Quantitative Representation of the Velocity Distribution along the Vertical

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Abstract

For accurate and efficient input of upper-wind observations into the air traffic control system, it is necessary a) to express the results of balloon ascents in quantitative terms, b) to transmit only skeleton wind messages from the upper-air stations for rapid communication and immediate input of the winds into a central computer, and c) to select parameters from the wind runs which are most suitable for traffic control purposes.

In this paper, computations directed toward accomplishing these objectives are discussed. At first, the concept of the Layer of Maximum Wind is expanded for purposes of automatic analysis of horizontal wind maps. In this context extrapolation of short runs is very necessary because of the marginal station density. Procedures for such extrapolation are given. Then, after a review of early attempts at quantitative analysis of balloon ascents, a method of harmonic analysis is described which gave encouraging results in an initial test sample of 20 ascents. Following this, a test with a large sample of 1000 ascents was performed. The results of this test are given. A final technique for numerical analysis of the wind-speed distribution along the vertical is given, and suggestions are made for complete numerical processing of the balloon ascents.

Introduction

For management of airways traffic in the jet aircraft age, rapid and adequate determination of the windfield at various flight altitudes is requisite. Given free-lift balloon techniques for upper-wind measurement, execution of the following steps will accomplish this purpose:

1) Selection of wind parameters suitable for flight planning and vectoring.

2) Quantitative analysis of balloon asecents.

3) Vertical extrapolation of incomplete wind soundings.

4) Horizontal analysis with quantitative methods.

5) Rapid communications for transmittal of wind data, including reduction of length of messages to minimum.

Layer of Maximum Wind

Several years ago the concept of a "Layer of Maximum Wind" (LMW) was advanced as a practical tool for jet aviation. The layer concept was formulated in response to three facts.

1) The level of greatest efficiency of jet aircraft increases as the gas load lightens. Hence, air traffic controllers should have at their disposal a simple means, in terms of wind, to permit aircraft to climb if other circumstances warrant this.

2) Winds in the upper troposphere and lower stratosphere as given by individual balloon ascents, are considered to be determinate at best to ten percent of the true wind, due to the micro-structure in the upper windfield and inadequacies of wind measurement. Hence, employment of averaging techniques is indicated.

3) The three-dimensional forecast problem is very difficult to solve. Meteorology can make its most satisfactory contribution to traffic control management if the forecast problem can be reduced to two dimensions.

Reiter (1957, 1958) has discussed meteorological and navigational aspects of the LMW. Four parameters characterize the layer:

Wind direction

Wind speed

Mean altitude

Thickness

Direction is not considered a problem in middle latitudes, especially in jet streams, since it is almost invariant with height across such currents. Fig. 1 illustrates determination of the other three parameters. Because of the limits of wind determinancy, the LMW is defined to extend over the layer with speed above 80 percent of the maximum wind. The average wind speed of the layer, obtained by integrating the velocity-height curve over the thickness of the layer, then will be very nearly within ten per cent of all wind values in the layer. Its field distribution is considered a good approximation to the mean wind encountered by aircraft over distances with order of the distance between rawin stations in the United States (U. S. Navy 1959).

With these definitions, only two-dimensional representation and prediction is required for aircraft within the layer. The vertical wind shear to be applied in case of aircraft leaving the layer will be defined below.

Soundings without Jet Stream Core

In the original concept, analysis was confined to regions with LMW; this usually implies presence of an atmospheric jet stream. For other areas, essentially a no-wind assumption was made, since the

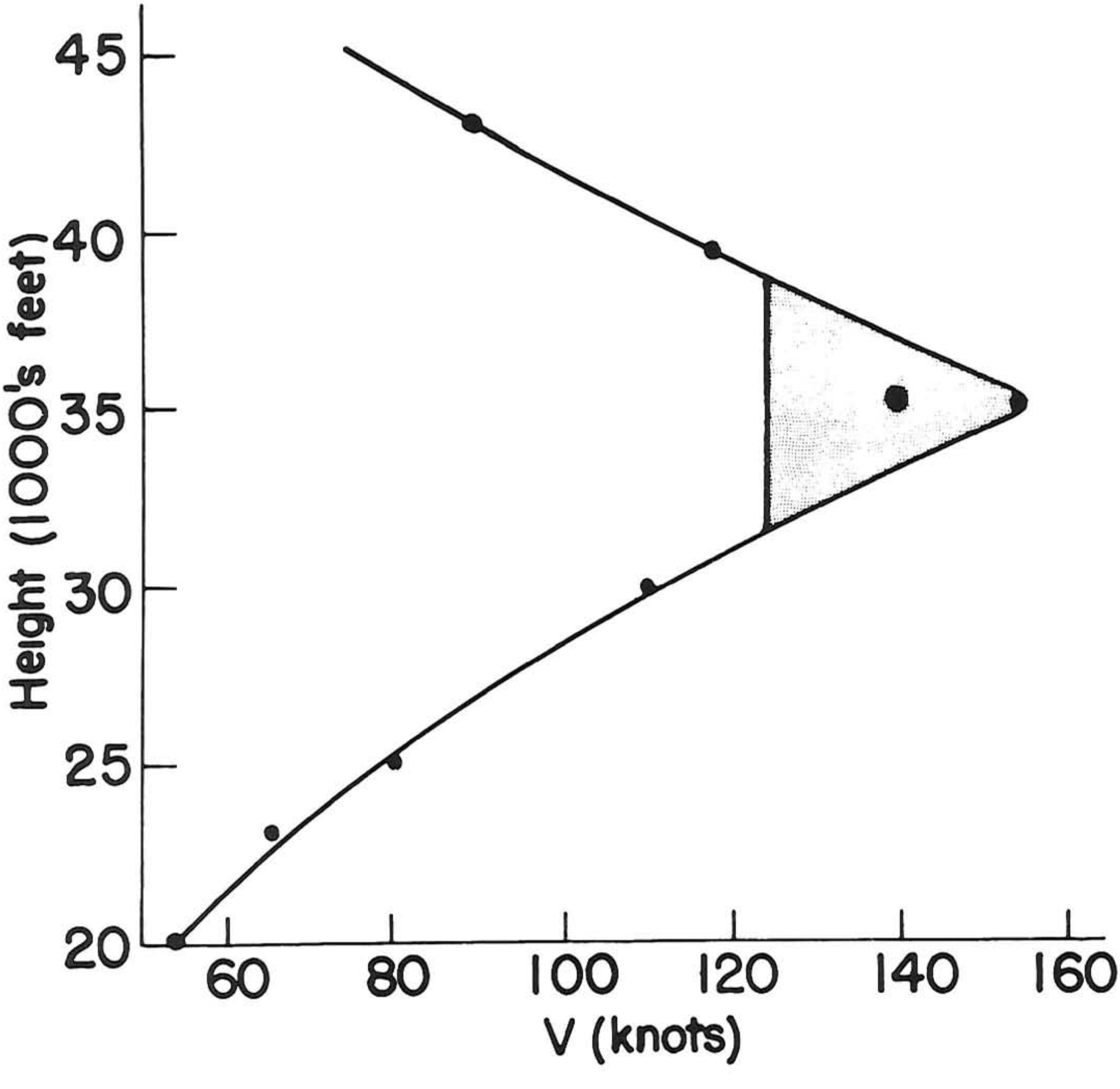

Figure 1. Vertical wind profile at Washington, D.C., 6 March 1958, 0000 GMT. LMW shaded, heavy dot indicates mean height and speed. Profile hand-analyzed. From Riehl (1961).

relatively light winds prevailing there were thought to be of little operational importance for jet aircraft. However, if the velocity field is to be determined by high-speed computing equipment over large areas of the size of North America, it is of advantage to remove this restriction and to define all winds in terms of the LMW concept.

In order for the LMW to serve as an operationally useful quantity, minimum speed of the strongest wind of 60 knots and maximum depth of the layer of 15,000 feet was prescribed to characterize a sounding with true LMW. For instance, in Fig. 1 the mean speed is 140 knots and the thickness 8,000 feet; hence, the sounding has considerable definition along the vertical. In contrast, the curve of Fig. 2 is quite rounded at relatively low speeds, so that a layer-depth well in excess of 15,000 feet would be computed. For definition, a thickness of 15,000 feet may nevertheless be assigned, centered on the maximum wind. Then all four parameters are readily computed.

The third ascent class, commonly encountered, consists of quasi-barotropic soundings (Fig. 3). For definition, soundings have been classified as barotropic when the range of windspeed between 25,000 and 50,000 feet does not exceed 30 knots. Such soundings yield only one parameter -- the mean speed. In middle latitudes, the wind direction is best ascertained from a layer of 15,000 feet thickness centered at 35,000 feet. Then the thickness parameter again will be 15,000 feet and the height may be entered as 50,000 feet which is to signify that the sounding is barotropic.

Extrapolation of Incomplete Soundings

Even over the North American continent the upper-wind density at best is marginal for numerical wind analysis in the quasi-horizontal plane following the LMW. Unless the slope of constant pressure surface is drawn upon as an aid -- at best a second rate device in jet streams -- it becomes imperative to extrapolate upward soundings which touch the vicinity of the base of the LMW but fail to penetrate the layer. For minimum requirements it is suggested that an ascent must reach 300 mb (30,000 feet) or extend to within 8,000 feet of the altitude of the LMW as given by a scan of surrounding stations. Extrapolation can be performed readily through use of the wind profiles at these stations. Since experience with this technique as yet is lacking, the suggestions initially advanced by Riehl (1961) will be described briefly.

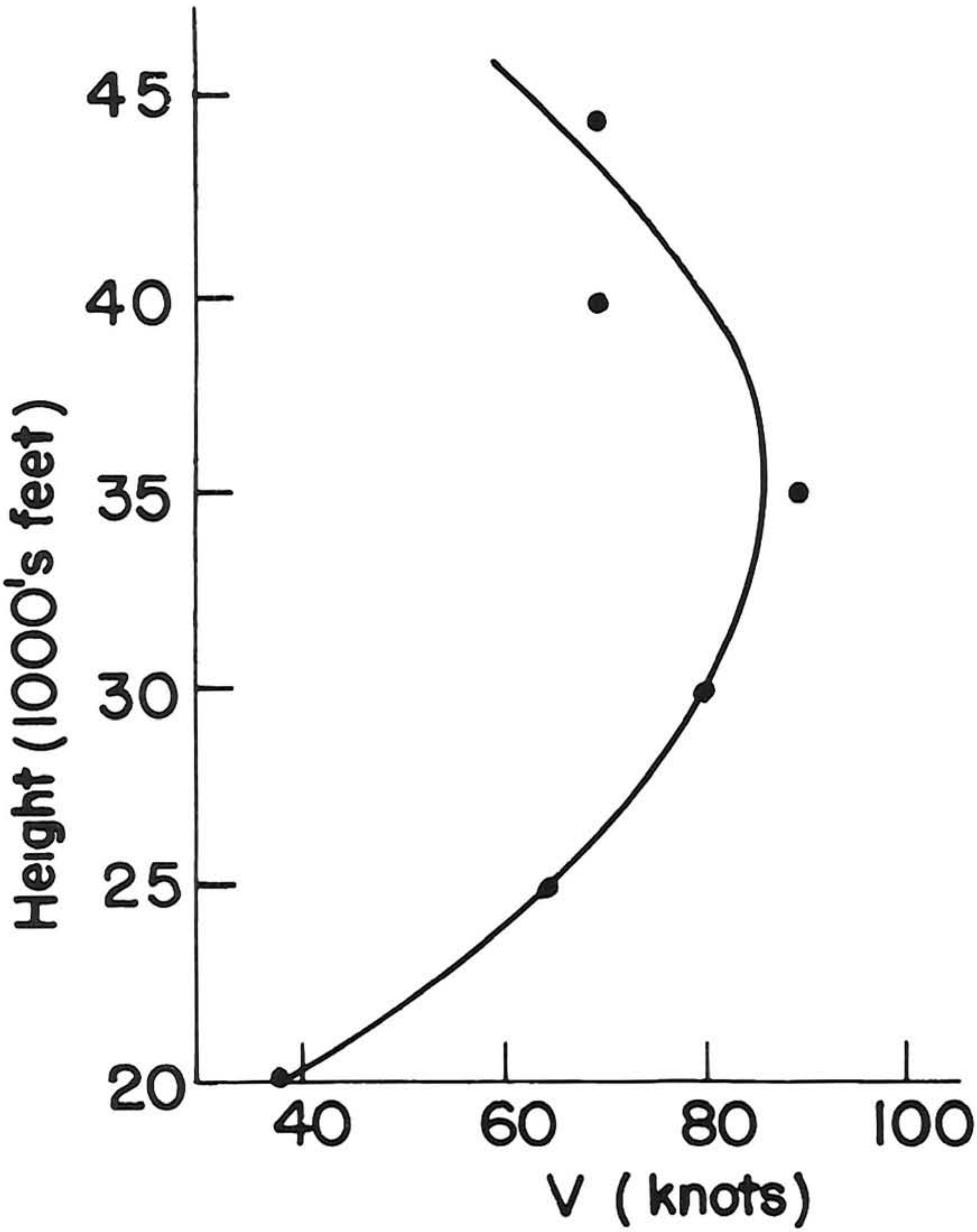

Figure 2. Vertical wind profile at Buffalo, N. Y., 6 March 1958, 0000 GMT. Hand-analyzed. From Fiehl (1961).

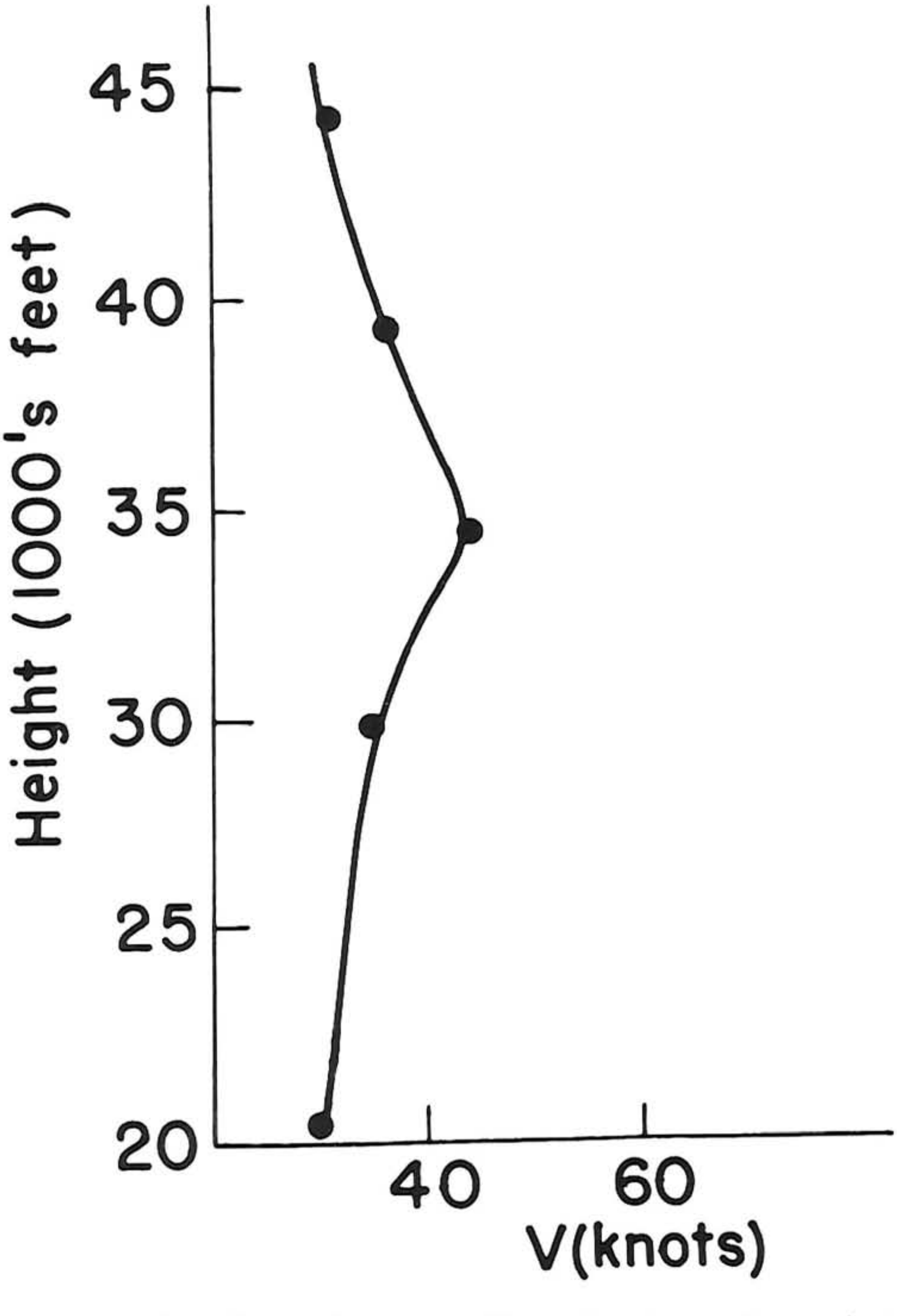

Figure 3. Vertical wind profile at Landers, Wyo., 6 March 1958, 0000 GMT. Hand-analyzed. From Riehl (1961).

The dots in Fig. 4 show the top of the message for a sounding taken at Peoria, Illinois. Since the height of the LMW varies only little along jet stream axes, we may scan upstream and downstream to determine the mean height at the nearest stations with complete soundings. The average of these heights should yield the best approximation, at incomplete stations, to within about 2,000 feet. For Peoria, a mean height of 35,000 - 36,000 feet evidently will be a good estimate. Hence, the sounding almost reached the core, and the best choice is to adopt the top wind for maximum speed. The sounding is completed by utilizing the mean slope, in percent, above the core at the two neighboring stations.

In Fig. 5 the sounding reached 30,000 feet, hence, qualifies for extrapolation. The best estimated mean height of the LMW is 41,000 feet from the nearest stations. Extrapolation is performed by using the mean percentual slope from 30,000 feet to the core, and above the core, at these stations. The direction at the top of the Jackson ascent may be used throughout the layer with the assumption of invariance of direction. Alternately, the mean turning, if any, at the other two stations may be adopted.

Fig. 6 finally illustrates an ascent with slope too great for a barotropic sounding and too small for LMW. Hence, the wind must be in the same class as that of Fig. 2. From adjacent stations the height of the maximum wind is 44,000 feet. The profile is extrapolated linearly to this altitude. Above this height the slope is taken as the mean of the other two stations as before.

It is seen that reasonable instructions for machine extrapolation can be developed readily. The precise limits to be adopted finally, of course, must await further experimentation with the proposed method on a pre-operational basis.

Initial Analysis of Vertical Wind Profiles

Delineation of the LMW and the extrapolation procedures just described depend for their successful execution on knowledge of the best possible description of individual wind profiles by quantitative methods. Such quantitative determination is requisite also for rapid transmission of the wind data in a form suitable for immediate use in high-speed computers. For the best description, the complete wind run obtained during the original wind evaluation evidently should be used. Hence, the calculation should be performed by small computers at the balloon sounding stations.

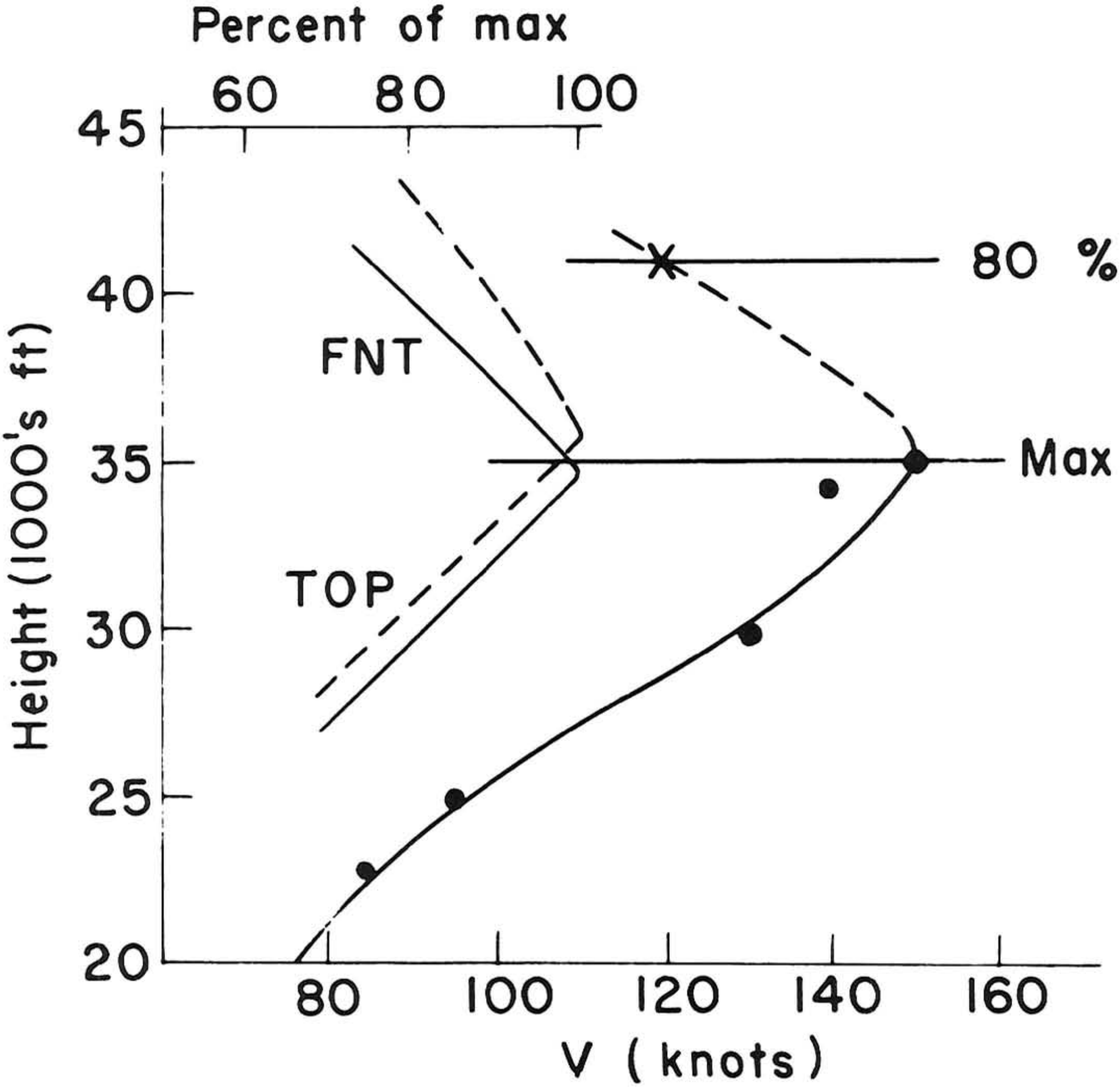

Figure 4. Vertical wind profile at Peoria, Ill., 6 March 1958, 0000 GMT. Also portions of wind profiles at FNT and TOP, expressed in percent of the maximum wind at these stations. Extrapolated part of wind profile dashed. From Riehl (1961).

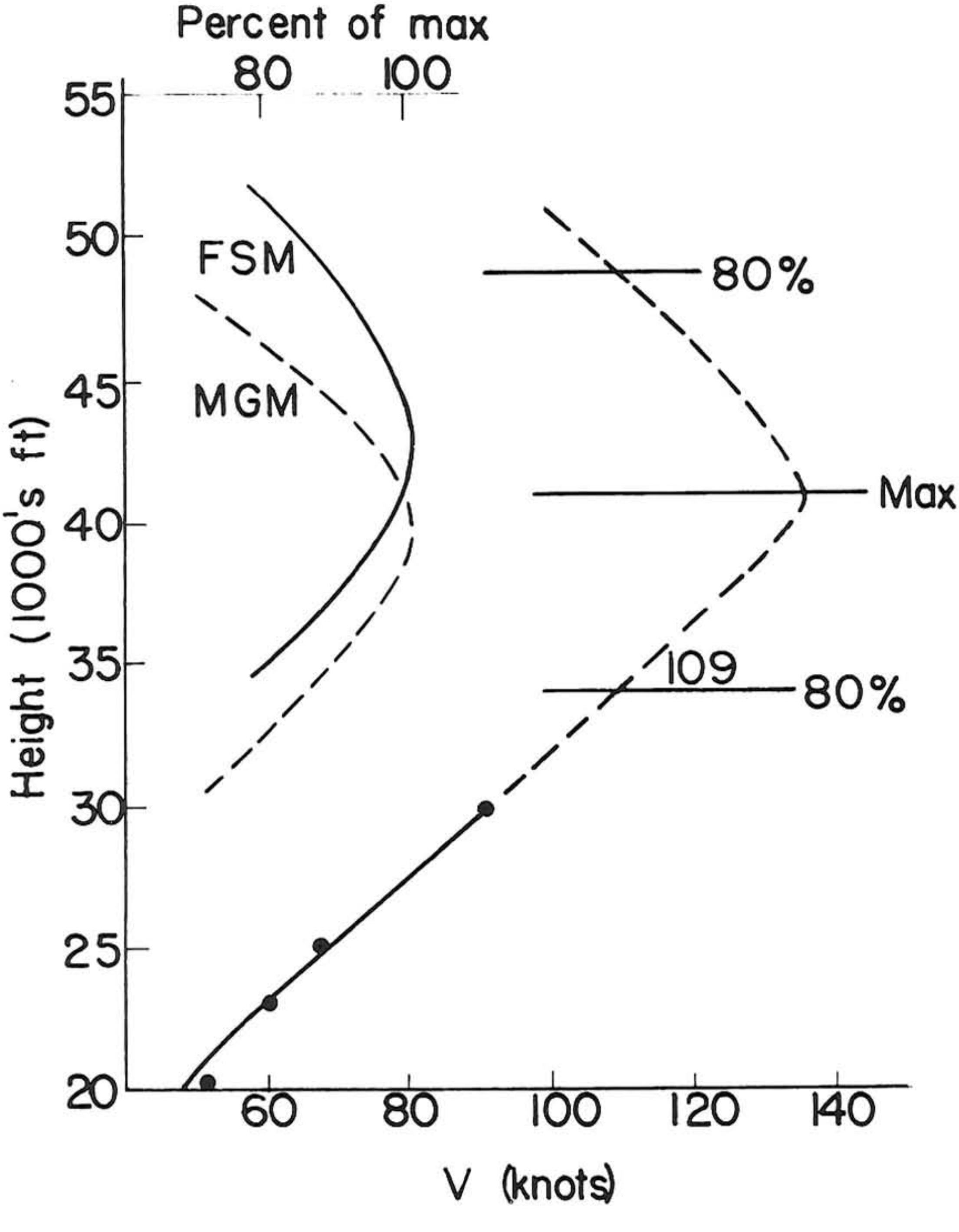

Figure 5. Vertical wind profile at Jackson, Miss., 6 March 1958, 0000 GMT. Also portions of wind profiles at FSM and MGM, expressed in percent of the maximum wind at these stations. Extrapolated part of wind profile dashed. From Riehl (1961).

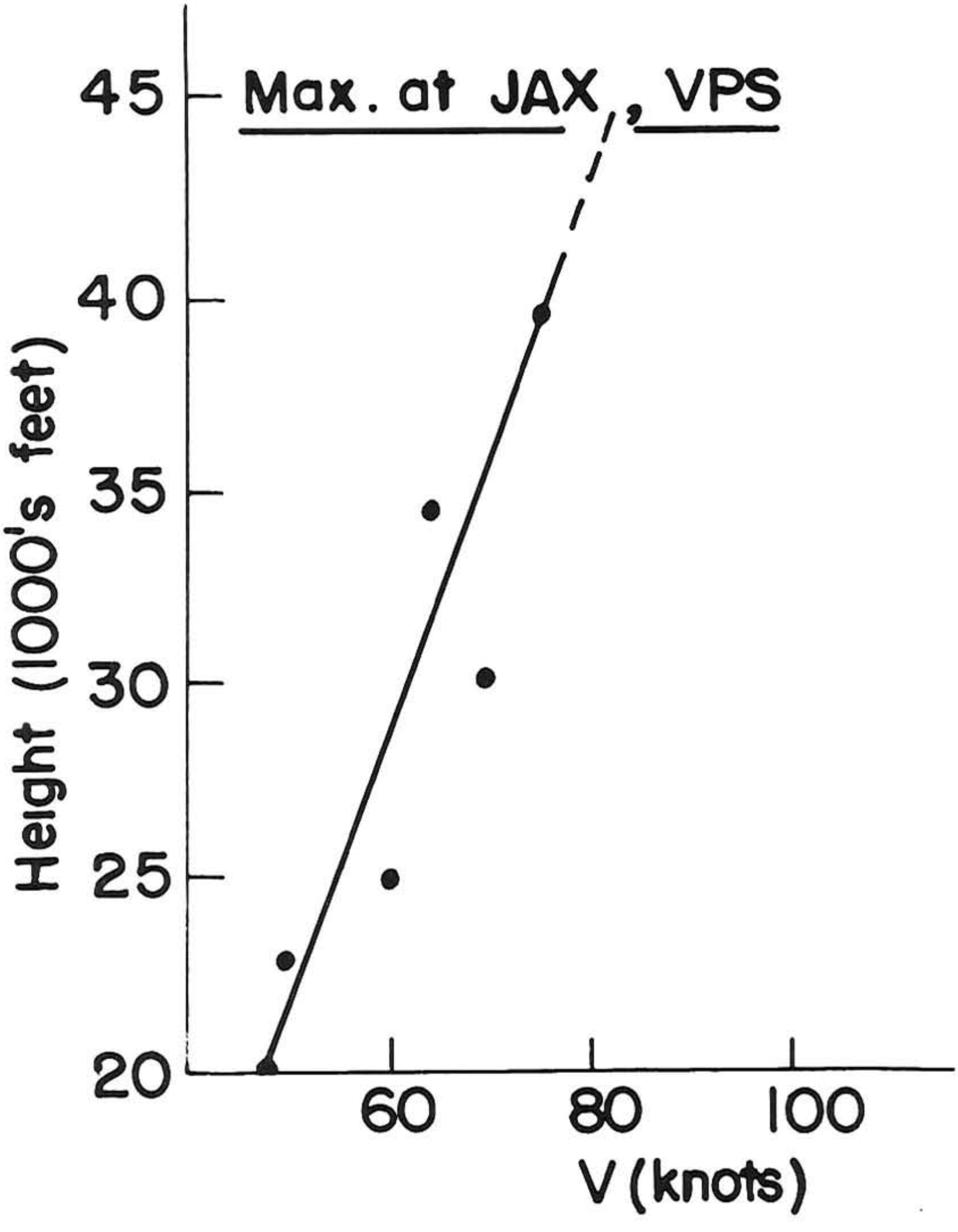

Figure 6. Vertical wind profile at Tampa, Fla., 6 March 1958, 0000 GMT. Also level of maximum wind at JAX and VPS. Extrapolated part of wind profile dashed. From Riehl (1961).

Early investigation: Several years ago the writer made a pilot study of the irregularities of the vertical wind profiles often encountered in the upper troposphere and stratosphere, with use of rawin ascents at Norfolk, Va. This led to the hypothesis that these fluctuations arose primarily from rapid hunting of the target by the GMD-1A ground equipment at low elevation angles. If the hypothesis is valid, the oscillations could be suppressed if elevation angles averaged over one or two minutes are used in wind evaluation rather than discrete values read at one-minute intervals.

Silver Hills Ascents: For further study the Chief of the United States Weather Bureau was approached. At his request, the station at Silver Hills, Md., printed both elevation and azimuthal angles 10 times per minute on 20 soundings around New Year 1959. From these printouts, the one- and two-minute means of the angles were determined and the wind recomputed. Surprisingly, only little improvement over the Silver Hills routine elevation resulted. Next, simple curves were fitted to the angles, especially by means of 5-point and 9-point parabolic smoothing, where points were one minute apart. Again the outcome was disappointing; it indicated that amplitude and frequency of the wind "perturbations" along the vertical were sufficiently large so that other methods had to be found for their suppression.

With this, the initial attempt of trying to eliminate the trouble directly through smoothing of the angles was abandoned. Instead, the possibilities of fitting curves to the winds reported at one-minute intervals were investigated next. A first try with fourth-order polynomials produced excellent results near jet stream cores. Due to the nature of the function, however, the computed curves departed sharply from hand-smoothed wind profiles only a short distance above and below the jet cores. After some further attempts, Dr. John Mihaljan programmed a routine for harmonic analysis on IBM-704 equipment. This program was considered successful. In the following, the steps undertaken in the course of the harmonic analysis will be described.

Harmonic Analysis of Silver Hills Ascents

Fig. 7 contains a plot of one of the Silver Hills ascents, picked because the oscillations above 30,000 feet are typical of what was observed. Even so, the range of the individual maxima and minima nevertheless approached the magnitude of the wind itself. Therefore, as pointed out by Reiter (1958), a small shift of 1,000 to 2,000 feet

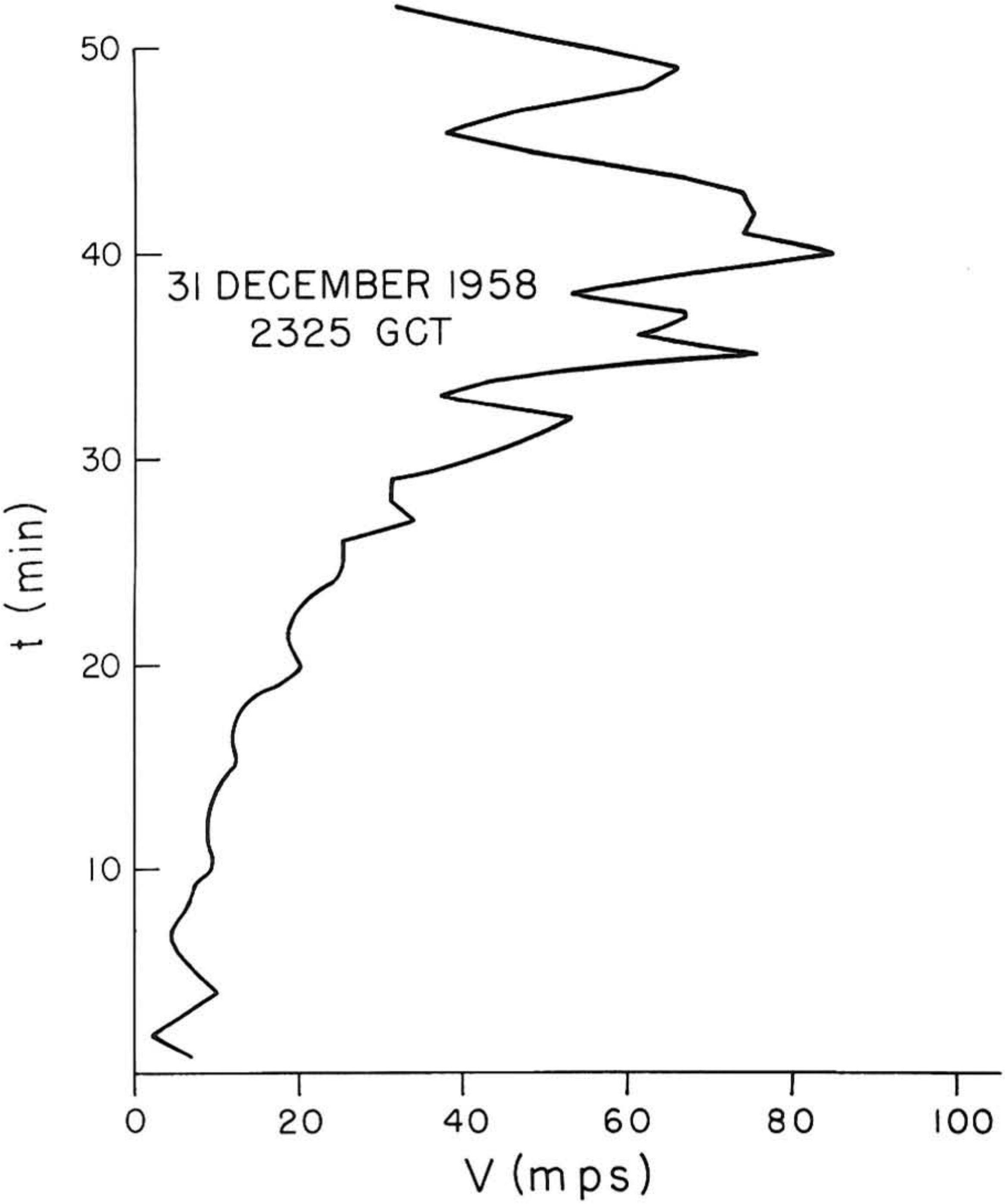

Figure 7. Profile of wind speed against time after balloon release, Silver Hills, Md., 31 December 1958, 2325 GMT. Profile drawn to follow winds plotted at one-minute intervals.

in the standard levels for wind transmission can produce large differences in reported wind speed. In our case this difference attains speeds up to 40 mps. Clearly, if all fluctuations of Fig. 7 were realistic, chaos would prevail in the high-altitude windfield and proper traffic control would be next to impossible to achieve.

The following steps were executed in the course of the quantitative analysis:

1) Time-height curves were drawn for all 20 cases. From these it was apparent that an excellent approximation to the relation between these variables over the lowest 60, 000 feet is given by a straight line. Therefore, the transformation from height to time was not investigated further; all analysis was performed with time as independent and wind speed as dependent variable. In routine practice, linear coefficients for the time-height transformation can be found readily from the input data into the machine program. If desired as a guard against occasional non-uniform ascent rates, a second order term can be programmed in addition.

2) For harmonic analysis, a closed set of data must exist, i.e., the first and last values of the function to be analyzed must be equal. This is not the case in Fig. 7, and at first a straight line must be subtracted from the profile so that starting and terminal values of the residual function will be identical. In view of the strong oscillations in the top region, it would be unsatisfactory simply to use the last reported point. We must search for a value representative of the highest portion of the ascent. Trials were performed by averaging the top 5, 7, 9 and 11 points. The mean of nine points (Fig. 8) gave representative results and was adopted. In Fig. 8 the line marked L_j (second from left) is the straight line subtracted from the sounding. The function marked D_j (center in Fig. 8) depicts the residual to be treated. This residual extends over four minutes less than the original sounding because of the method adopted in stabilizing the top value.

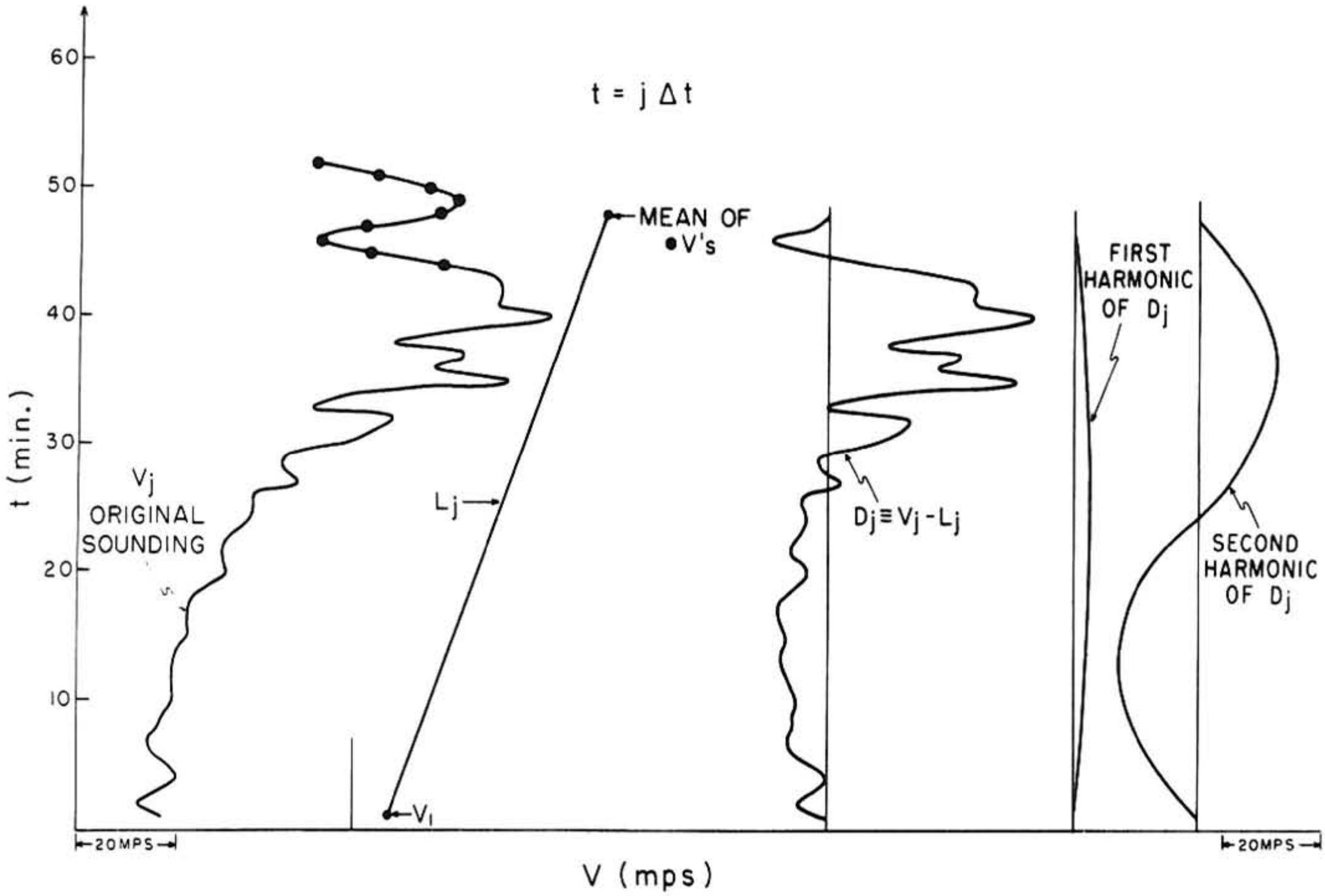

Figure 8. Harmonic Analysis scheme for sounding of Fig. 7. Profile of Fig. 7 repeated on left with heavy dots for points used to determine top wind through which finished sounding will pass. Second from left is straight line subtracted from the wind profile to produce residual (center of diagram) where beginning and end points match. Contributions by first and second harmonic on right.

3) The harmonic analysis may be performed now. On the right side of Fig. 8, the first two harmonics have been plotted for the example. Of these, the first harmonic contributes very little, and this is due to the fact that the sounding terminated at 52,000 feet. If the ascent had continued to 60,000 feet where speeds may have been very small, the amplitude of the first harmonic would have been much larger (see Figs. 14-16). This dependence of the amplitude of the lowest harmonics on the terminal point of the sounding is without relevance for the procedure.

4) The straight line plus individual harmonics may now be added cumulatively; this is illustrated in Fig. 9 up to the seventh harmonic. Clearly, the higher order fluctuations are suppressed in these curves. An excellent fit already is obtained by the sum of five harmonics, portrayed in Fig. 10, where the original sounding is repeated and the smoothed curve using five harmonics has been superimposed.

With this, a solution of the problem is given in principle. As readily apparent, the LMW parameters and other parameters desired in air traffic management can be extracted by computer procedure from the smoothed sounding. All intermediate steps of plotting the soundings from teletype data and attempting to reconstruct the whole ascent manually are eliminated. In addition to improved quality obtained by utilization of the entire balloon run, the routine provides for a very considerable time saving in making the winds rapidly available to air traffic management.

Design of Large Sample Test

In the foregoing, feasibility of the harmonic analysis approach to quantitative description of wind profiles has been demonstrated. Two questions to be resolved now are as follows : 1) is the method satisfactory for a very high percentage of all types of wind soundings encountered; 2) at which harmonic should the integration of the wind profile be terminated?

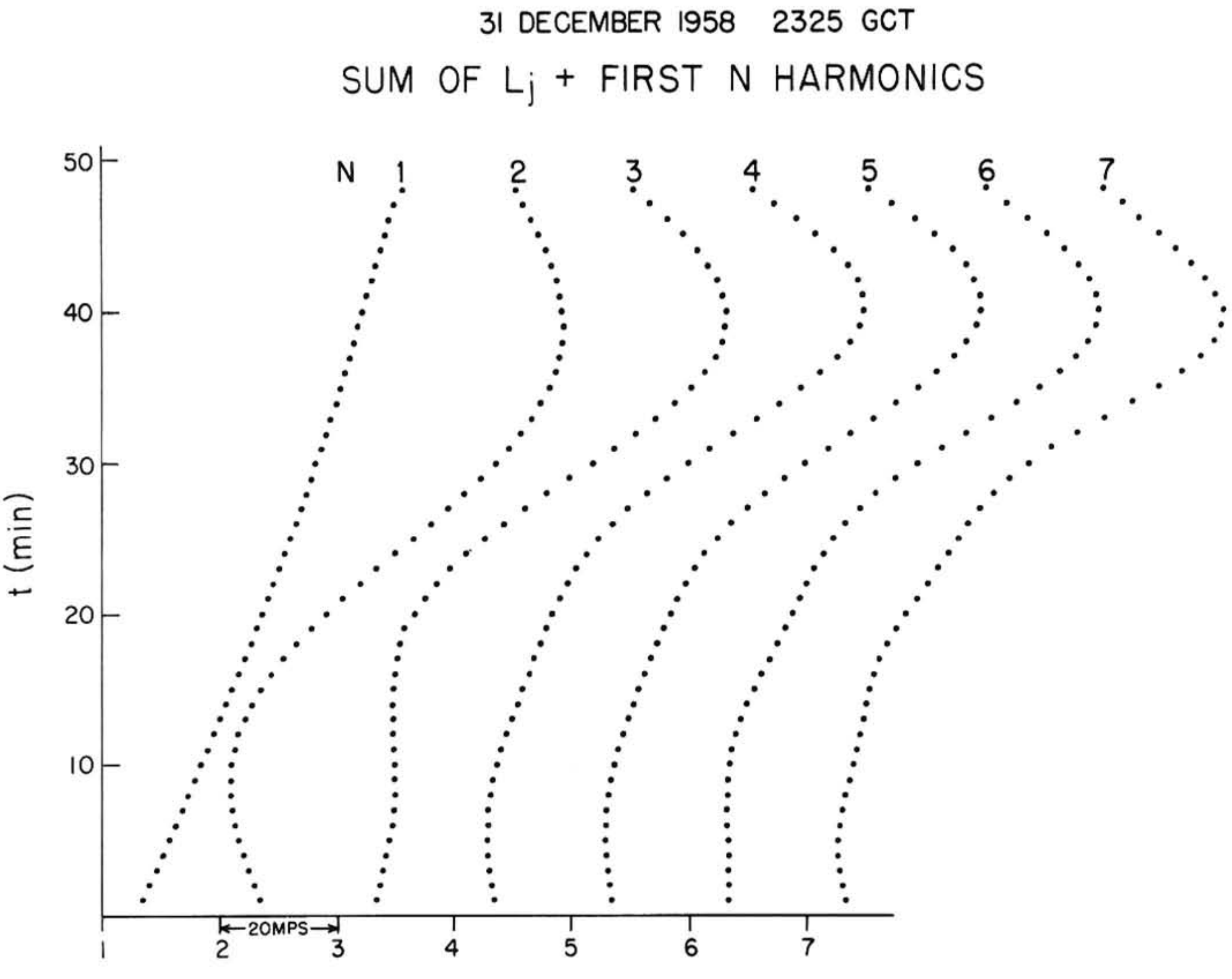

Figure 9. Harmonic analysis: representation of profile in Fig. 7 through accumulative adding of straight line plus first n harmonics up to sum of straight line plus seven harmonics.

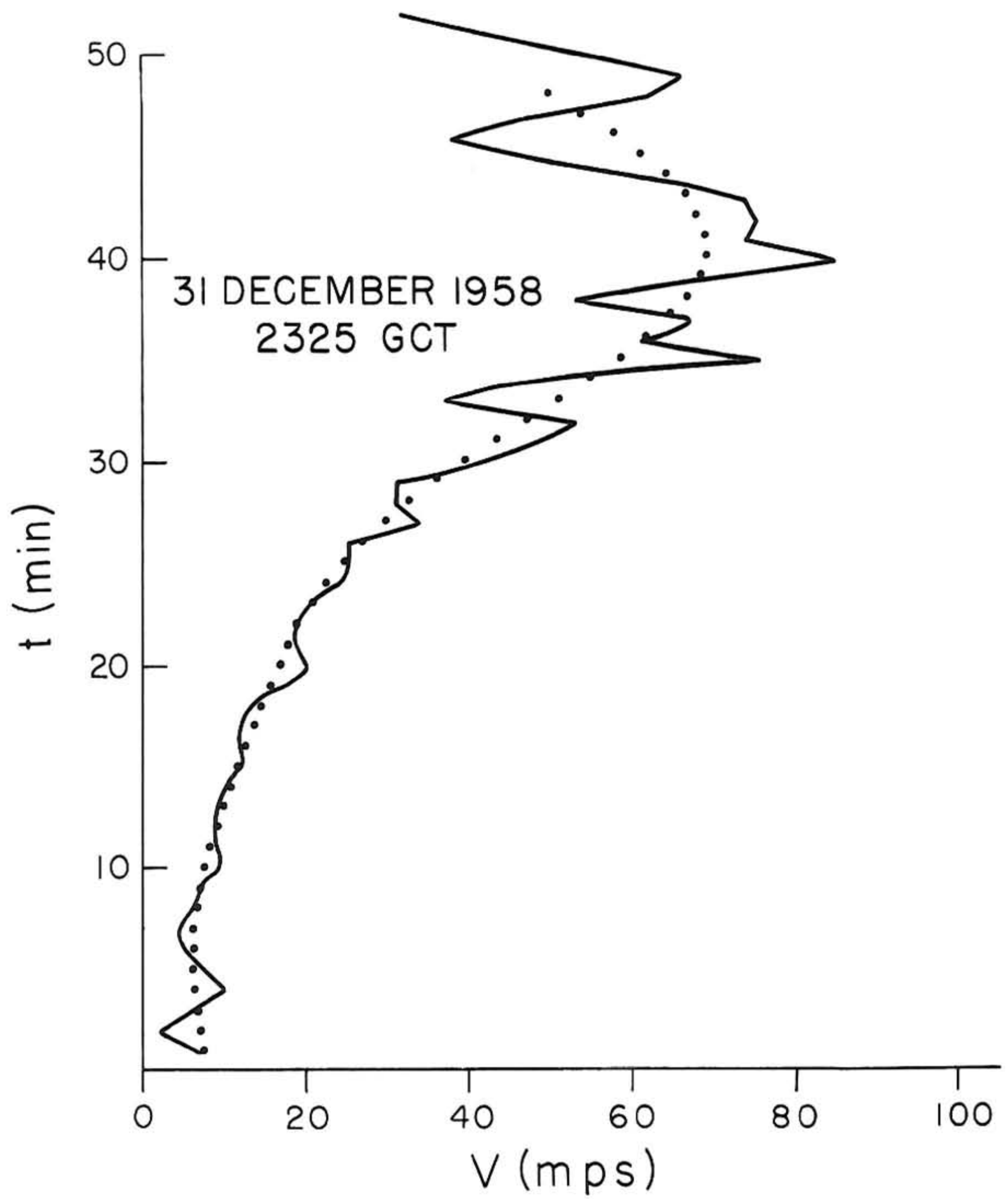

Figure 10. Profile of Fig. 7 repeated and approximation of ascent by straight line plus five harmonics (dots).

An early thought was to cut off at the first minimum of amplitude of the harmonics, but this proved untenable. For further guidance, an enlarged test sample was needed. In view of the rapidity of modern calculating methods, the limitations placed on this kind of analysis in pre-electronic computer days are no longer present. It was decided to test the scheme with a full thousand soundings.

The Chief of the United States Weather Bureau again was approached with the request for selection of soundings at the National Weather Records Center, Asheville, N. C., and for computation of the harmonics at the Joint Numerical Prediction Center at Suitland, Md. The following specifications were given, including recommendations made by Dr. Helmut Landsberg of the United States Weather Bureau:

1) The selection of observations should be spread over all stations in the continental United States with GMD-1A equipment.

2) The most recent winter period should be used (October 1958 - March 1959).

3) At a given station, observations accepted should be spaced at least three days apart in time to avoid possible auto-correlations

4) Three quarters of the soundings accepted should have winds in excess of 100 knots. Fig. 11 contains the frequency distribution of maximum wind actually realized.

5) The minimum length of run of any sounding should be 50 minutes.

6) For long runs, the analysis should terminate at the 64th minute so that after the nine-point smoothing at the top a total of 60 minutes (60 points at one-minute intervals) would be available for processing. Almost 90 percent of the ascents met this specification so that the sample is nearly homogeneous in this respect.

The selection program was carried out at Asheville. Then the Joint Numerical Prediction Center performed the calculations on the IBM-704 equipment formerly in use there with the FORTRAN program provided by Dr. Mihaljan. Computations were carried to the tenth harmonic which was thought to lie well beyond the anticipated cut-off point, a prediction not fully realized later.

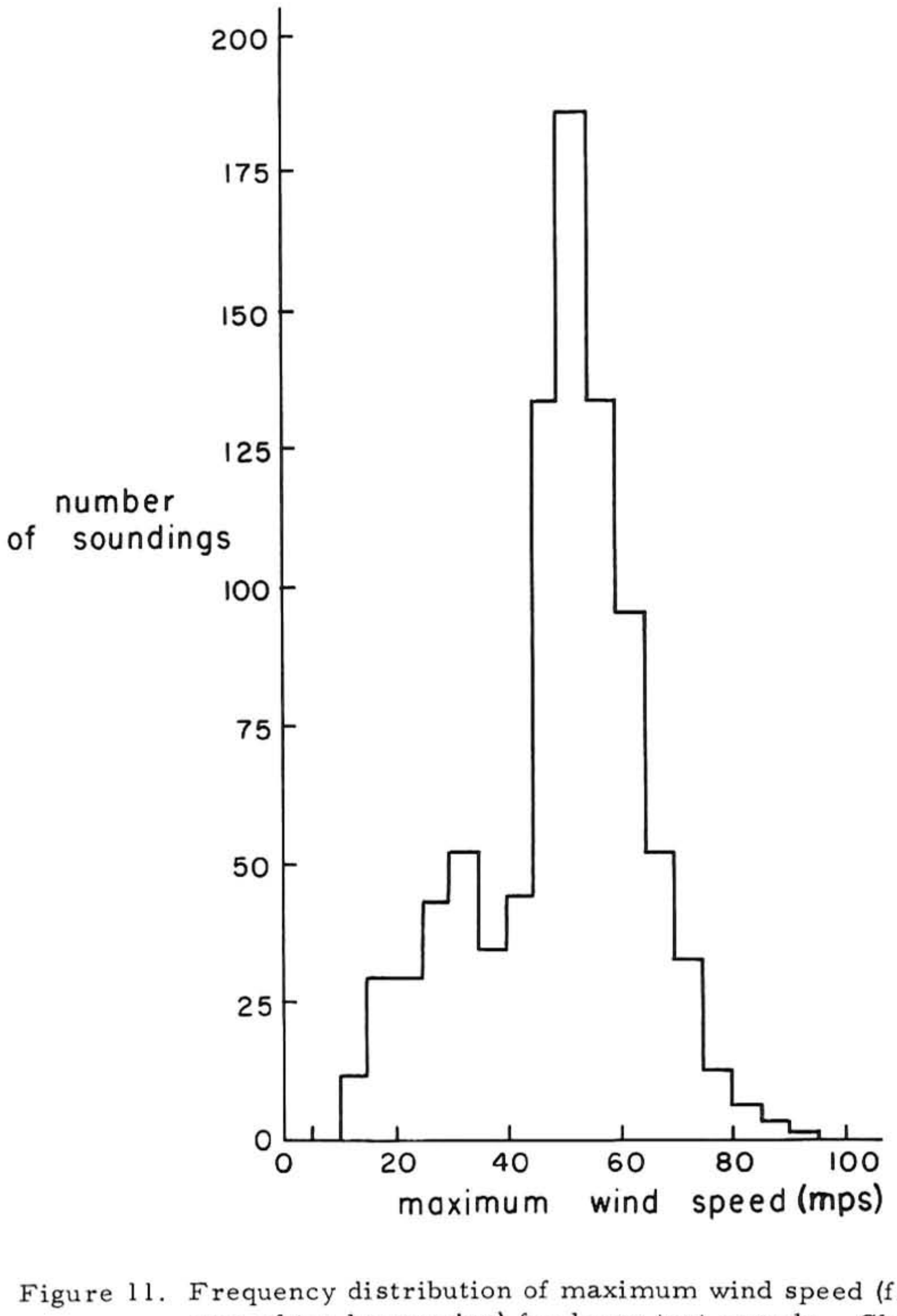

Figure 11. Frequency distribution of maximum wind speed (from sum of ten harmonics) for large test sample. Class interval is five mps.

Results were transmitted by the Weather Bureau in tabular and in card form.

Evaluation of the Large Sample

The initial intent was to superimpose plots of original soundings as in Fig. 7 on successively higher approximations (Fig. 9) to find the best fit by qualitative methods. At the time of the calculations, however, the Joint Numerical Prediction Center did not yet possess an automatic plotting device. Since manual plotting of the 600,000 output values obviously was out of question, it became necessary to develop statistical tests only, in a problem where the route to be taken in statistical analysis was not altogether clear. No doubt, however, it was all to the good that quantitative evaluation was enforced.

Since it was possible that the optimum representation of an ascent was, at least in part, a function of the maximum wind speed itself, the sample was divided into four groups with strongest wind less than 30 mps, 30-45, 45-60, and greater than 60 mps. We may note immediately that a fundamental dependence of the results on maximum wind speed fortunately did not materialize so that this parameter may be omitted with safety from the final procedure.

Decay of amplitude with frequency: For determination of relations between amplitude and frequency of the harmonics, the amplitude of each harmonic was expressed in percent of the maximum wind as given by the sum of 10 harmonics. Since the highest-frequency oscillations are already eliminated by restricting the calculations to 10 harmonics, this maximum wind is considered as an acceptable value for purposes of normalizing.

Fig. 12 contains the frequency distribution of amplitude vs percentage of soundings in each velocity group on an accumulative basis. As may be expected, the amplitude decreases with wave number though at a rapidly diminishing rate at higher wave numbers. The amplitude of the first harmonic generally exceeds 50 percent. Thus this first approximation has considerable magnitude, especially when it is recalled that the low-percentage end of the distribution

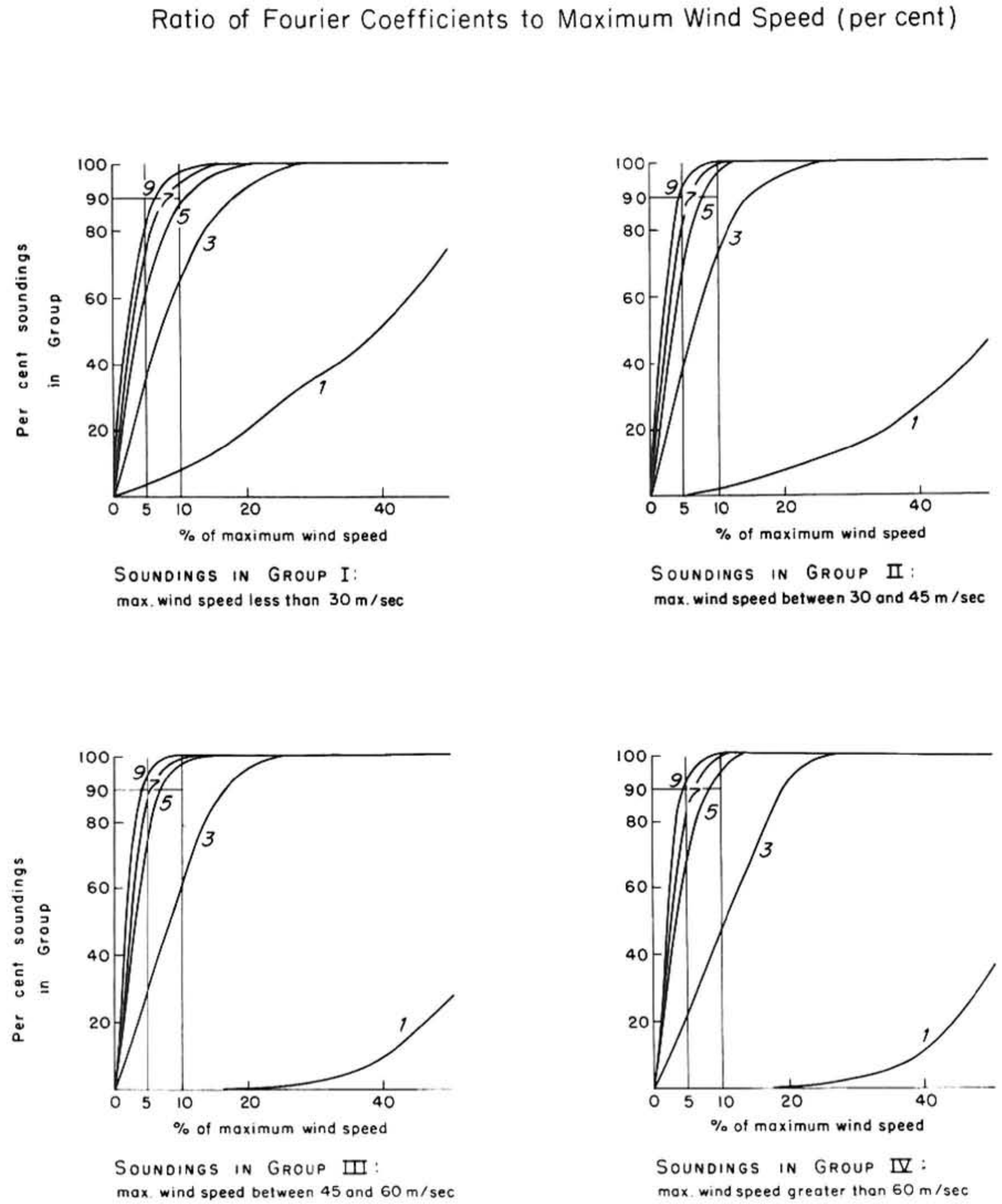

Figure 12. Analysis of large test sample: ratio of Fourier coefficients of harmonic analysis to maximum wind speed as given by the sum of ten harmonics (percent). Profiles are accumulative along both coordinates. Curves given for first, third, fifth, seventh, and ninth harmonic.

for this harmonic arises from the terminal point of the balloon runs rather than from the wind profile itself.

Fig. 12 can furnish guidelines for the highest harmonic to be accepted. For instance, if we specify that the amplitude should not exceed 10 percent of the maximum wind, as defined above, in more than five percent of the soundings, we would be satisfied in carrying the routine analysis to five harmonics. If the criterion is set at five percent of the maximum wind for no more than 10 percent of the soundings, routine evaluation must be extended to nine harmonics at maximum wind speed of the higher classes. Various attempts to follow through on this basis, however, did not lead to fully satisfactory results for reasons which will appear presently.

Percent deviation of individual winds: The main operational question regarding a computed wind at a given altitude is this: to what extent does this wind approximate the true wind integrated over the typical length of the microstructure? Given the individual wind V_n composed of the sum of n harmonics and the true wind V_T, then the quantity $(V_n - V_T)/V_T$ furnishes a measure of the departure. Now we do not know V_T but only V_{10}, composed of the sum of 10 harmonics, a wind in which most effects of microstructure and inaccuracies in wind determination have been suppressed already. We may therefore consider the quantity $(V_n - V_{10})/V_{10}$. However, we presume that V_{10} itself is not always acceptable; otherwise we should adopt this wind directly. We shall specify that V_n need approximate V_{10} only to a certain percentage for a given fraction of all the points on an individual wind run, such as 90 percent of V_{10} for 80 percent of the points, i. e., 48 points out of 60. This criterion must then be met by a specified fraction of the sample. With suitable assumptions about these limits, the undesirable oscillations still present in many of the profiles composed of ten harmonics will be eliminated.

This calculation, specifying $(V_n - V_{10})/V_{10} = 10\%$, was performed with the additional provision that $V_n - V_{10}$ of 3 knots or less was always acceptable since this difference is without operational consequence. Fig. 13 gives the results, and it is immediately evident that the lower harmonics satisfy the criterion quite poorly. For instance, for the sum of five harmonics at maximum speeds above 60 mps, only 30 percent of the cases have 80 percent of the points in

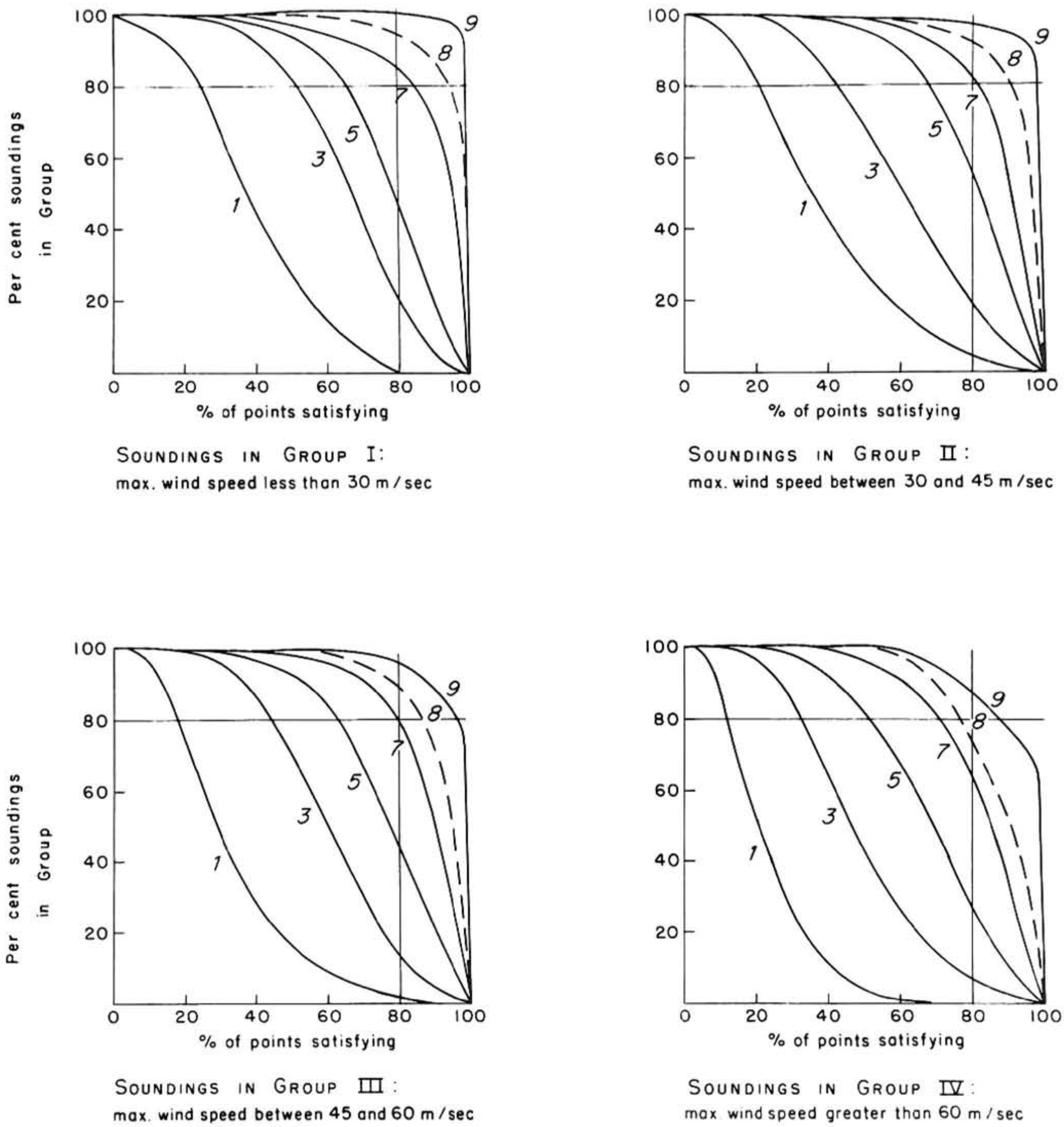

Figure 13. Analysis of large test sample. For explanation of this graph see text.

the individual runs satisfying the criterion. We must go to eight harmonics to reach the 80 percent level, and to seven harmonics for the lowest maximum speeds. It is not possible to ascribe the poor performance of the sum of five harmonics mainly to undesirable oscillations of the profiles with ten harmonics. Therefore, we must conclude that the profiles composed of five harmonics do not render a sufficiently good approximation to the true wind in most cases, so that we must integrate at least over seven harmonics.

This is a rather surprising outcome. It could, of course, be improved by raising the level of absolute acceptability, say, to five knots and by lowering the requirement on $(V_n - V_{10})/V_{10}$, say, at $\overline{\leq}$ 20 percent. But with this the limits are very relaxed; given V_{10} = 100 knots, anything from 80 to 120 knots will verify. This is considered excessive latitude, and the conclusion was drawn that in most instances the wind profile had to be approximated with seven or more harmonics. This conclusion was verified further by qualitative spot-checking of about 200 wind runs.

Amount and altitude of maximum wind: From experience, the quality of a whole sounding is correlated with representativeness of amount and altitude of the strongest wind itself. Therefore, the maximum points of the different harmonics were investigated, next, this time in relation to the original soundings. All original input data were plotted in the form given in the upper left of Figs. 14-16. The soundings with well defined or at least recognizable maximum were sorted out and the "center of gravity" of five wind values centered on the maximum point was computed for each ascent. The peaks as given by the sums of five, seven, and nine harmonics were compared with the maximum wind so defined, with the test specification that speed should be within 10 per cent and altitude within 2,000 feet.

It turned out that the altitude criterion was met in nearly all instances. Regarding speed, the sum of nine harmonics failed to meet the criterion in only 30 cases, the lower harmonics more frequently. Taking this test together with the last one, it would appear that the highest harmonic treated gives the best results. Yet the position at the conclusion of the three tests still was not considered as entirely satisfactory.

Frequency of maxima along the vertical: The trouble is apparent in Figs. 15-16, where the sum of nine harmonics breaks over into the irregular type of profile with several maxima, one of the main features of the original ascents to be eliminated. Of course, more than one real maximum may exist along the vertical, so that a guide is desired to distinguish true double maxima, presumably also with large-scale horizontal extent, from maxima

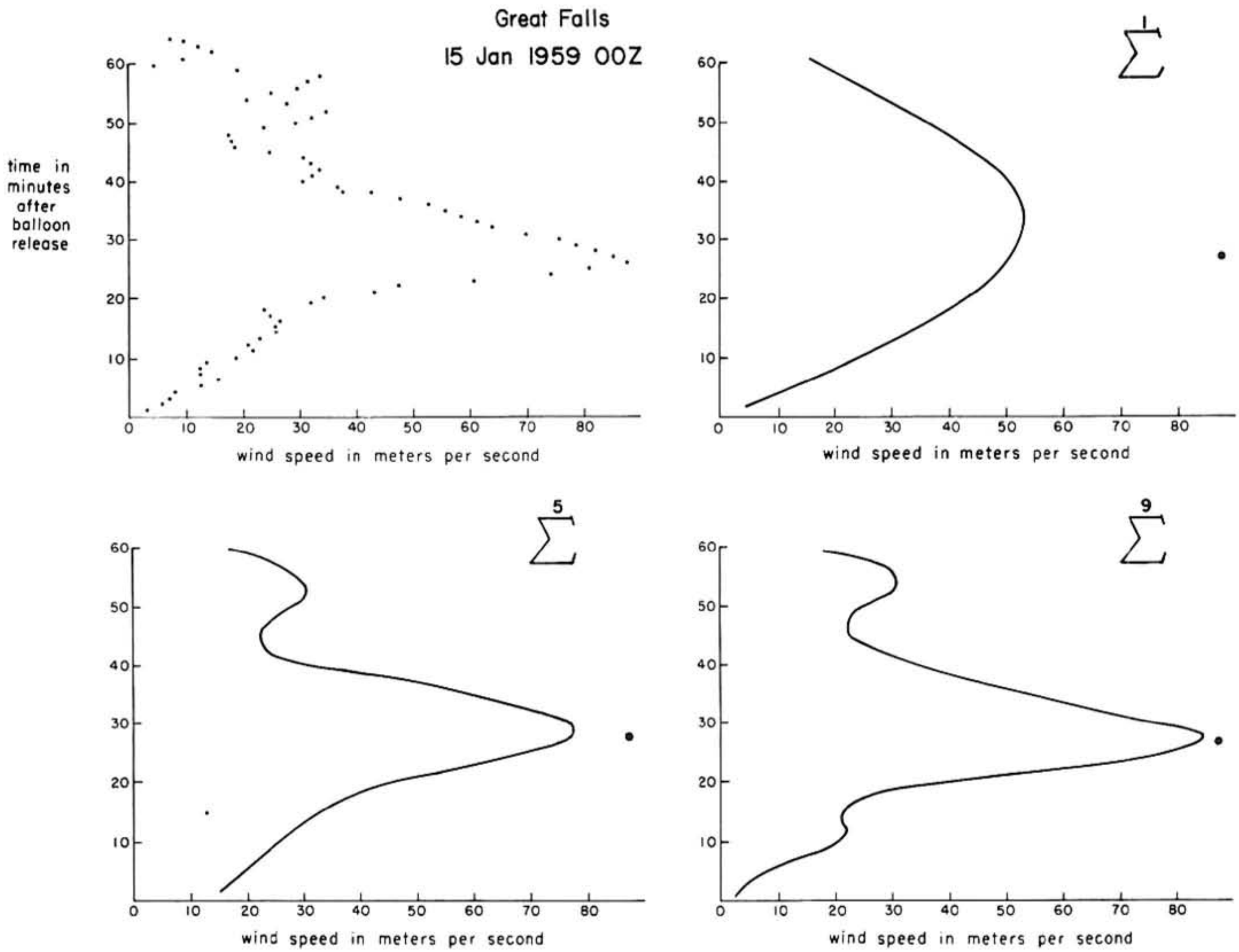

Figure 14. Harmonic analysis for Great Falls, Mont., 15 January 1959, 0000 GMT. Upper left: original sounding. Upper right:. straight line plus first harmonic. Lower left: straight line plus sum of five harmonics. Lower right: straight line plus sum of nine harmonics. Heavy dot marks maximum wind from original profile.

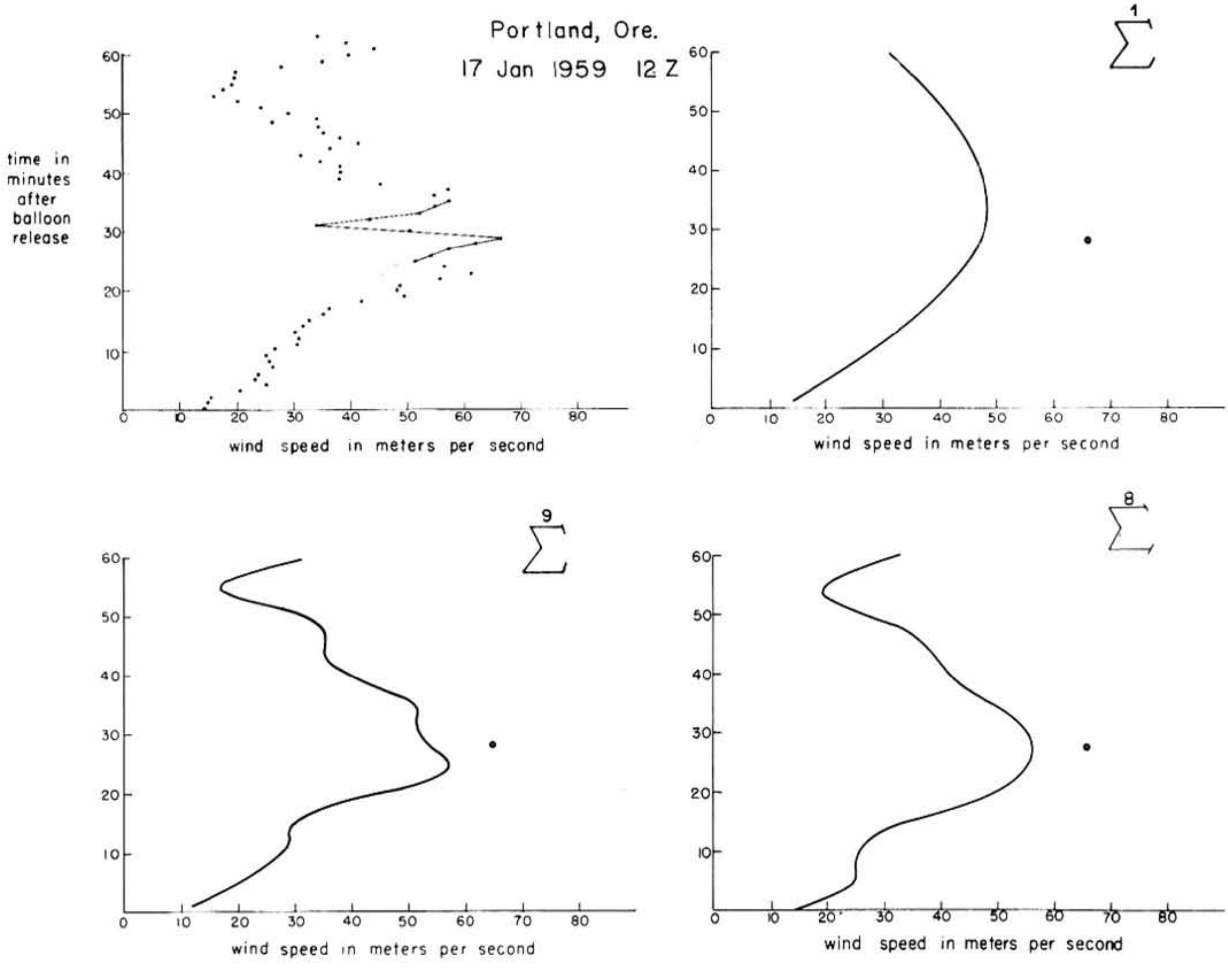

Figure 15. Harmonic analysis for Portland, Ore., 17 January 1959, 1200 GMT. Upper left: original sounding plus lines for layer with strongest oscillation. Upper right: straight line plus first harmonic. Lower left: straight line plus sum of nine harmonics. Lower right: straight line plus sum of eight harmonics. Heavy dot marks maximum wind from original profile, in this case evidently without much significance.

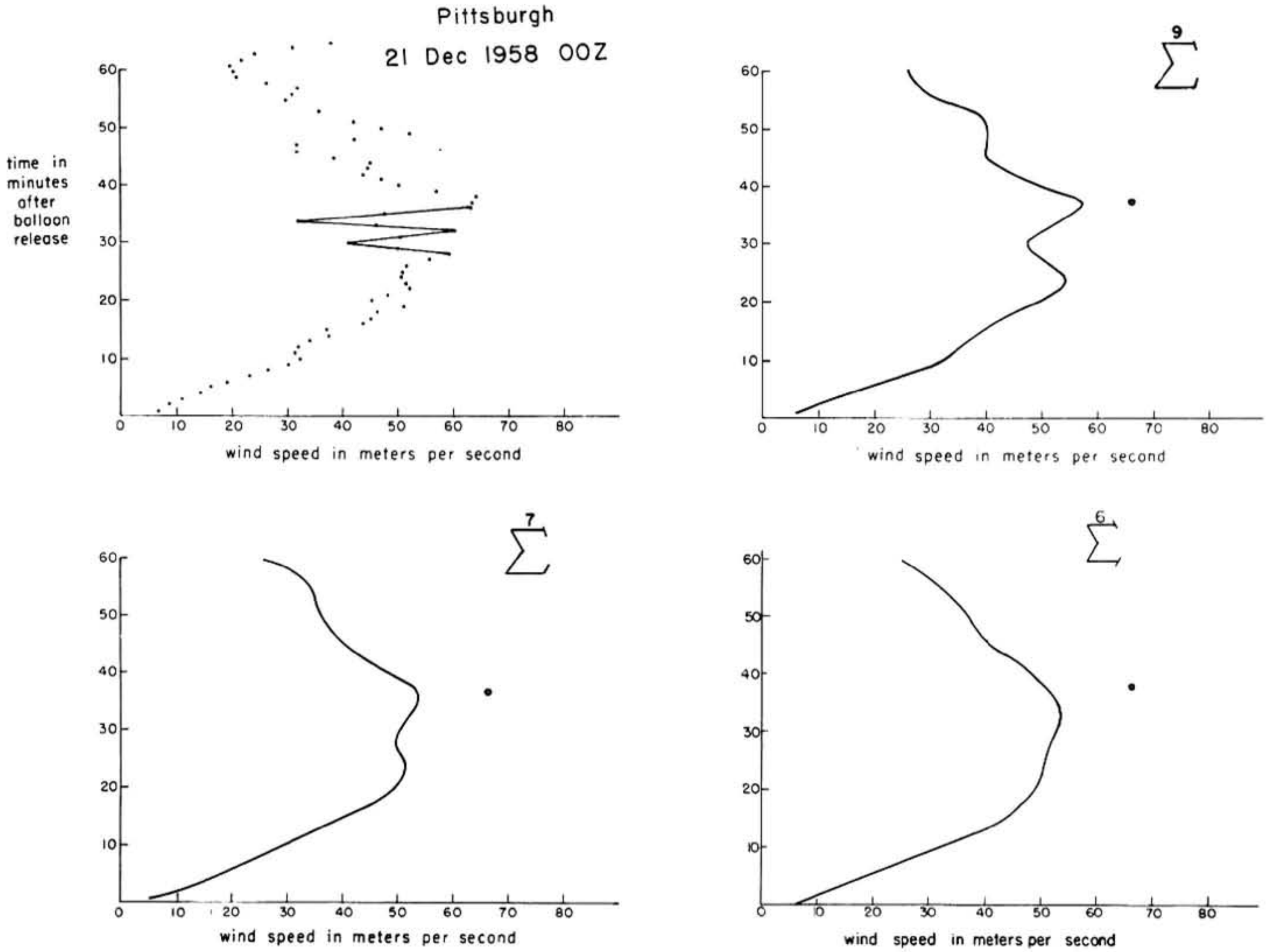

Figure 16. Harmonic analysis for Pittsburgh, 21 December 1958, 0000 GMT. Upper left: original sounding plus lines for layer with strongest oscillation. Upper right: straight line plus sum of nine harmonics. Lower left: straight line plus sum of seven harmonics. Lower right: straight line plus sum of six harmonics. Heavy dot marks maximum wind from original profile, in this case also without much significance.

introduced by microstructure and inaccurate wind readings. The sample contained 180 soundings with quality of that shown in Fig. 14. Clearly, the whole profile must be accepted in such cases, including the double structure. From a survey of double maxima which appeared in these soundings (47 out of 180), it was found that time separation between two maxima exceeded 15 minutes (about 15, 000 feet altitude) in nearly all instances. Hence, we may form the criterion that maxima with such time separation should be accepted, but that with small separation a lower harmonic should be adopted.

Recommended Procedure

a) Form the sum of nine harmonics and test whether maxima in the altitude range 20, 000 to 50, 000 feet are separated by more than 15 minutes.

b) If the 15-minute criterion is not met, test successively lower harmonics until it is satisfied.

Examples: The Great Falls ascent (Fig. 14) should be reproduced closely, except for the confused structure of the second peak. A crude approximation is furnished by the first harmonic. But the quality of the approximation increases markedly with successively higher harmonics. The sum of nine harmonics yields a very fine approximation; hence, the computation routine, in which this wind should be examined at first, can terminate immediately.

The Portland and Pittsburgh soundings (Figs. 15-16) are much poorer; though they by no means portray the worst that has been encountered. Some of the most objectionable features of these runs have been emphasized by connecting the points in the layers with extreme oscillation. In neither instance are these oscillations eliminated within desired limits -- though strongly damped -- by the profiles composed of nine harmonics. We next examine the sum of eight harmonics and find that this rectifies the Portland ascent to a quite acceptable profile which terminates the calculation there. The Pittsburgh sounding retains the double peak and this still holds for the sum of seven harmonics. Finally, the sum of six harmonics yields a useful profile, and the computation is finished.

Conclusion

An attempt has been made to demonstrate that the method of upper-wind analysis developed here provides an operationally useful tool for numerical representation of certain aspects of the upper-wind observations. The objective was limited in that the program was concerned mostly with the high-speed layer normally found in middle latitudes between 20,000 and 50,000 feet, i.e., the layer frequented by subsonic jet and high-flying propeller-driven aircraft. In this layer wind direction varies very little with height, so that only the speed distribution was scrutinized. It is not claimed that the perfect approximation technique has been determined. But is believed that parameters for air traffic control extracted from the numerical profiles, such as the LMW, can be computed satisfactorily in almost all instances.

In view of this encouragement an extension of the work described here may be considered for the future:

1) For a new sample, the winds are broken into east-west and north-south components.

2) Harmonic analysis is performed for each component separately.

3) The component are recombined.

Such a procedure is likely to yield a useful quantitative expression for the low levels and the higher parts of the stratosphere where turning of wind with height is apt to be large. Further, a unique determination of the optimum number of harmonics for the wind representation can be made. Such an optimum evidently must exist between the crude approximation of the lowest harmonics and the high frequency oscillations which produce the marked irregularities of the wind profiles. The best solution will be given by the wind composed of n harmonics where n is the number which most often does not require testing for lower harmonics when the 15-minute side condition is not satisfied. It may well be that the sum of nine harmonics will turn out to represent the optimum. Due to the fact that the present analysis was not carried beyond ten harmonics, this matter cannot be settled conclusively with the present sample.

Assuming a satisfactory outcome for this new analysis, the whole wind message can be greatly compressed, compared with present-day messages. It would contain the length or height of the run, the surface wind, the slope of the straight line and two sets of coefficient for the two wind components. Given nine harmonics, the whole message would contain no more than ten 5-figure groups at most. The sounding would be prepared with small computers at the rawin stations, and the message would be transmitted to a large central computer without need for any intermediate hand-analysis steps.

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