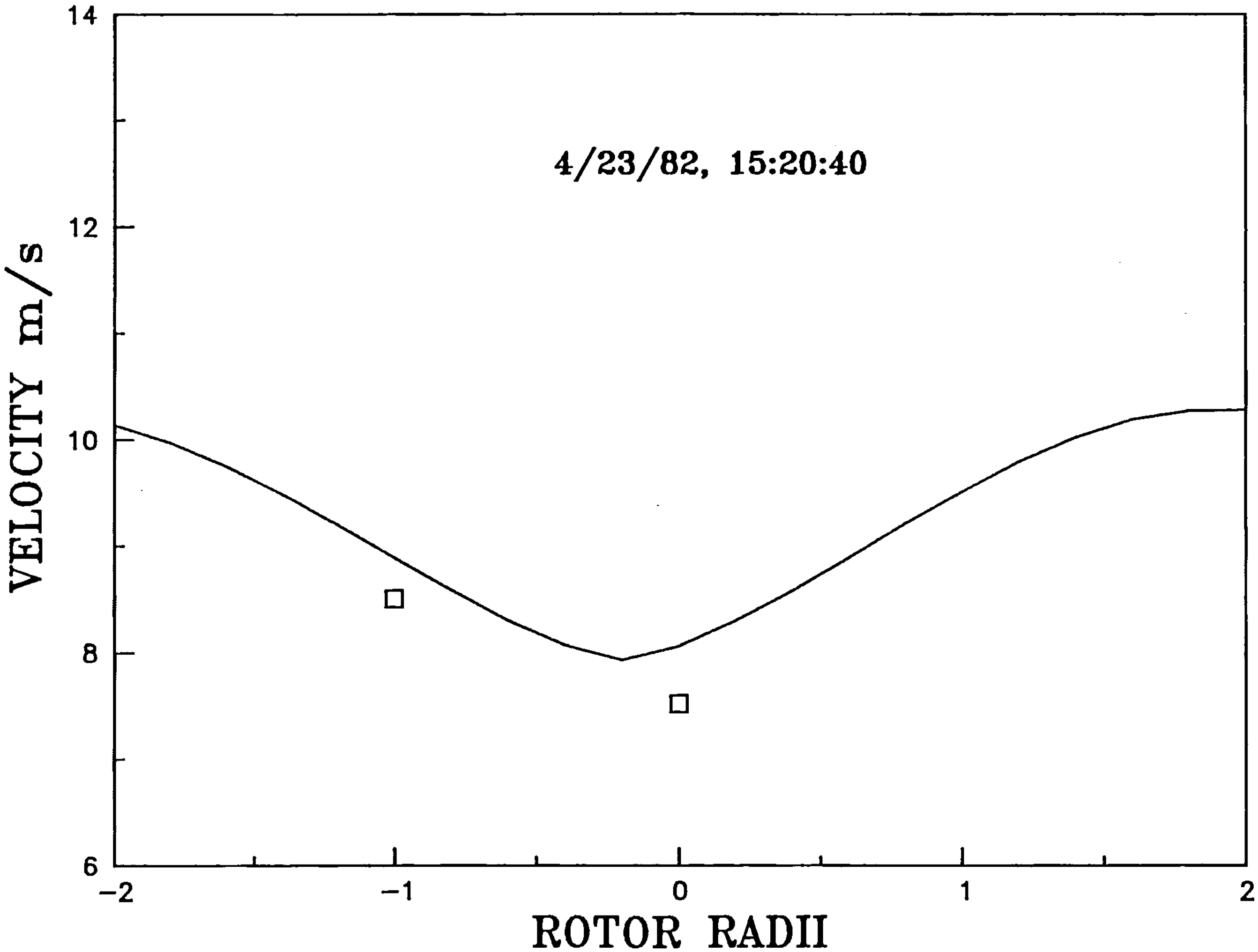

FIGURE 16. Comparison of Lissaman's Model Results (—) With Observed Speeds (□), 4/23/82, 15:20:40

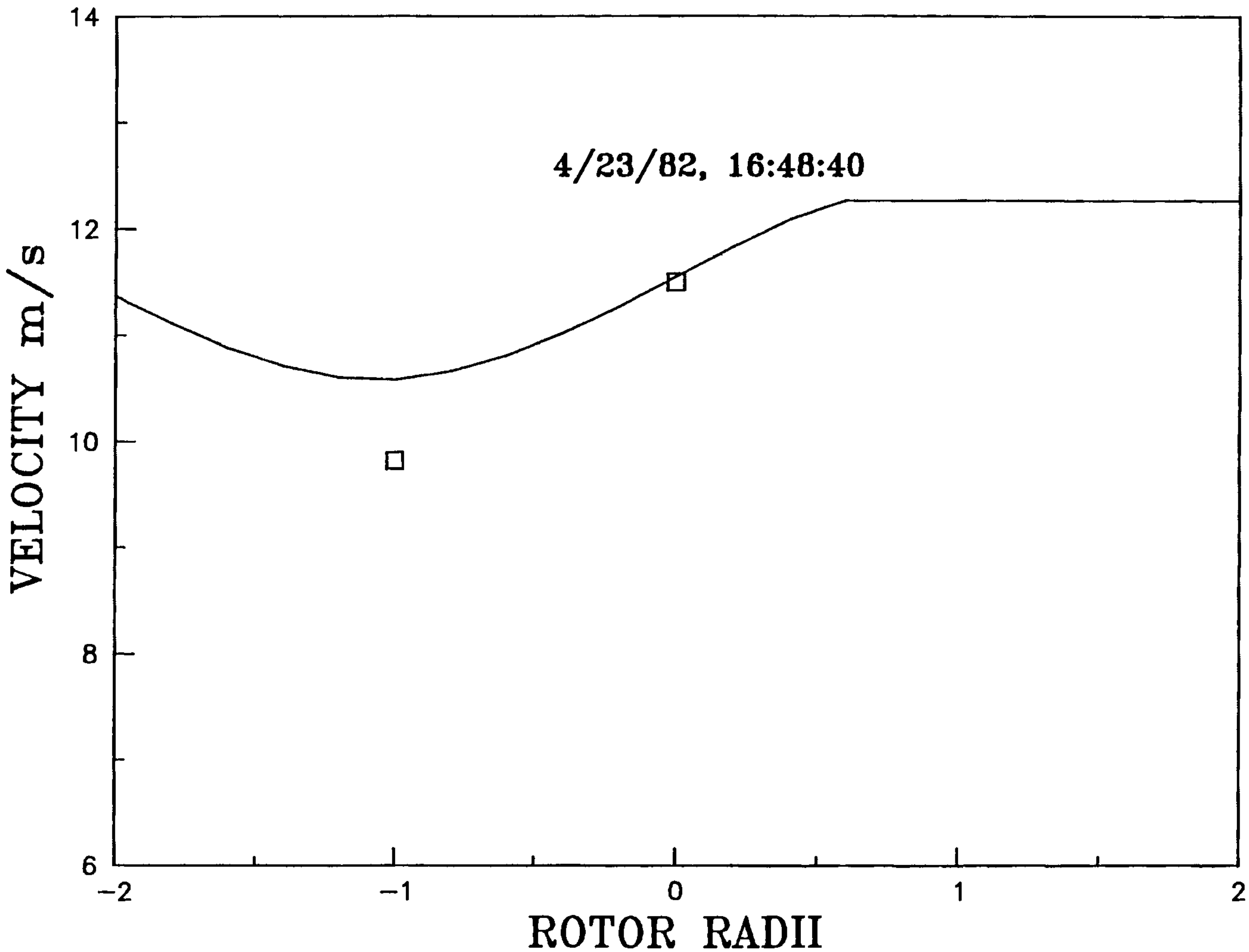

FIGURE 17. Comparison of Lissaman's Model Results (—) With Observed Speeds (□), 4/23/82, 16:48:40

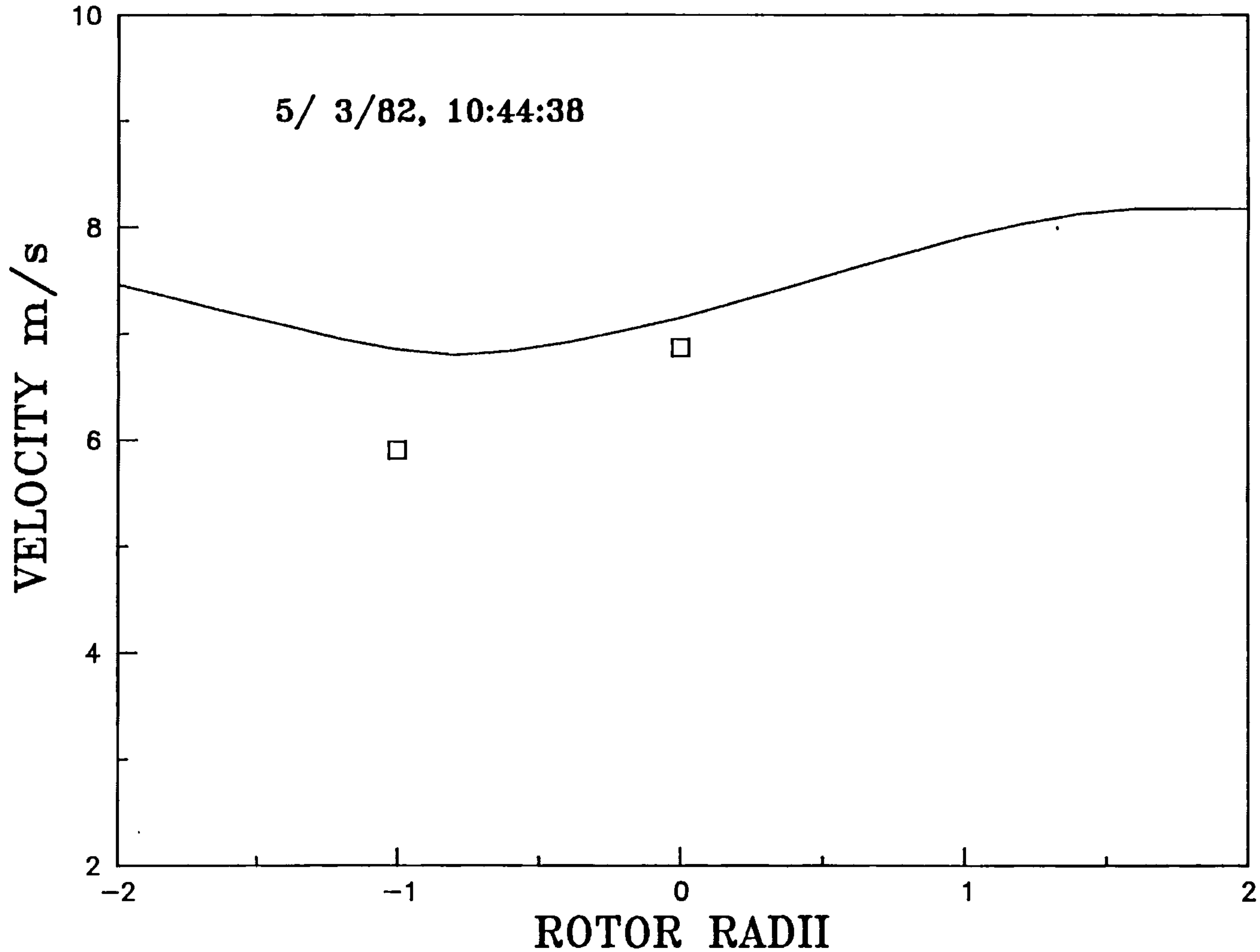

FIGURE 18. Comparison of Lissaman's Model Results (—) With Observed Speeds (□), 5/3/82, 10:44:38

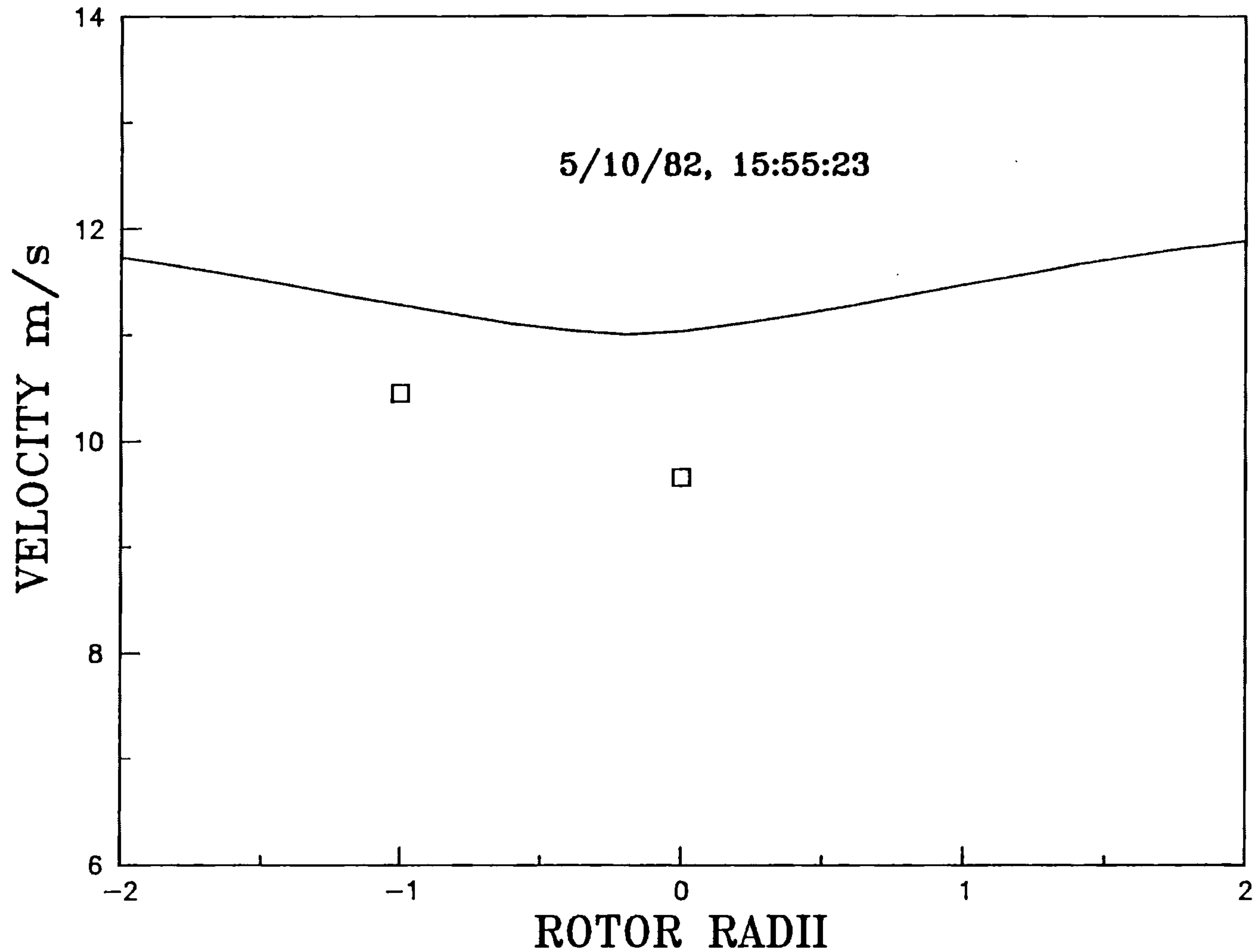

FIGURE 19. Comparison of Lissaman's Model Results (—) With Observed Speeds (□), 5/10/82, 15:55:23

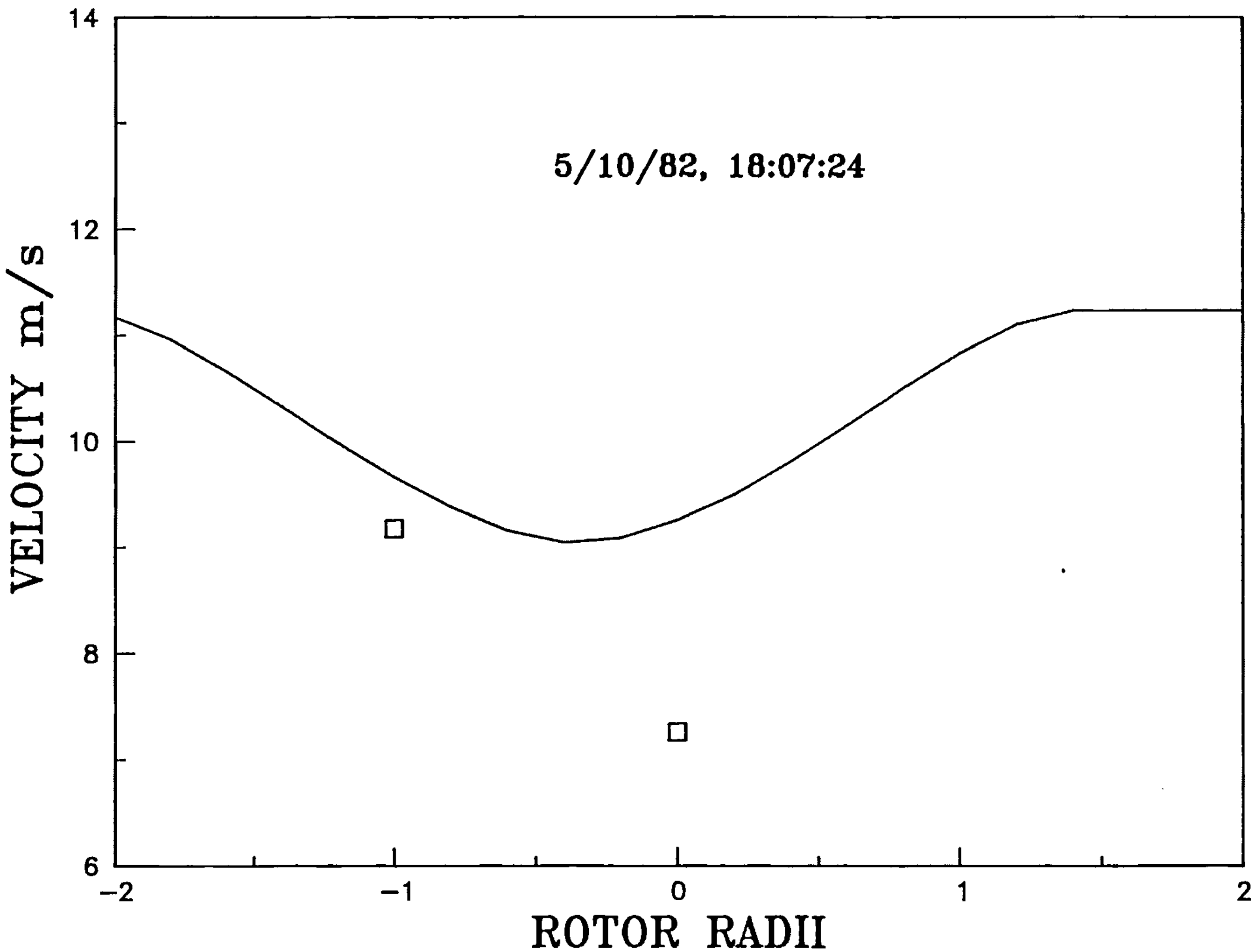

FIGURE 20. Comparison of Lissaman's Model Results (—) With Observed Speeds (□), 5/10/82, 18:07:24

5. RECOMMENDATIONS

While the observations reported here are useful in evaluating some aspects of wakes, they are necessarily limited in scope. Additional measurements, at greater downwind distances (5 to 10 rotor diameters), are suggested. Further studies of wake performance for winds near rated turbine speeds would also be valuable.

The turbine location at Clayton is not suitable for wake measurements at the larger distances. Another flat homogeneous site with a well-defined predominant wind direction is needed. Only one upwind anemometer would be required, although a second provides an often welcome backup. There are a number of possibilities for downwind configurations of anemometers. One would be to have three towers at each of three downwind distances, e.g., 5, 7 and 10 rotor diameters (D). In each set of three, one anemometer would be located along a line passing through the turbine in the most likely wind direction of interest; the other two instruments would be located to one side of this line. The spacing within each set of three would increase with downwind distance, e.g., 0.751 D, 1.25 D and 1.75 D.

The use of the three rather than two downwind anemometers, as sometimes used in this study, would allow greater revolution of the shape of the wake. Initial tests could use only hub-height anemometers, with more levels being added later if desired. The use of several downwind areas of towers would also permit the study of the decay of the wake in regions where the placement of additional turbines has been contemplated. Wake "profiles" based on a single anemometer at one downwind distance and on a knowledge of the wind direction are also possible, but far less desirable.

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