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Characteristics of Trackable Radar Angels

T. H. Roelofs

Prepared for Geophysics Research Directorate, Air Force Cambridge Research Laboratories, Office of Aerospace Research, United States Air Force, Bedford, Massachusetts.

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CHARACTERISTICS OF TRACKABLE RADAR ANGELS

T. H. Roelofs

Center for Radiophysics and Space Research
CORNELL UNIVERSITY
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CHARACTERISTICS OF TRACKABLE RADAR ANGELS

Abstract

Clear air radar angels were tracked with an FPS-16 radar at Wallops Island, Virginia. Observations were made at different times of the year under a variety of weather conditions. On cloudy days, echoes having characteristics similar to clear air angels were tracked.

The radar had a beam width of 1.2 degrees, a wavelength of 5.5 centimeters, and was operated at a pulse length of .25 microsecond with a peak power of 1.2 megawatts.

Data consist of flight trajectories of the echoes and a record of power returned. Radiosonde profiles of the atmosphere were obtained from an on-site weather station.

It may be that this kind of data can not only clarify the angel problem but also provide convenient means for studying local atmospheric motions, such as the sea breeze. Evidence is given that indicates the meteorological nature of angels. A tentative model is suggested which would account for most of the observed characteristics.

INTRODUCTION

Generally speaking radar "angels" may be defined as radar echoes coming from a region in the troposphere that contains no objects visible to even the aided eye.

There is disagreement among writers concerning the cause of radar angels. Some maintain the view that the echoes are from birds, insects, or particles in the troposphere.[1,2] Although these targets will undoubtedly explain some observations, there is evidence that angel occurrence is related to meteorological phenomena as well. This claim has not been fully substantiated however, because large changes in refractive index within a few centimeters distance are required, and the presently available refractometer techniques are not capable of such resolution.

Many studies of radar angels have been performed,[3] for the most part either with a weather system[9] (PPI) or a vertically-pointed, stationary beam.[10,11] The observations on the PPI may take the form of line echoes having considerable horizontal extent, or localized dot echoes. The observations on the vertically-pointed system may be either persistent bands or coherent echoes that persist only for the order of seconds.

A third method of observation makes use of a tracking radar.[7] Roughly the procedure is to locate an echo by manually searching and then to attempt to lock-on and track

it automatically. This attempt is not always successful because of the characteristics of both the tracking system and the echo. However when the echo is trackable, one can obtain information concerning its radar cross section, its motion in the atmosphere, and its "lifetime".

This report presents the characteristics of a number of angels, all having the somewhat special property of being trackable with the FPS-16 system.

EXPERIMENTAL PROCEDURE

The track data were recorded automatically on magnetic tape and later transferred to IBM printout. These data consisted of time (usually in 10 second intervals), target range, azimuth angle, and elevation angle. In some cases, J-scope photographs were taken to record the character of the return pulse.

As a measure of power return, a record of receiver AGC voltage was kept. The relation between AGC voltage and power return was determined by tracking an aluminum sphere of known cross section. This relation was then used to obtain angel cross sections.

On all days when observations were attempted at least one radiosonde profile of the atmosphere was obtained.

The usual procedure was to search upwind from the radar at an elevation angle of 50 degrees or higher. This increased the probability of detection since (as will be shown) the magnitude of reflection increases markedly with elevation angle. This procedure also increased the potential observation time of a particular echo, since those upwind approach and pass nearly overhead of the radar site.

GENERAL CHARACTERISTICS

The general characteristics of the observed echoes will be given in this section. Detailed descriptions of angel behavior are found in the Appendix.

Days on which observations were attempted are listed in Table 1. This includes two clear days, four cloudy days, and two days with variable skies. On 26 March 1962 (cloudy) and 27 March 1962 (clear) it was not possible to lock-on and track a single angel. However several birds were tracked and it is interesting to compare and contrast them with angel echoes. During the cloudy morning of 30 April 1962, it was again impossible to locate a trackable angel. However, when the skies cleared at noon, a number of angels were tracked for relatively short periods of time.

On 28 May 1962, seven angels were tracked in a sensibly clear sky and three during a period of developing clouds. The onset of rain presented a cluttered picture on the A-scope and it was no longer possible to locate any trackable echoes.

On other days, the sky conditions and number tracked are as indicated in Table 1 and need no clarification.

Vertical motions will be discussed in greater detail in a later section. The figures given in Table 1 for vertical velocity are average values for each day of observation.

TABLE I

	1961			1962				
	12 July	26 Mar	27 Mar	30 April	28 May	9 July	30 July	31 July
Sky Condition AM	Clear	Cloudy	Clear	Cloudy	Clear**	Cloudy	Cloudy	Cloudy
Noon	Clear	Cloudy	Clear	P.Cloudy	Cloudy	Cloudy	Cloudy	Cloudy
PM	Clear	Cloudy	Clear	Clear*	Rain	Cloudy	Cloudy	Cloudy
Number Tracked	7	0	0	11	10	10	13	1
Average Tracking Time, Minutes	15.7	-	-	2.6	7.5	9.8	8.9	6.5
Number Having Upward Velocity	5	-	-	2	5	4	6	1
Average Upward Velocity Feet/minute	37	-	-	60	43	32	89	9
Number Having Downward Velocity	2	-	-	9	8	2	9	-
Average Downward Velocity Feet/minute	129	-	-	190	56	116	63	-

* All angels tracked in clear sky

** Angels No. 1 through No. 7 tracked in clear sky, No. 8 through No. 10 in cloudy sky

Radiosonde profiles showing temperature and dew point as a function of altitude are shown in Figures 10-14 (see Appendix). The altitudes of the observed angel echoes are plotted here also.

Perhaps the most consistent behavior of these angels is the strong dependence of radar cross section upon elevation angle. The mean dependence for individual days is shown in Figures 1 and 2. The abscissa is the elevation angle at which the angels were observed, 90 degrees being directly overhead. Angles to the left of 90 represent an approaching target and those to the right represent a receding target.

In Figure 2, it is seen that for 28 May 1962 and 9 July 1962, the mean dependence does not behave in the same manner as that observed for other days. It is suspected that this inconsistency is due to an inoperative AGC amplifier, since the AGC voltage remained essentially constant throughout all observations on these two days. Thus the cross section data for 28 May 1962 and 9 July 1962 are probably unreliable.

Plots of some individual targets are shown in the Appendix (Figures 15-17).

Another outstanding property is the apparent coherence of the echoes. The following Figures 3 to 6 illustrate this. Each figure is a record of azimuth position error, elevation position error, receiver AGC voltage, and time.

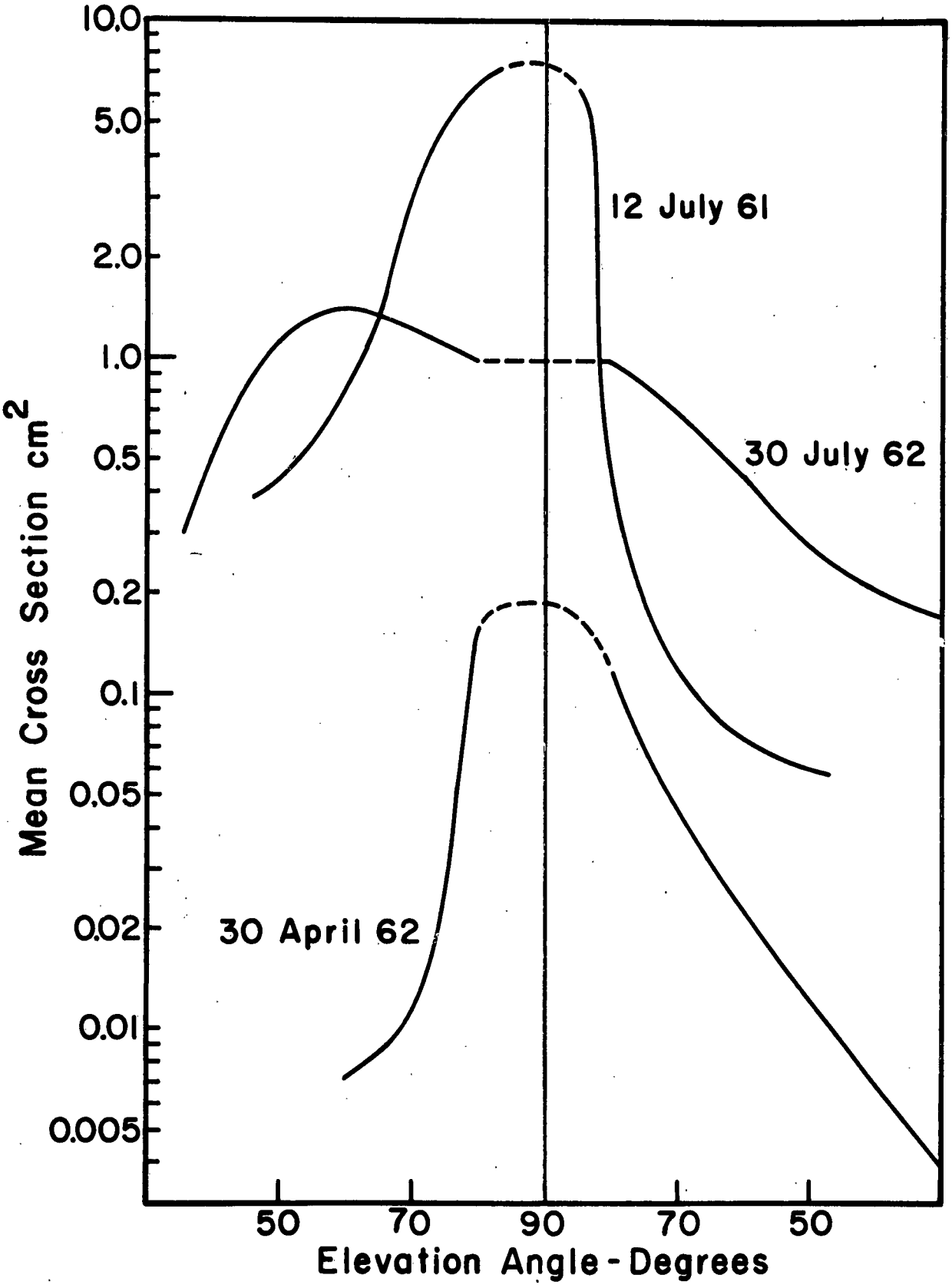

Figure 1

Mean Cross Section Versus Elevation Angle

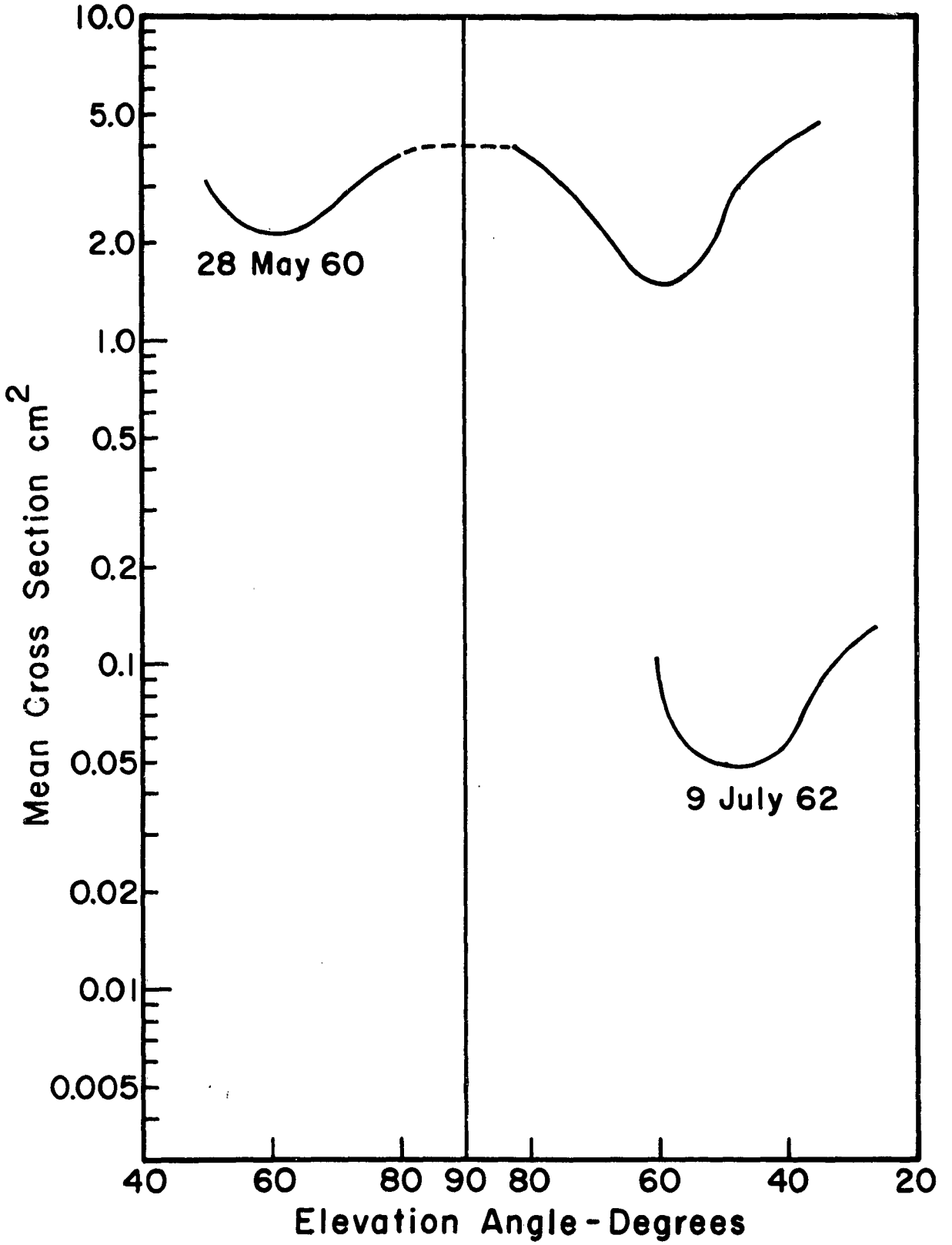

Figure 2

Mean Cross Section Versus Elevation Angle

The position error records give a qualitative indication of the degree to which the target may be distributed as opposed to an idealized point target. The receiver AGC voltage is a measure of the received signal strength. These records are shown for:

Figure 3 - A typical angel: range 6.6 kilofeet elevation angle 78°

Figure 4 - The same target: range 10 kilofeet elevation angle 25°

Figure 5 - A 6" aluminum sphere range 45 kilofeet

Figure 6 - A large bird (wing span of approximately 5 feet), range 4 kilofeet, elevation angle 10°

From Figure 3 to Figure 4 there is a noticeable increase in the scintillation of the elevation error signal at the lower elevation angle. Angel targets cause scintillation in position error much greater than that caused by the sphere at the same range. At the same power level the angel target scintillations are usually only slightly greater, which suggests that observed angel scintillation may be attributed, for the most part, to system noise. In a few cases large amplitude scintillations occurred sporadically which suggests a target capable of becoming distributed momentarily.

The fluctuations of echo signal strength received from most angels are on the order of those from the metal sphere, and far less than those from large birds.

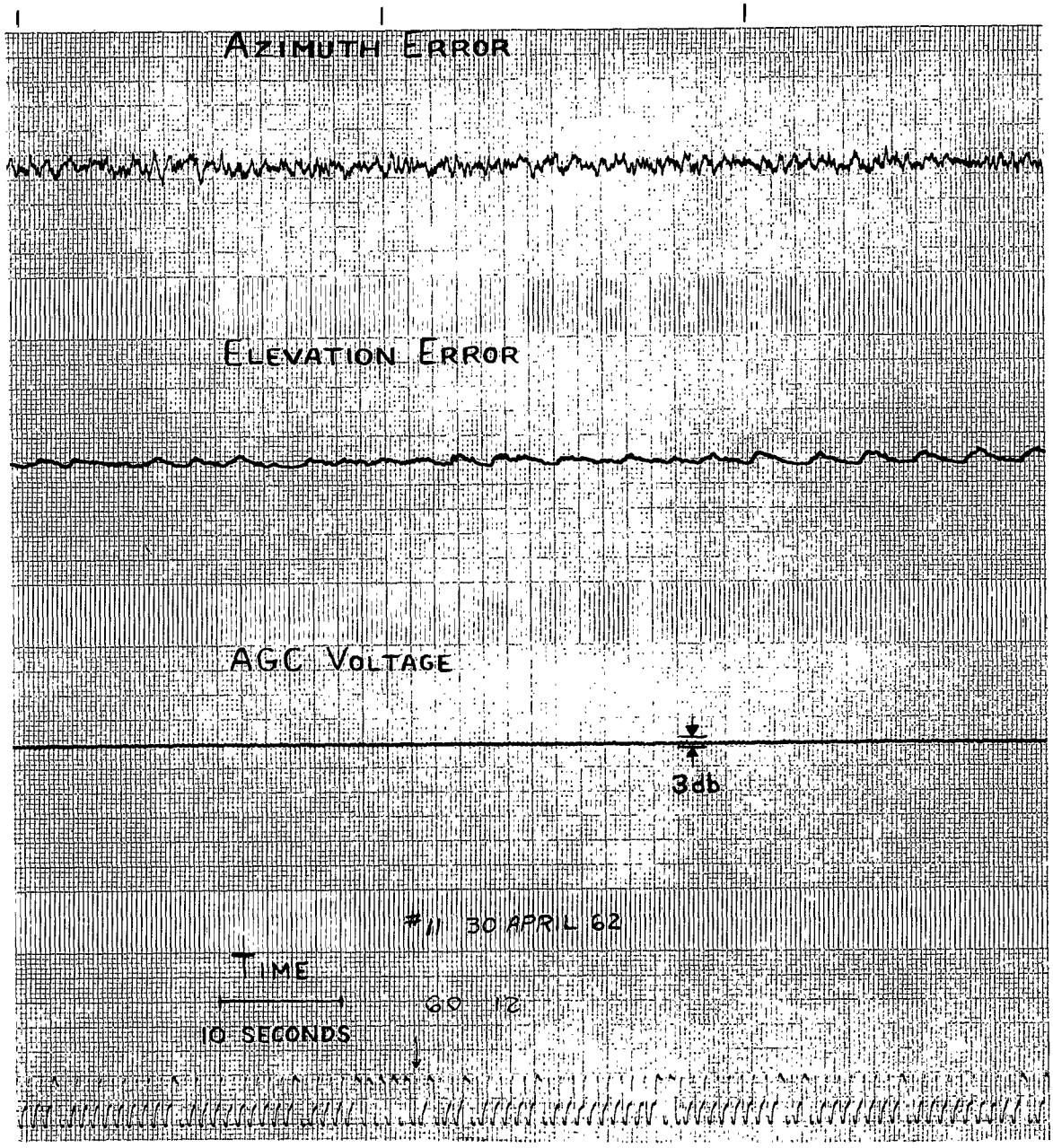

Figure 3

Typical Angel: Range: 6.6 kilofeet
Elevation Angle: 78°

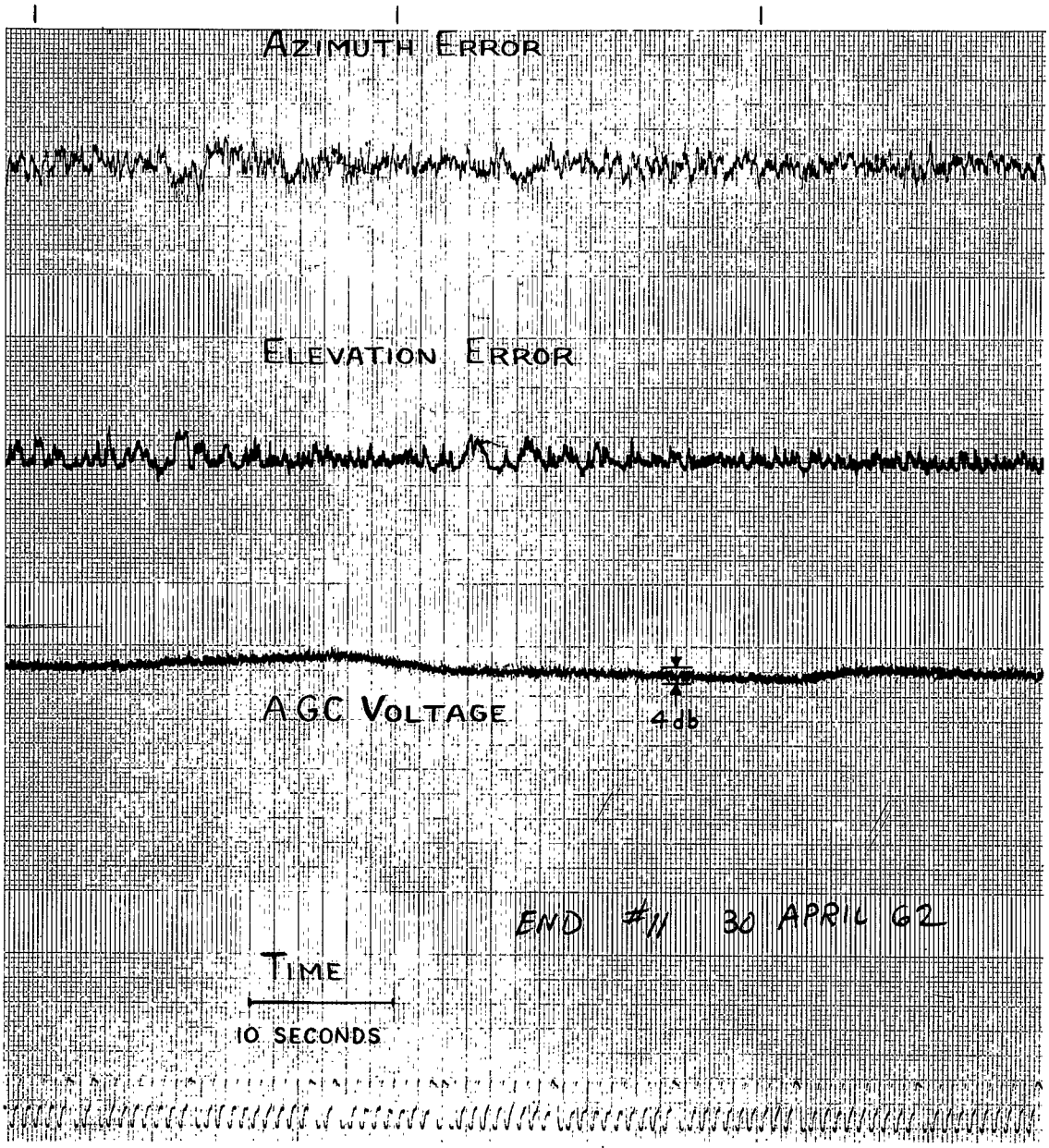

Figure 4

The Same Target as in Figure 3: Range: 10 kilofeet
Elevation Angle: 25°

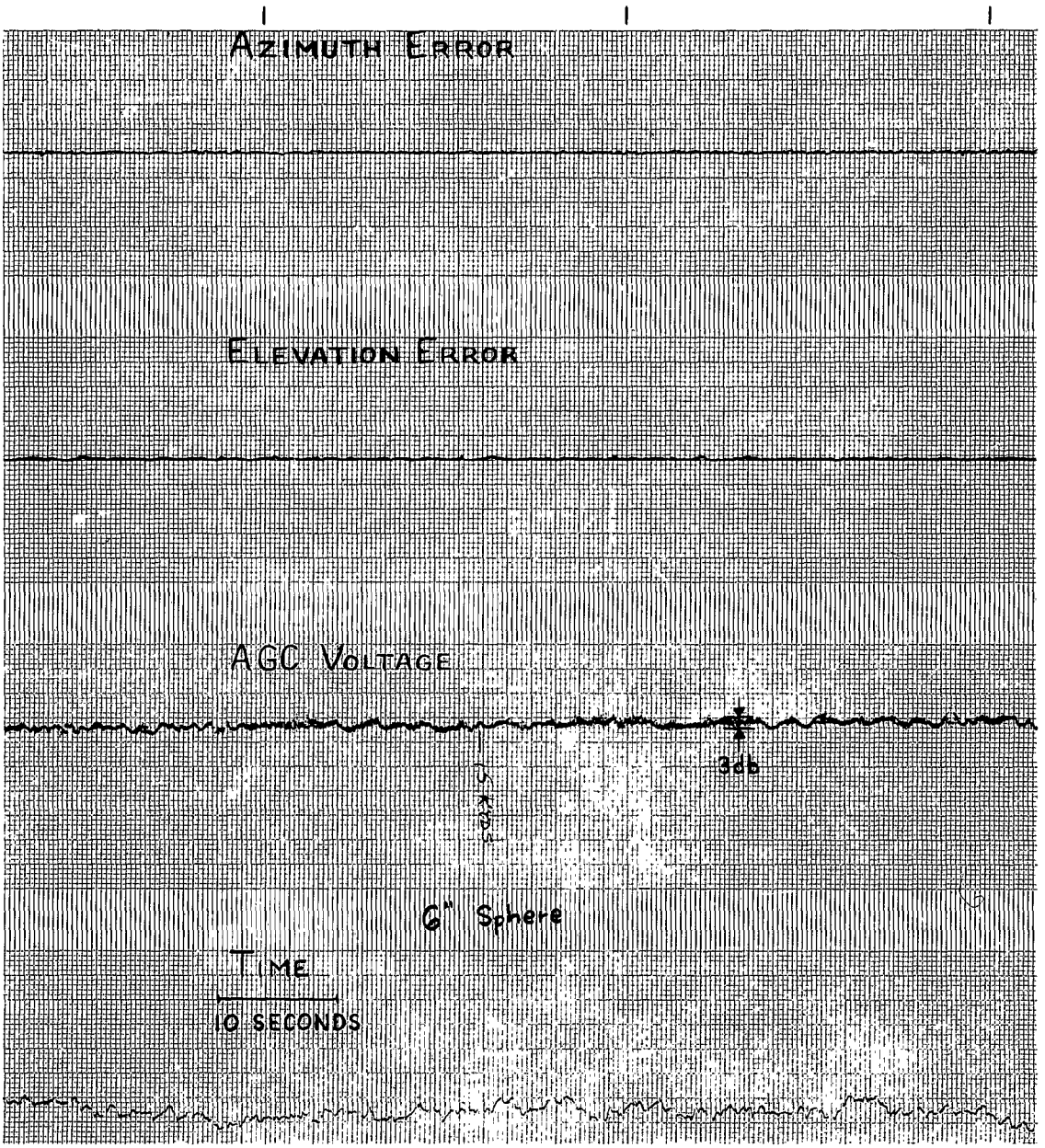

Figure 5

6-inch Aluminum Sphere. Range: 45 kilofeet

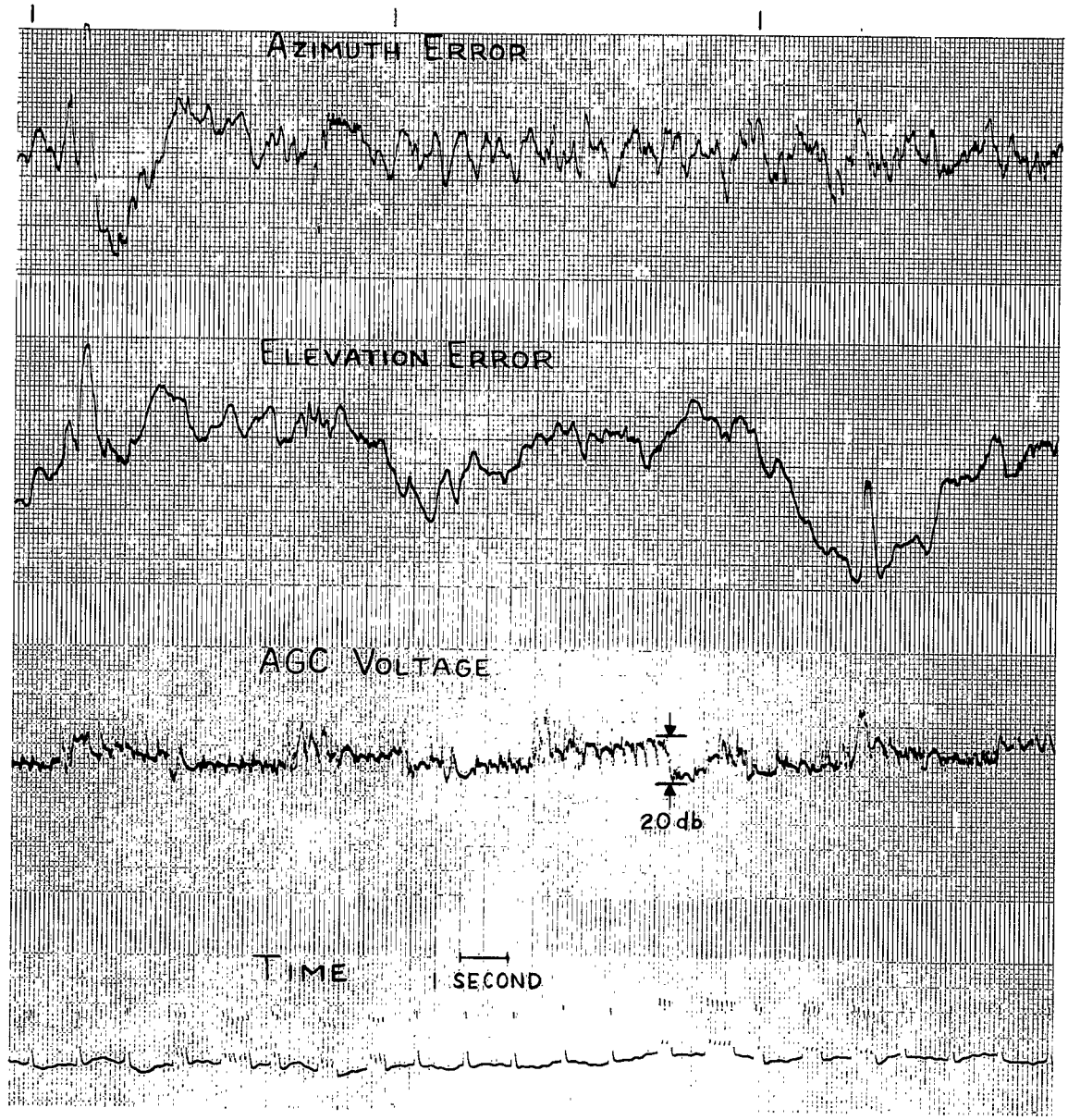

Figure 6

A Large Bird. Range: 4 kilofeet
Elevation Angle: 10°

Comparison of these records suggest that most of these angel echoes are caused either by very smooth layers of refractive index gradient or by a single intense discontinuity rather than by a large number of scintillating reflections. This evidence of small target size is supported by a number of J-scope photographs. Any appreciable target depth (greater than 10 meters) along the range coordinate would be detectable in these photographs. No detectable target depth was found among those investigated (about ten, over a range of elevation angles from 30 to 80°).

In Figures 18-22 (see Appendix), the horizontal velocities of a number of angels are compared with the wind velocity at the appropriate altitude. Generally, all angels observed on a particular day exhibited a consistent pattern of horizontal motion regardless of the agreement with wind data. A notable exception was found during the development of a strong sea breeze (12 July 1961, see Appendix for details). The existence of a small-scale front, indicated by the radiosonde profile, could have created winds of high variability.

In comparing angel velocities to wind velocities in the horizontal, one must keep in mind that the wind velocities are obtained by an averaging process separated in time from the angel observations by several hours. Generally, those angels tracked near the time of a radiosonde ascent showed better agreement. In some cases the angel

motions showed agreement with the winds to within the measurement error of the wind data. In other cases, this error was exceeded somewhat but the time factor can explain the discrepancy.

Upon examination of many cases, one finds that angel motions have fair to good agreement with wind motions, and are highly consistent for most days. This supports strongly the notion that these angels are windborne.

Vertical Motions. The height variations of the angel sources are indicated in Figures 29-31 wherein the target heights have been plotted as functions of time. The vertical motion shows either a uniform ascent or descent or oscillations about a mean trajectory very nearly level. Often the height variations along the path are a combination of all three types mentioned above. If one considers as a unit the area within several miles of the station, and assumes that the height variations of the targets represent the vertical air motions in the region, the flow pattern obtained is not inconsistent with the existing knowledge of airflow in the vicinity of mesoscale systems.[4,5] On some of the days there is a definite suggestion of a change in the flow pattern indicating the possible passage of a small-scale front characterized by different vertical air motions on the two sides of the front.

The height variations on 12 July 1961 represent such a case (see Figure 29). The angel tracks in the forenoon

show an appreciable upward velocity whereas those detected in the afternoon show a downward velocity. On this particular day a shift in the direction of horizontal motion was also noticed at approximately 1100 hrs. The data immediately after this time show a well defined periodicity in the height variations with a period of 8 to 10 minutes. This has a remarkable similarity to waves of short wavelength which can conceivably occur in association with travelling disturbances such as fronts. The wavelength in this case is of the order of 2 or 3 miles.

A study of constant-level balloon flight trajectories was performed at this same location in January 1960.[6] The vertical motions which Angell and Pack recorded have the same character as those of the angel trajectories.

Some of the constant volume balloon (tetroon) flights showed height variations of only several hundred feet over a time interval greater than one hour. Other flights showed small regular height oscillations. A few exhibited rapid large scale oscillations, with vertical velocities up to about 30 feet per second.

An air parcel rising through the atmosphere undergoes expansion which decreases its density. This increases the tendency to rise further. Similarly a downward moving air parcel undergoes compression and tends to be unstable. The constant volume balloons do not change density and would therefore be expected to exhibit vertical motions less

pronounced than those of air parcels. In no cases did the angel vertical velocities exceed the largest observed value attained by the tetroon flights. Thus the oscillatory motions and occasional large vertical velocities of angels are not out of accord when compared with the atmospheric motions measured by tetroon flights.

The data on any particular day are too scant and the duration of individual records, except in a few cases, are too short to attempt a synthesis of the prevalent airflow. However there is sufficient evidence to suggest that the target path does represent the existing airflow pattern.

Correlation of Cross Section with Vertical Velocity. The average value of cross section σ as a function of elevation angle has been plotted in Figure 1. Some targets showed significant deviations from this average value. In many cases the deviation is correlated with vertical velocity, particularly when the target is at high elevation angles. In Figures 7 and 8, the observed value of σ divided by the average value of σ (at the same elevation angle) is plotted as a function of time. In the same figure the vertical velocity of the target is represented by a dashed line. It can be seen that in these cases, the target cross section is strongly dependent upon the absolute value of vertical velocity.

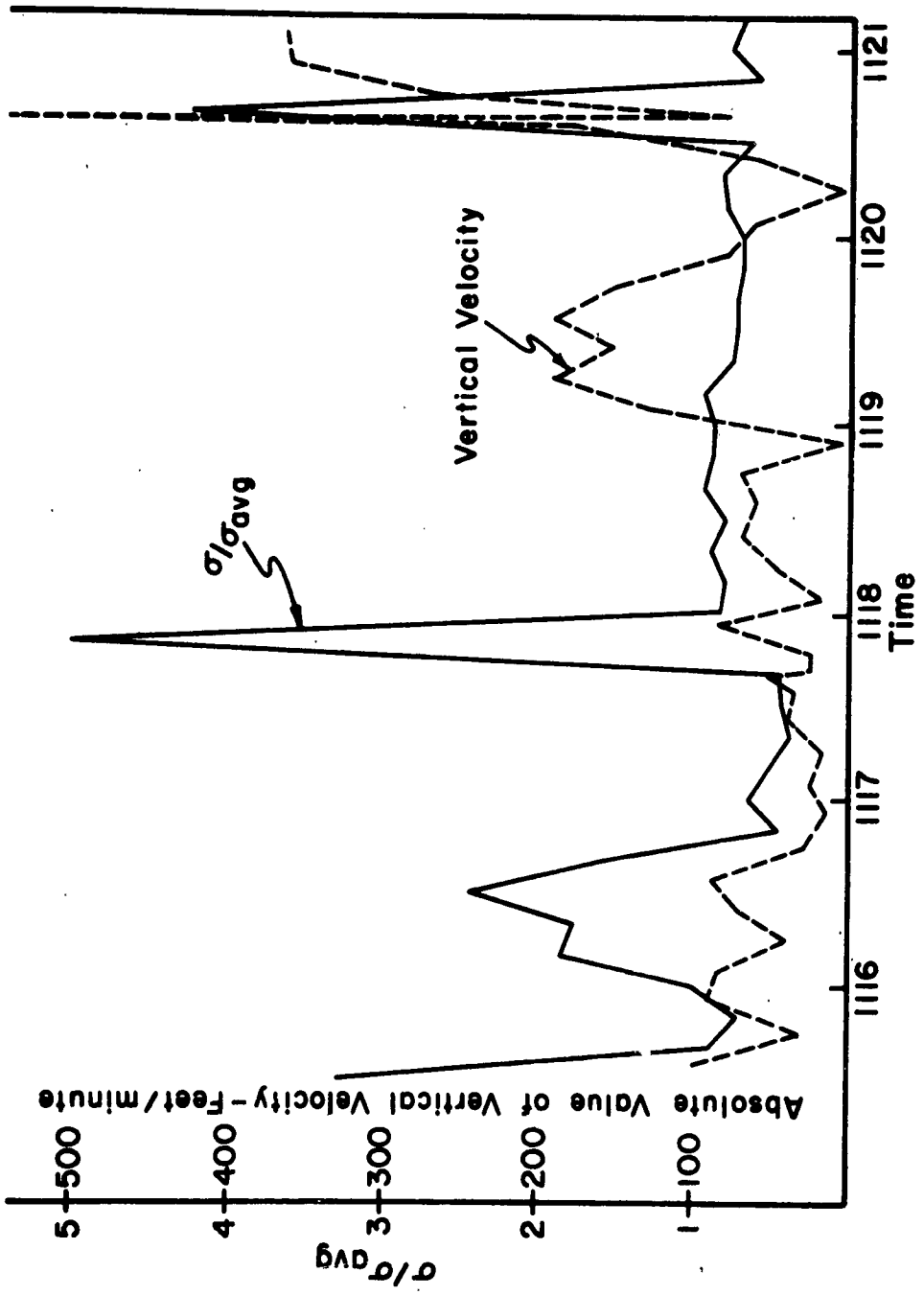

Figure 7

Illustrating Correlation of Cross Section and Vertical Velocity

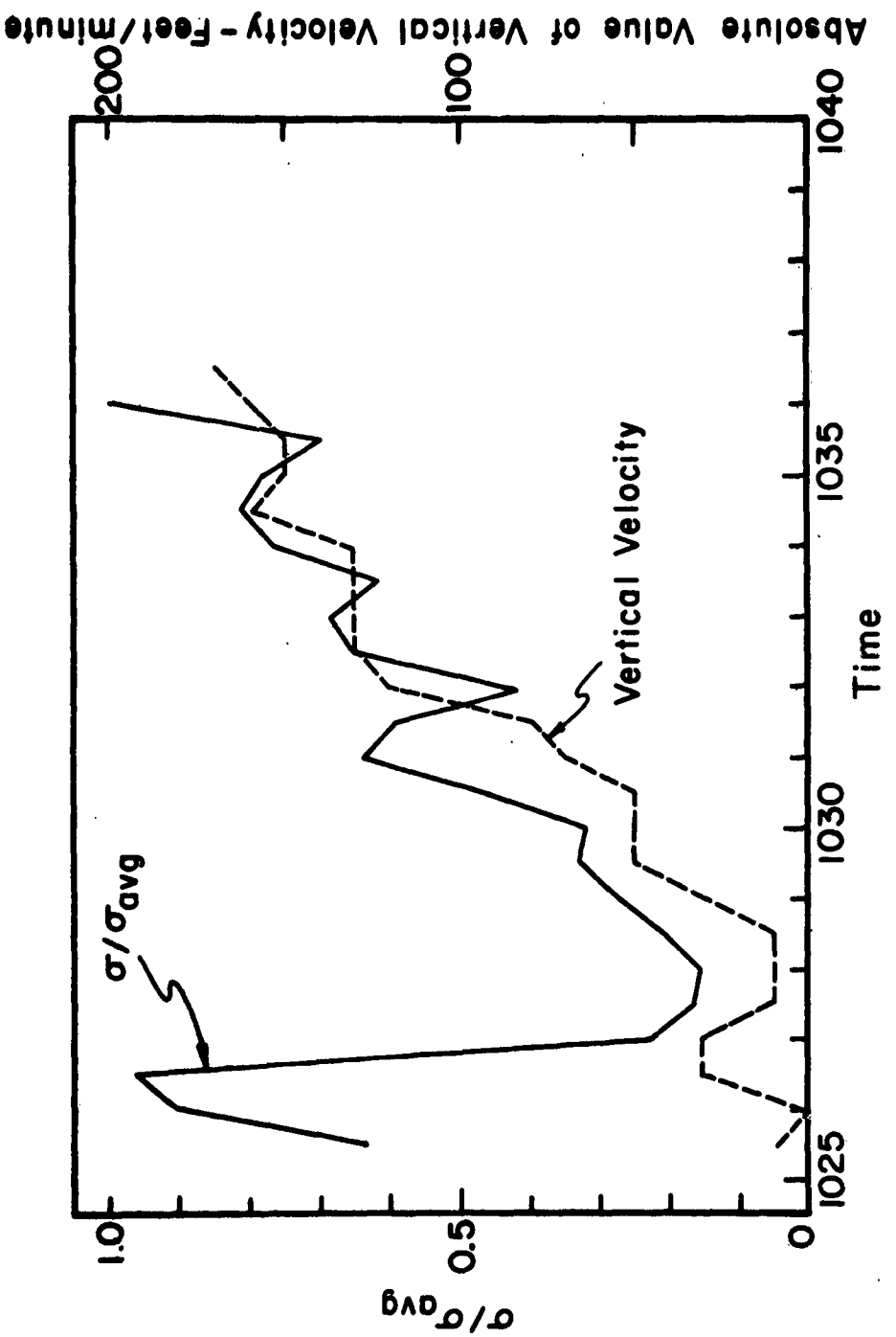

Figure 8

Illustrating Correlation of Cross Section and Vertical Velocity

CONCLUDING REMARKS

The preceding section contains a description of a number of trackable angels. In this section it will be shown that these angels must be meteorological rather than particulate. It should suffice to observe that the echo cannot be caused by an object imbedded in the atmosphere, but does have properties which could be explained by an appropriate meteorological model. A tentative model is suggested below.

A careful examination of the horizontal and vertical angel motions has shown that these targets are undoubtedly windborne. This completely eliminates the possibility of birds, large insects or any flying thing as an explanation for these targets. A flying target would have to show an appreciable speed relative to the wind in order to maintain altitude.

The straight-line tracks of these angels are not consistent with the flying habits of birds. Most bird trajectories are erratic both in the horizontal and the vertical.[7] Migrating flocks might be the exception to this rule. However, one would not expect to observe migratory flights throughout the summer months and certainly not headed for the open sea.

The horizontal velocity vector of a bird is shown in Figure 20 for comparison with angel motions. The bird's velocity is significantly different both in magnitude and

direction from the angel pattern and the available wind data. Furthermore, the radar cross section of the bird fluctuated regularly from 20 to 200 square centimeters - several orders of magnitude greater than the steady angel echoes. These distinguishing features make it difficult to attribute these angel echoes to birds.

The consistent, very strong dependence of target cross section upon elevation angle places stringent requirements upon the nature of any object. The targets must appear to be 30 to 100 times larger when directly overhead as compared to a "view" at 60° elevation angle. It is difficult to conceive of foreign objects in the atmosphere having this plate-like shape. It is even more difficult to imagine that such objects would invariably maintain a consistent horizontal orientation while passing over the radar station.

Horizontal refractivity stratifications in the atmosphere might be the cause of such a mirroring phenomena. Refractometer soundings indicate there frequently are irregularities in the refractive index profile. Apparently these irregularities are sometimes intense enough to create short-persistence angels, such as those observed on 26 and 27 March 1962. On one of these days, from clear skies, echoes rose sharply out of the noise on the radar A-scope; but they disappeared before automatic tracking could be established.

It is surprising to observe that some echoes persist for many minutes, and can be tracked. It may be that the more persistent angels are caused by the distortion of a horizontal refractive index stratification by a vertically moving air parcel such as a thermal. From a study of motion in and around isolated thermals, Woodward[8] has shown the distortion of an initially horizontal layer of fluid caused by the mean motions of a thermal (turbulent motions were neglected). The distortion so obtained by Woodward is shown in Figure 9.

In the region near the cap of the thermal, the layers of fluid have been intensely compacted and drawn out like rubber sheets. This would intensify existing refractivity gradients in the vertical. More realistically, the cap is a region of intense turbulence. This turbulent region may be responsible for many trackable angel echoes. The long persistence of the echo could be attributed to the long life of the large scale motion. The small intense region at the cap would account for the apprently small target size. The crowding of layers would most likely increase with increasing vertical velocity of the thermal, and this would probably increase the reflecting ability of the layers, in agreement with the observed correlation of vertical velocity and cross section.

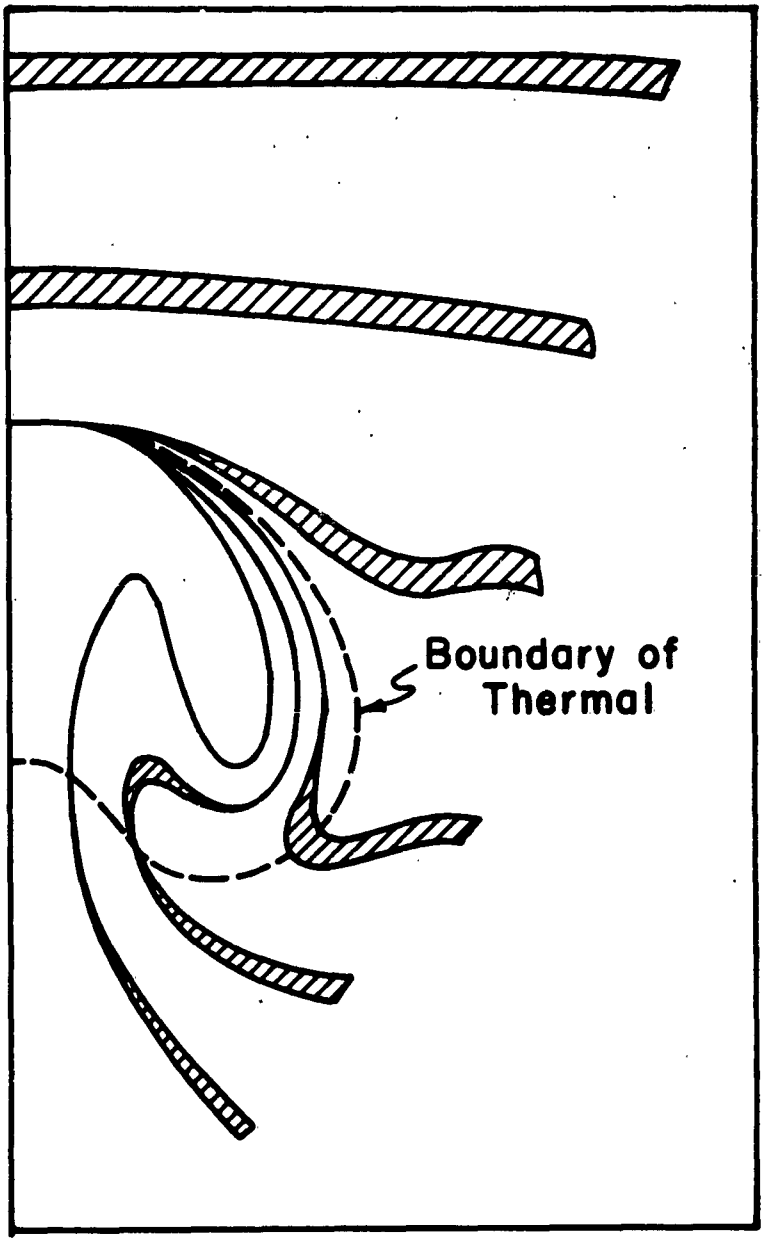

Figure 9

Distortion of Initially Horizontal Layers of Fluid Caused by a Thermal

Qualitatively it is this kind of model that seems to fit best the present body of data. At the time of this writing there remain further data to be reduced. This new information will be analyzed to determine if it substantiates or refutes the model suggested above.

In a similar model proposed by Atlas[12] it is suggested that the air within the thermal, having come from some distance below, would have properties sufficiently different from the surroundings to give the required reflectivity.

APPENDICES

Radiosonde Profiles and Vertical Motion

In the following Figures temperature and dew point, obtained by radiosonde are plotted as a function of altitude. The vertical trajectories are shown also. It should be remembered that these are partial tracjectories indicating only that portion during which the echo was tracked.

The time of radiosonde ascent is indicated in the lower left corner of each profile. On some days two soundings were taken.

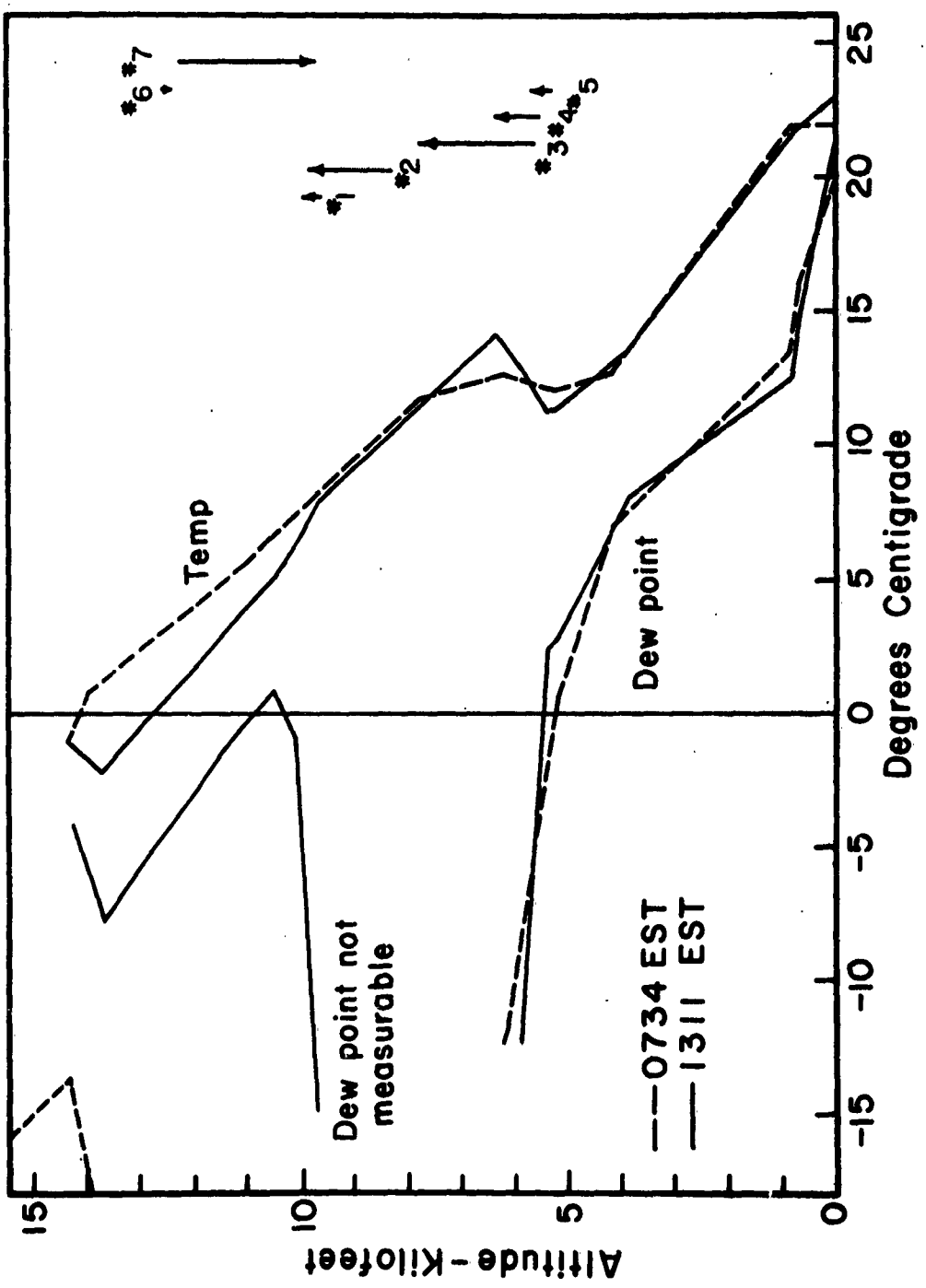

Figure 10

Radiosonde Profiles, 12 July 1961

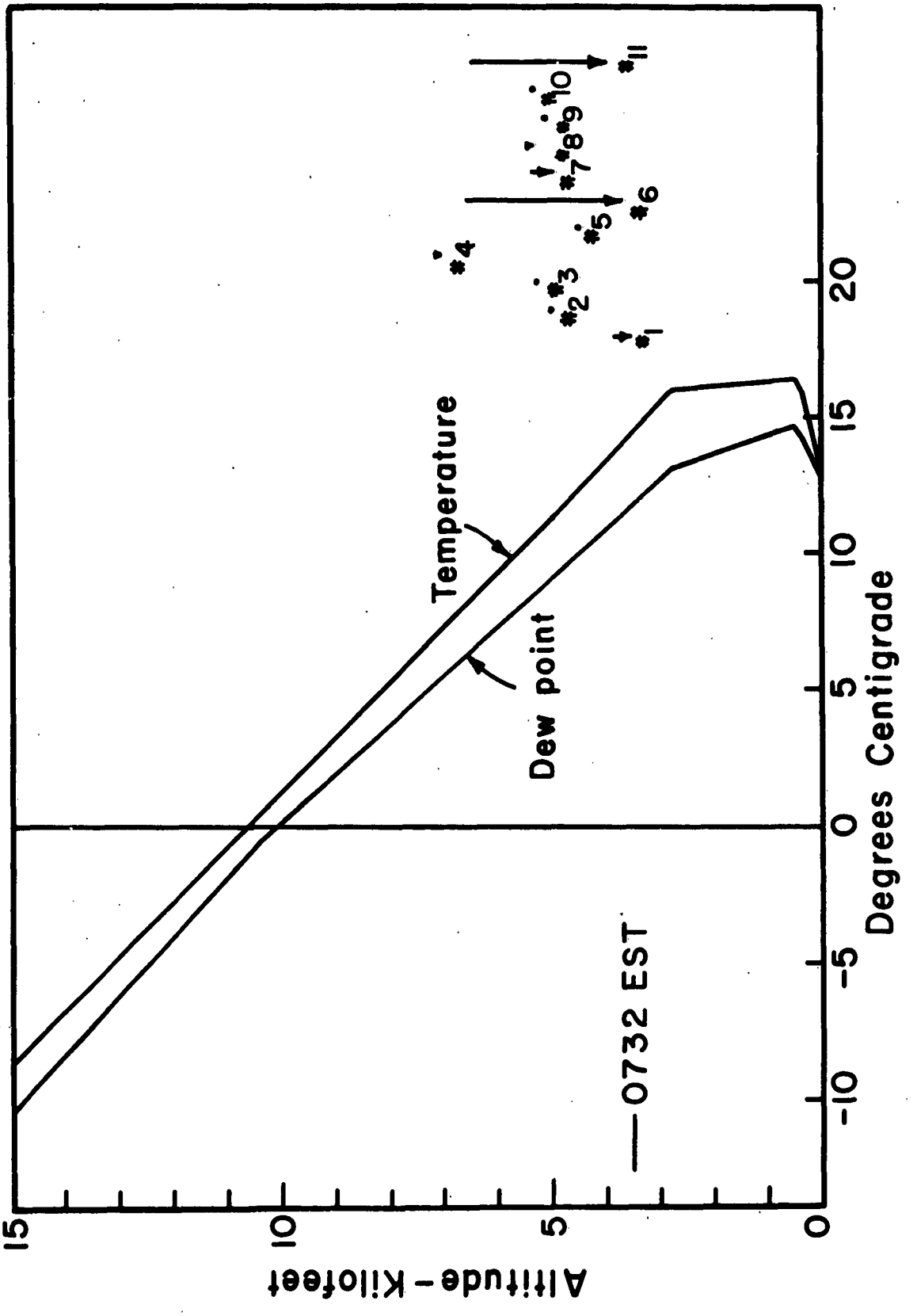

Figure 11

Radiosonde Profiles, 30 April 1962

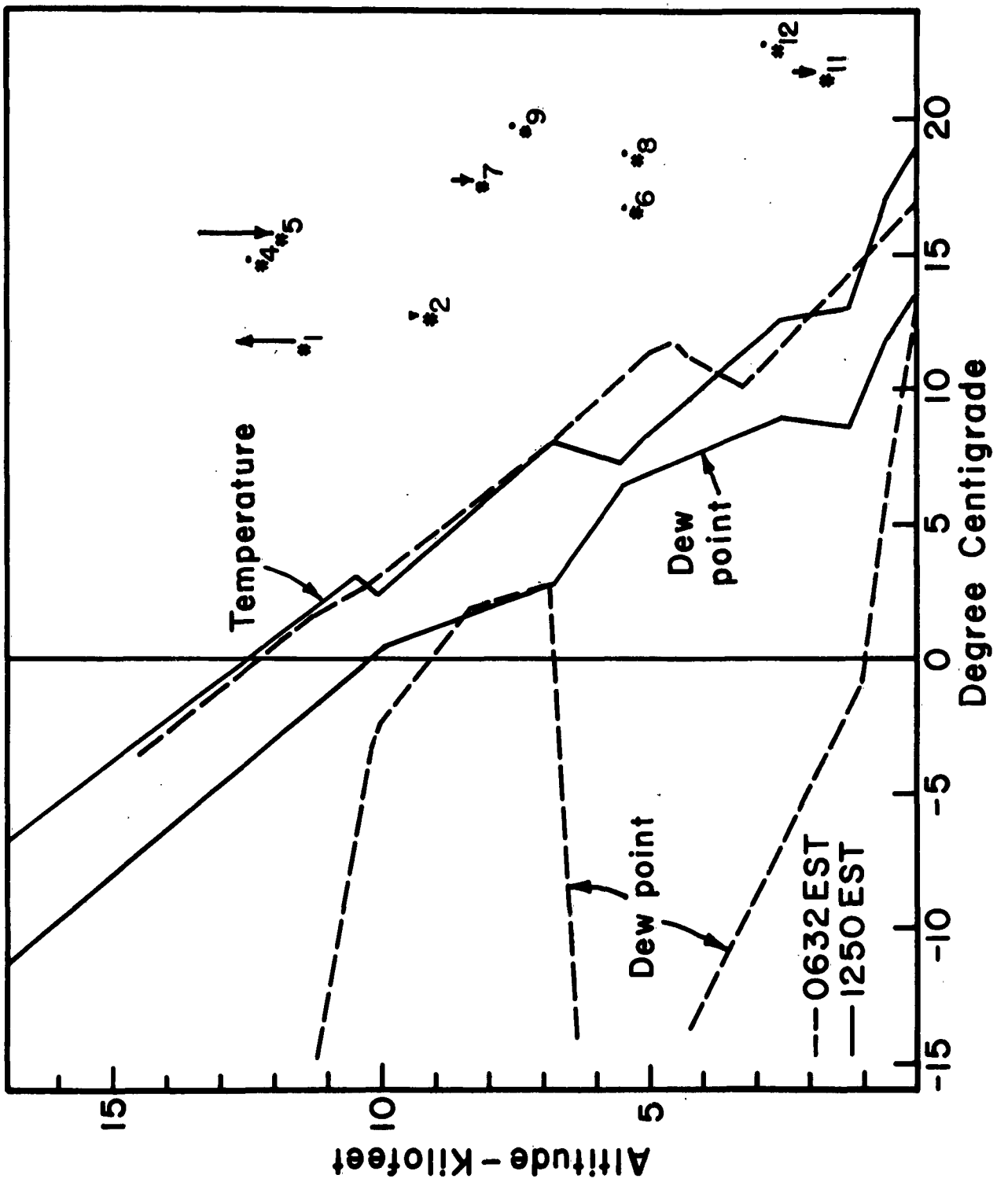

Figure 12

Radiosonde Profiles, 28 May 1962

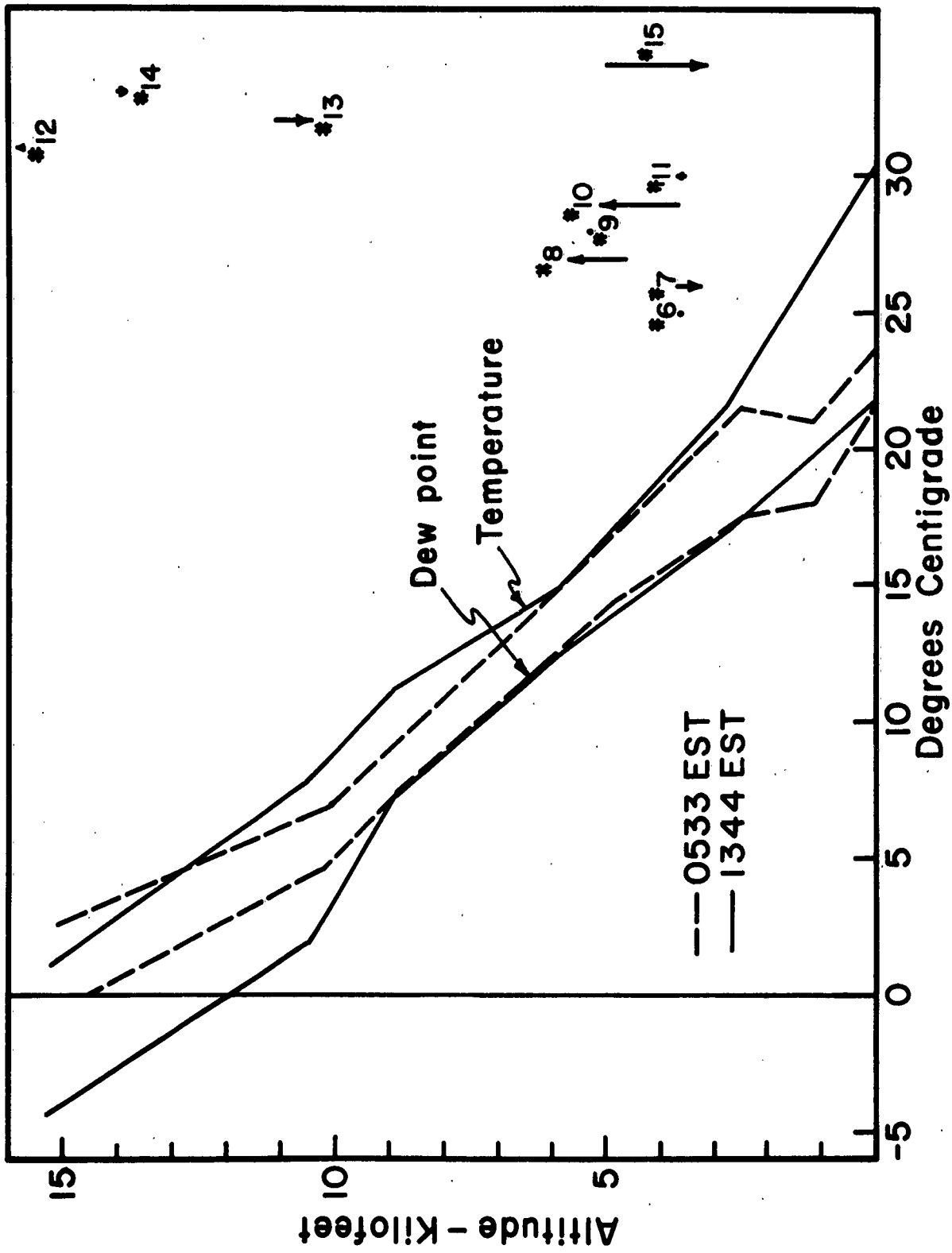

Figure 13

Radiosonde Profiles, 9 July 1962

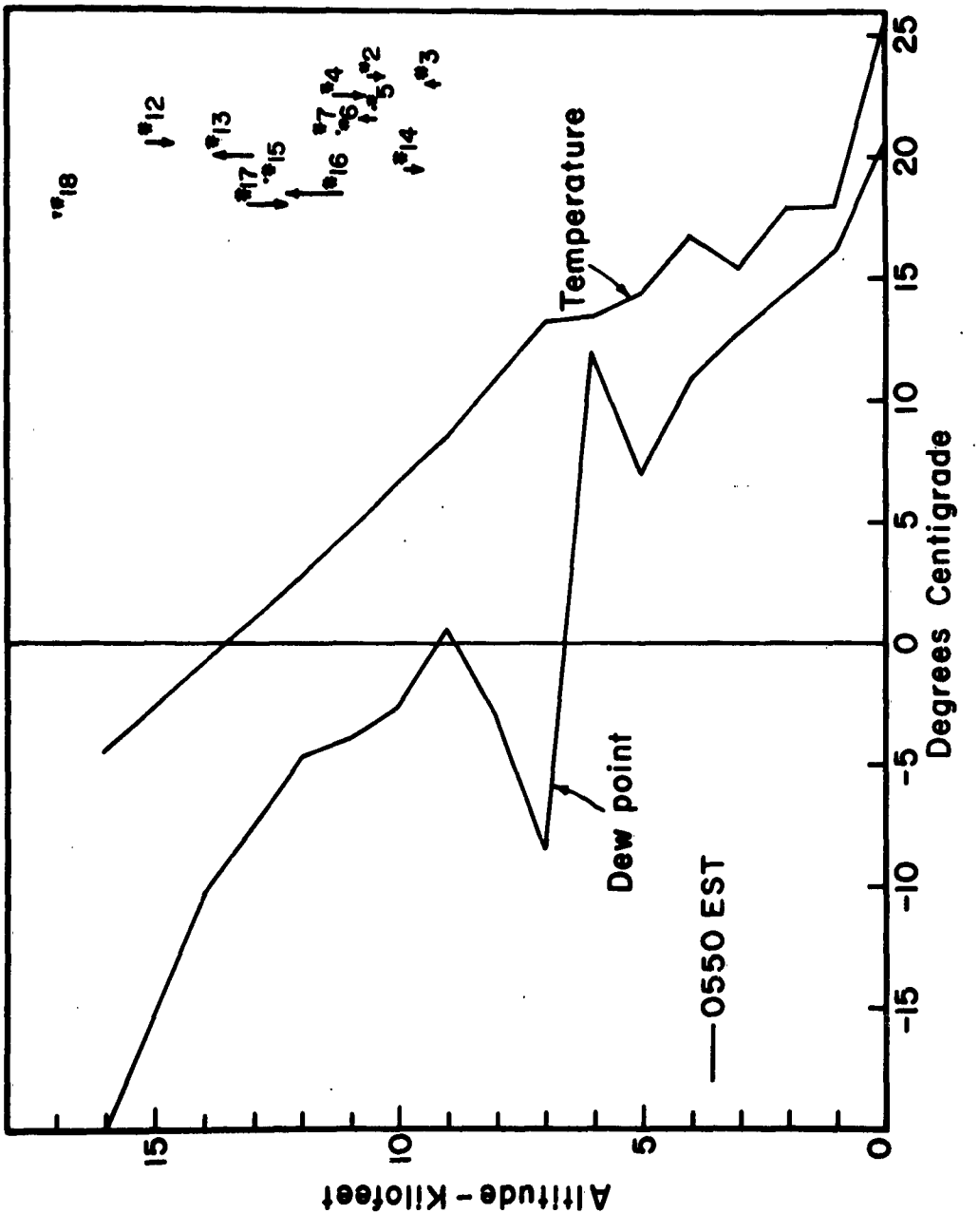

Figure 14

Radiosonde Profiles, 30 July 1962

Radar Cross Sections

In the following Figures plots of radar cross section versus elevation angle are given for individual angels, grouped together by days.

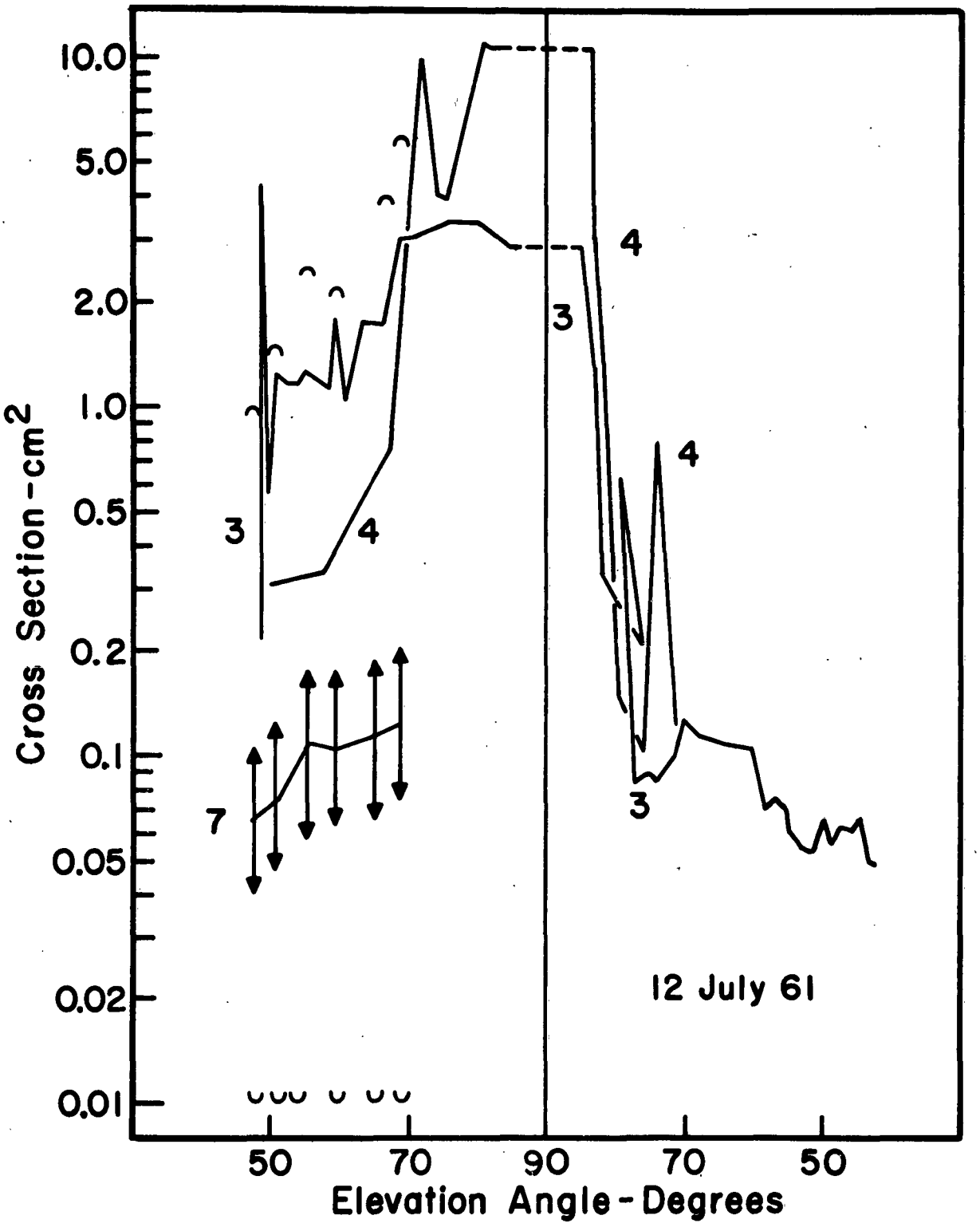

Figure 15

Cross Section Versus Elevation Angle

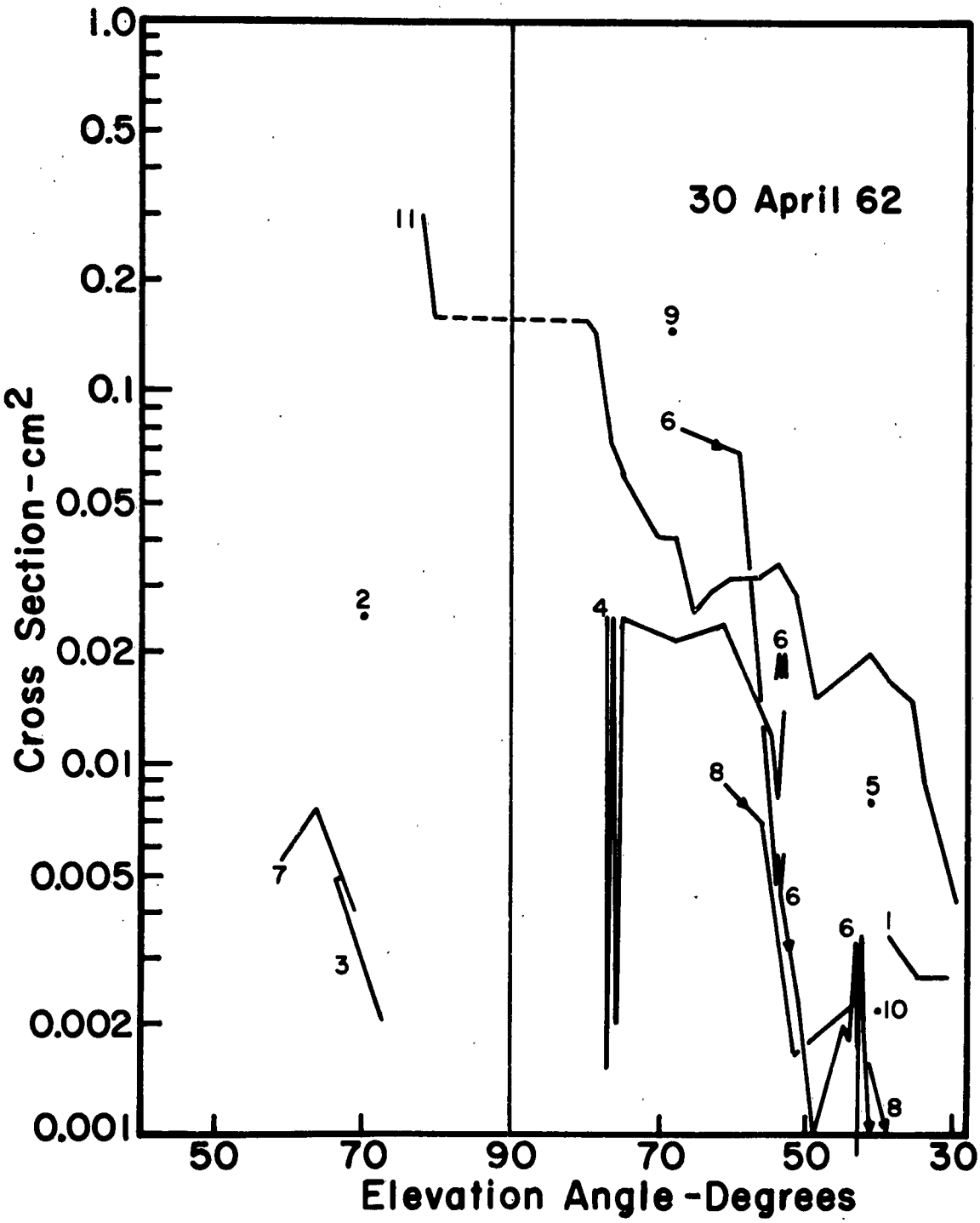

Figure 16

Cross Section Versus Elevation Angle

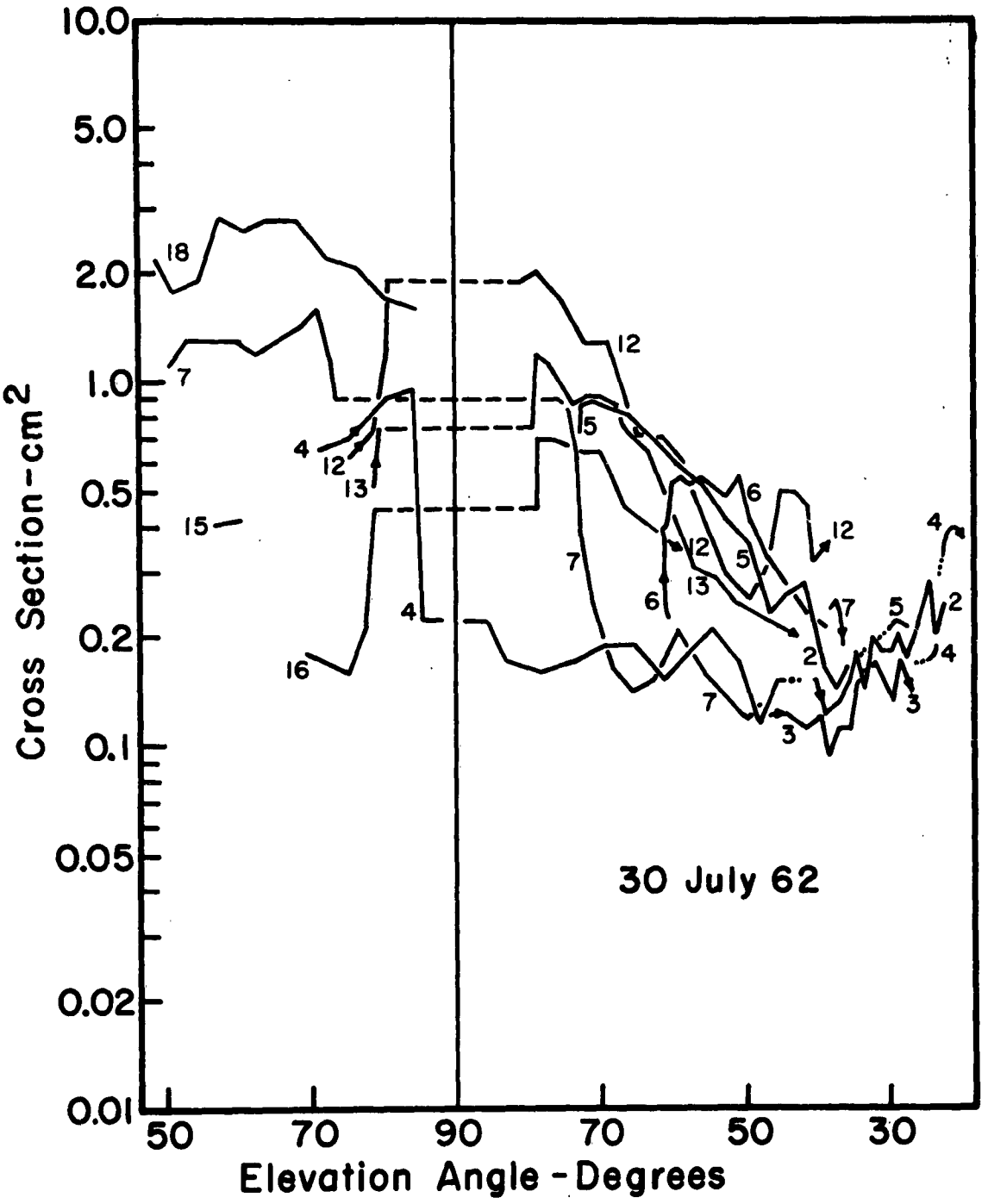

Figure 17

Cross Section Versus Elevation Angle

Horizontal Motions

The following Figures compare the horizontal velocities of angels with available wind data. Each vector shown represents a horizontal velocity which was observed at the altitude indicated by the ordinate and at the time indicated by the abscissa. Solid vectors represent wind speed and direction as obtained by radiosonde. Broken arrows indicate angel speed and direction.

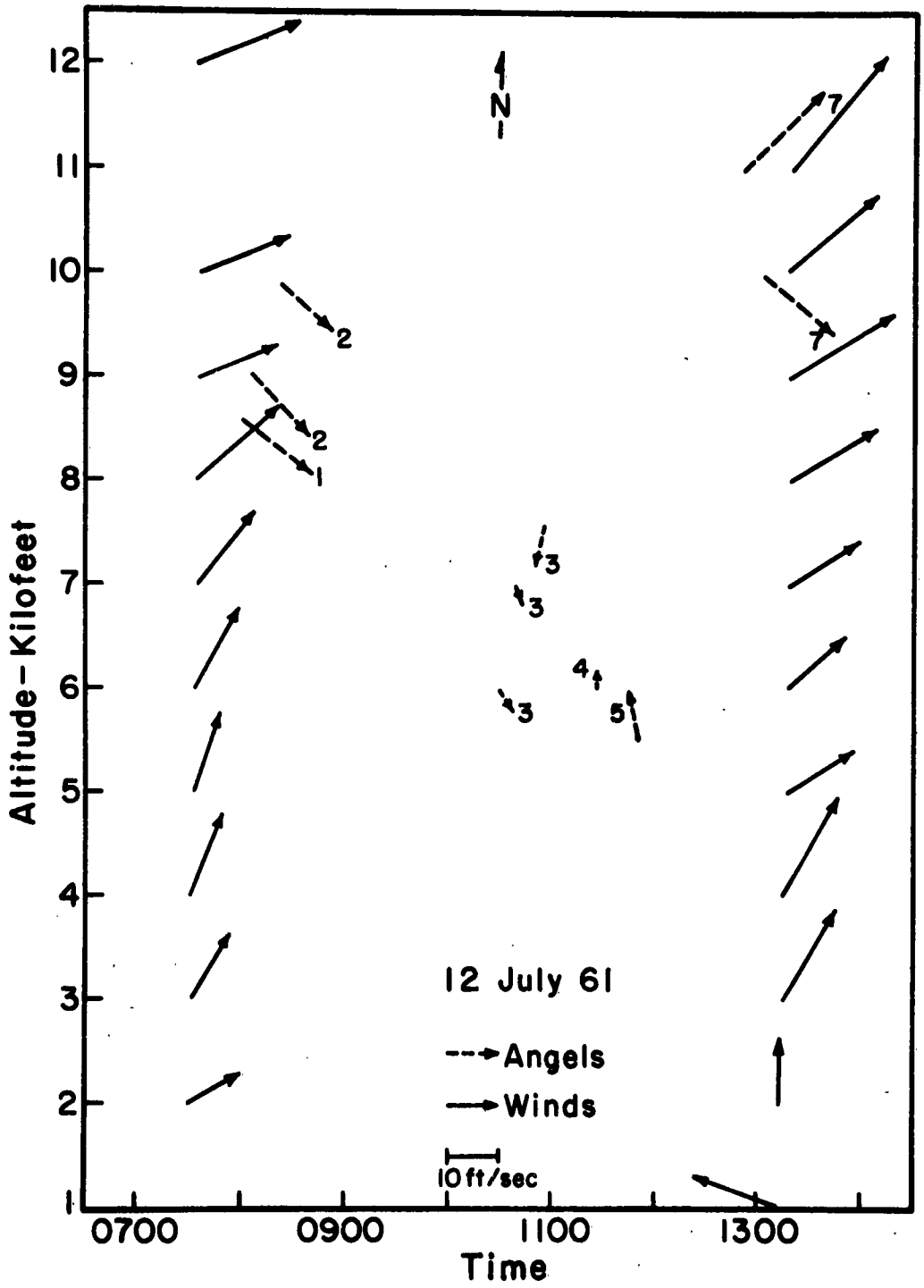

Figure 18

Horizontal Velocity Vectors as Functions of Altitude and Time

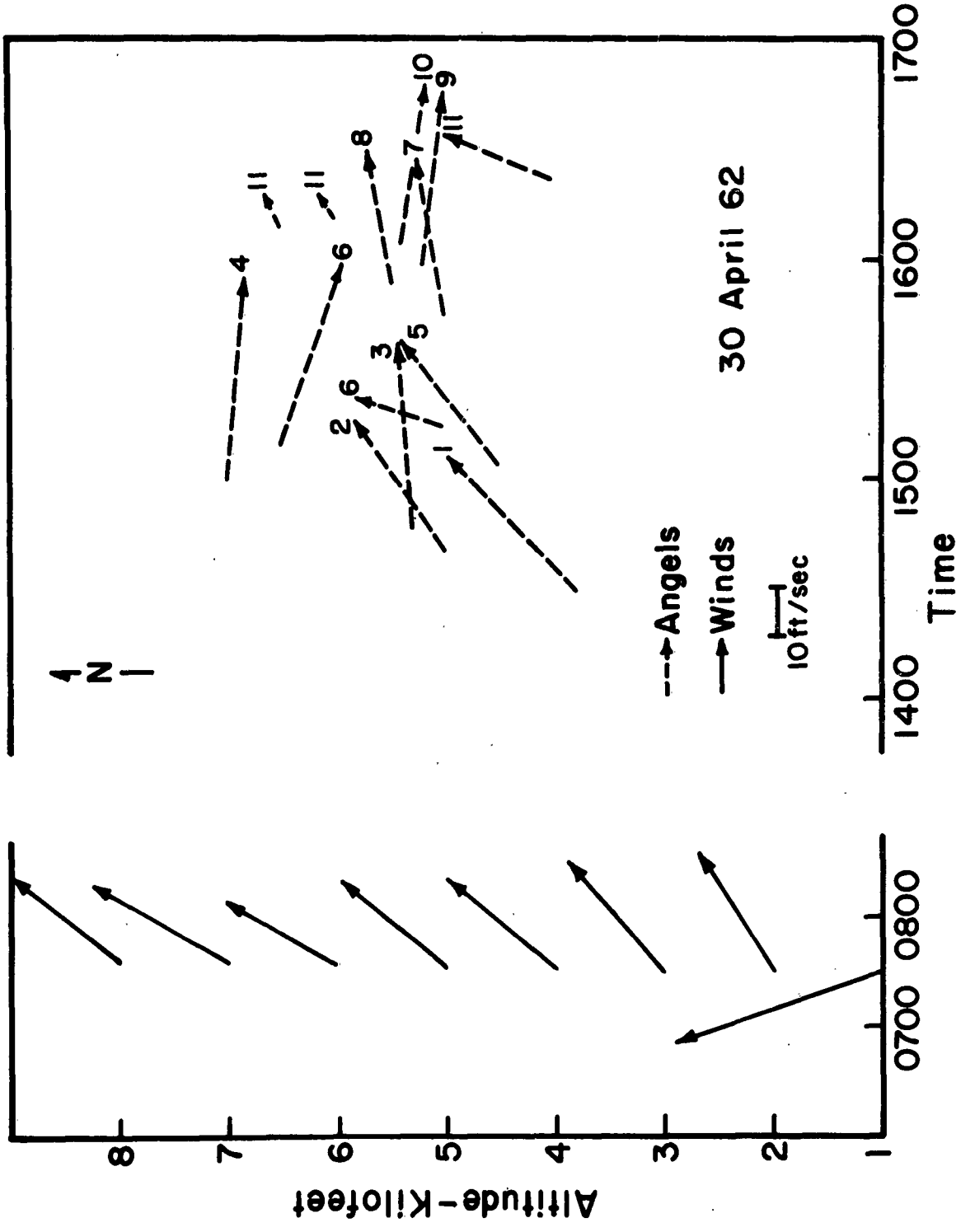

Figure 19

Horizontal Velocity Vectors as Functions of Altitude and Time

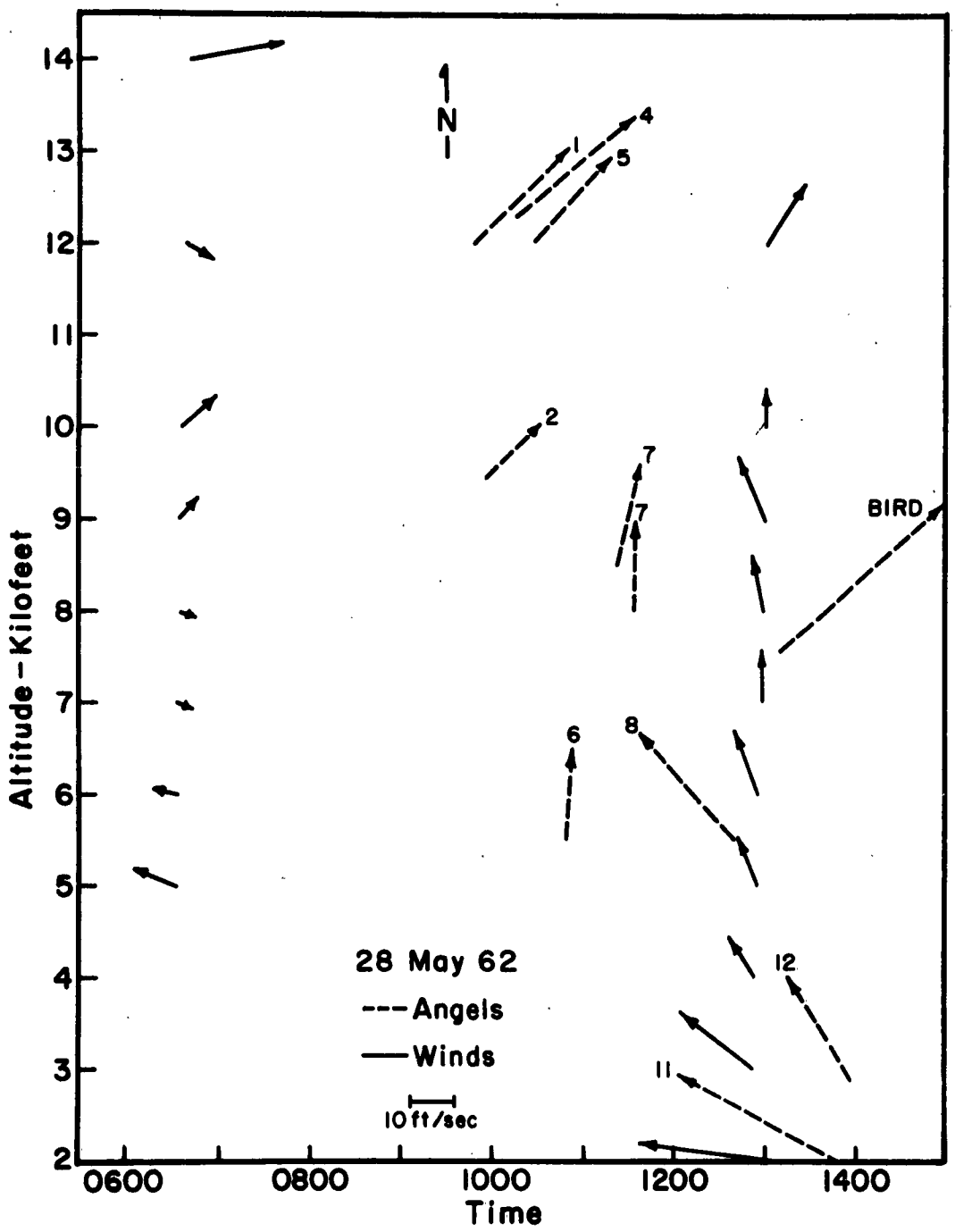

Figure 20

Horizontal Velocity Vectors as Functions of Altitude and Time

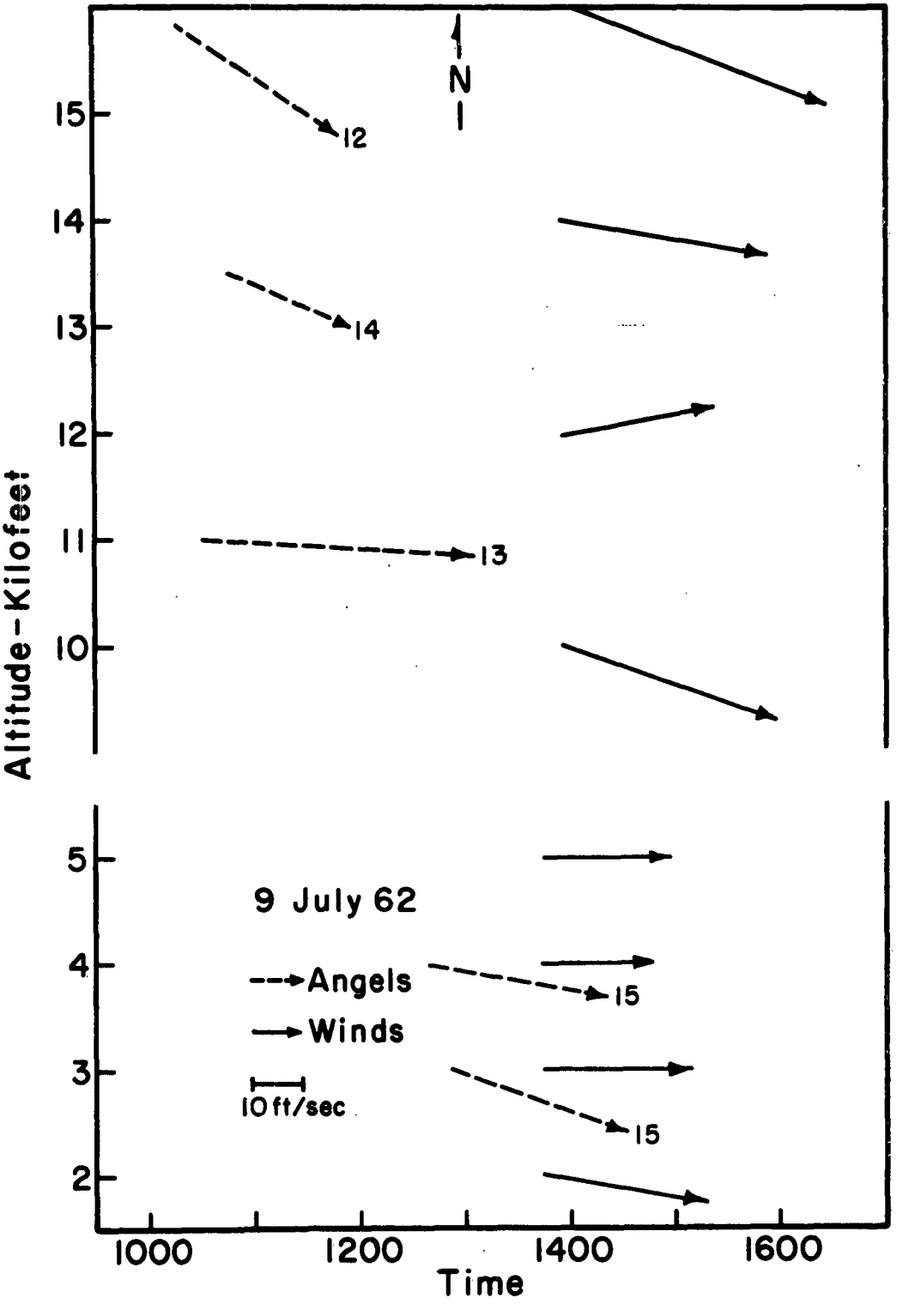

Figure 21

Horizontal Velocity Vectors as Functions of Altitude and Time

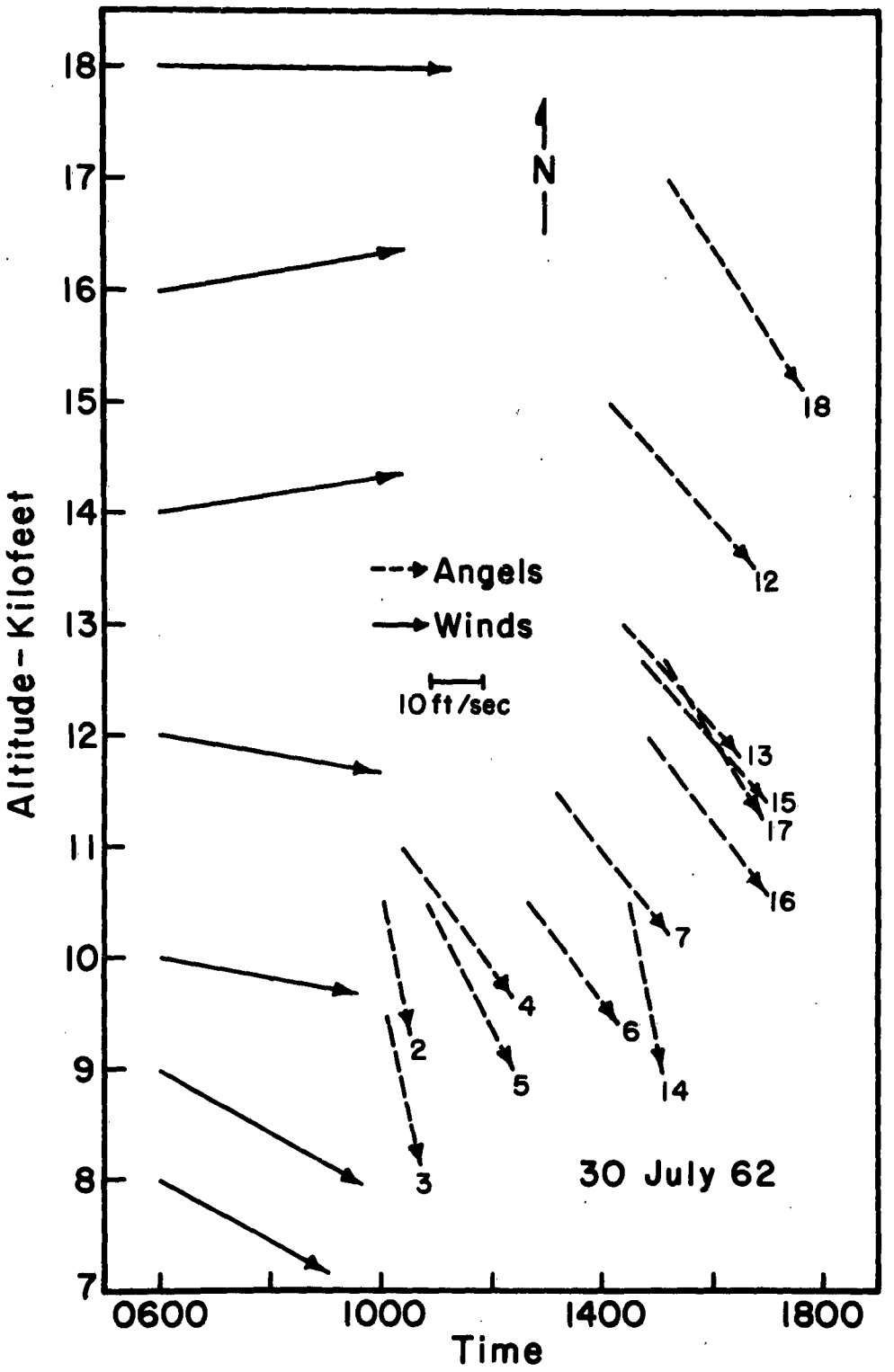

Figure 22

Horizontal Velocity Vectors as Functions of Altitude and Time

Horizontal Trajectories

The following Figures show the horizontal trajectories of Angels grouped together by days. The shoreline lies at an angle of approximately 30°N and is several hundred yards East of the radar. In Figure 25 is shown the erratic flight pattern of a bird, typical of most birds which were tracked.

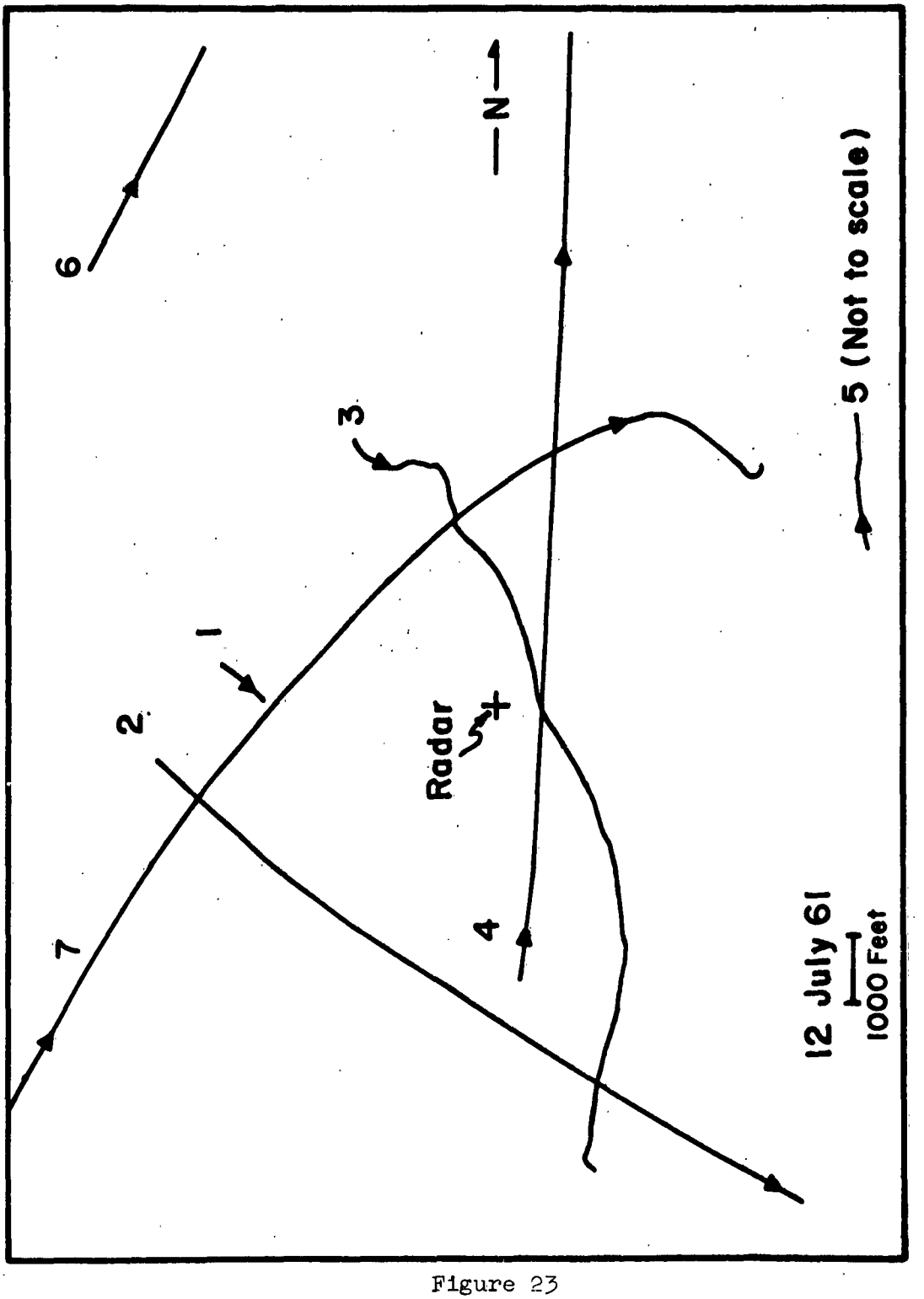

Figure 23

Horizontal Trajectories

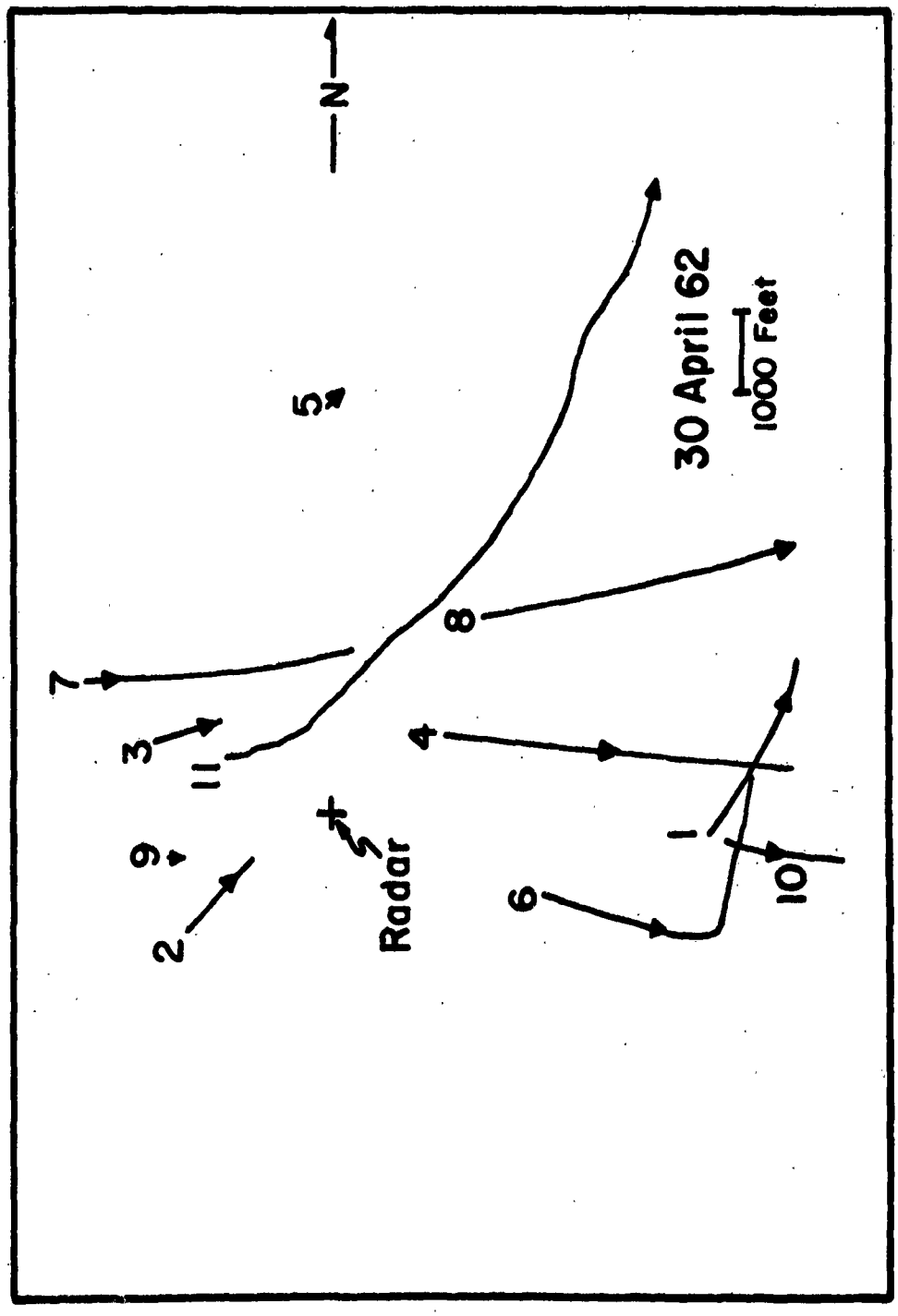

Figure 24
Horizontal Trajectories

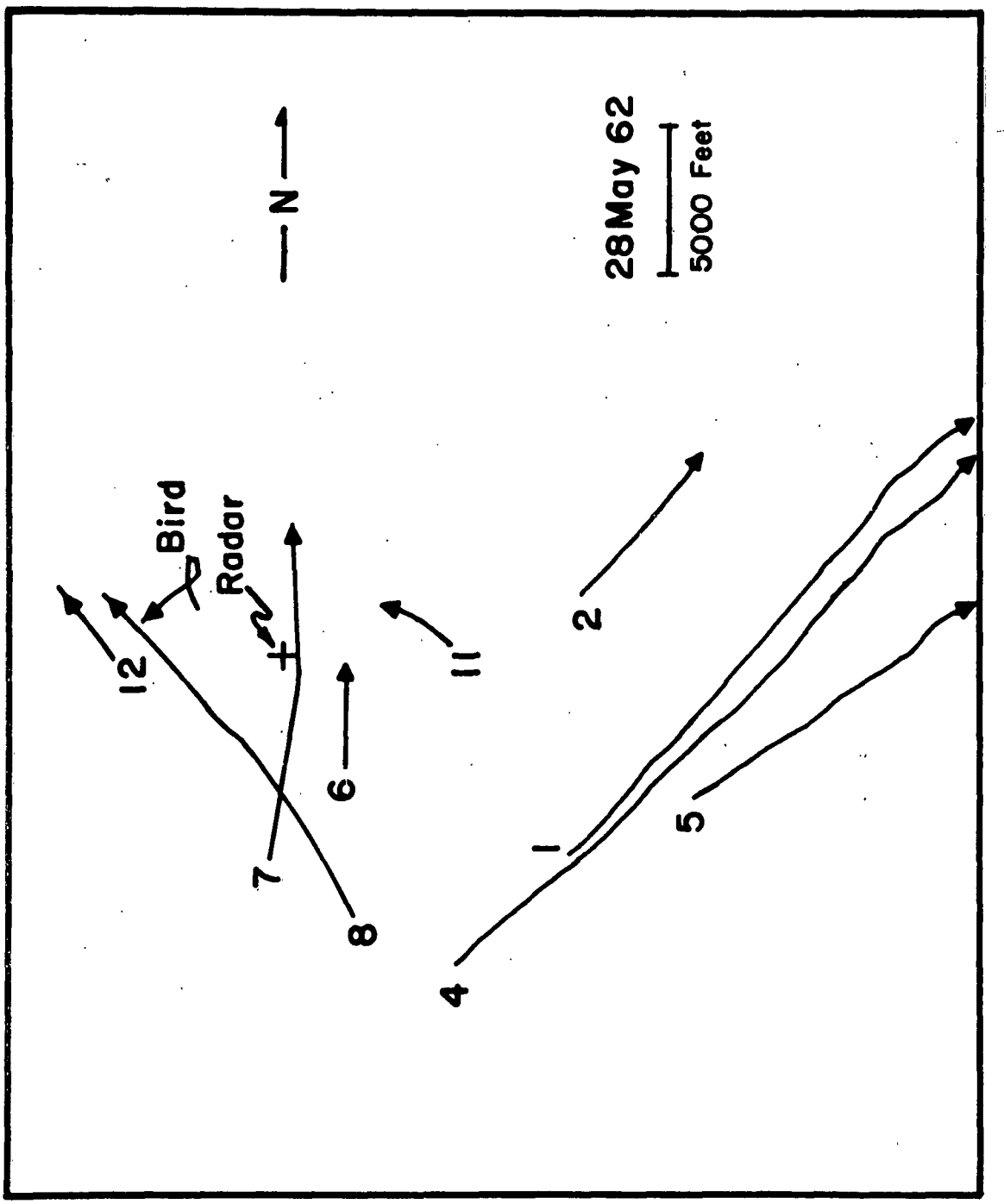

Figure 25

Horizontal Trajectories

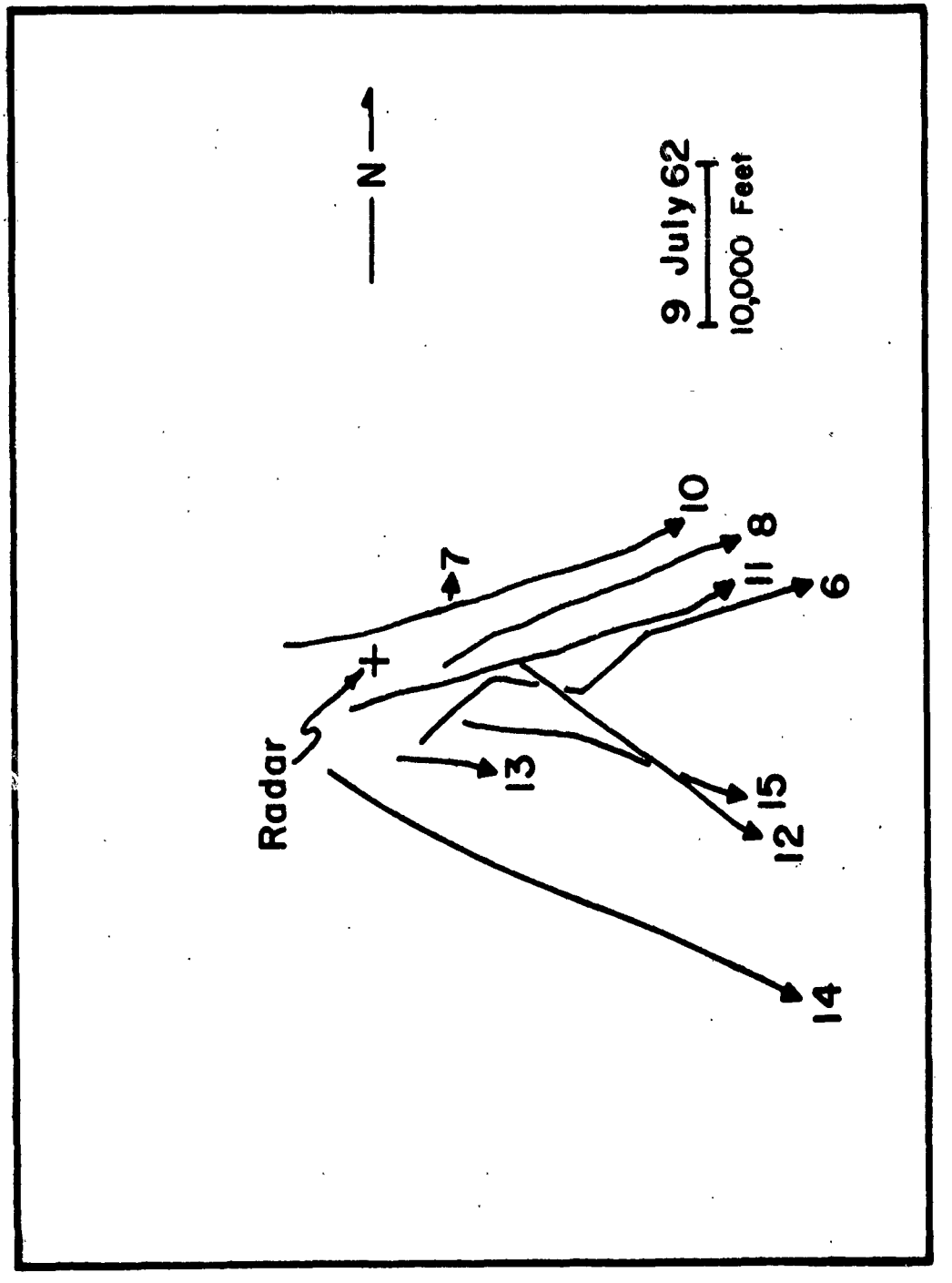

Figure 26

Horizontal Trajectories

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DOCUMENT

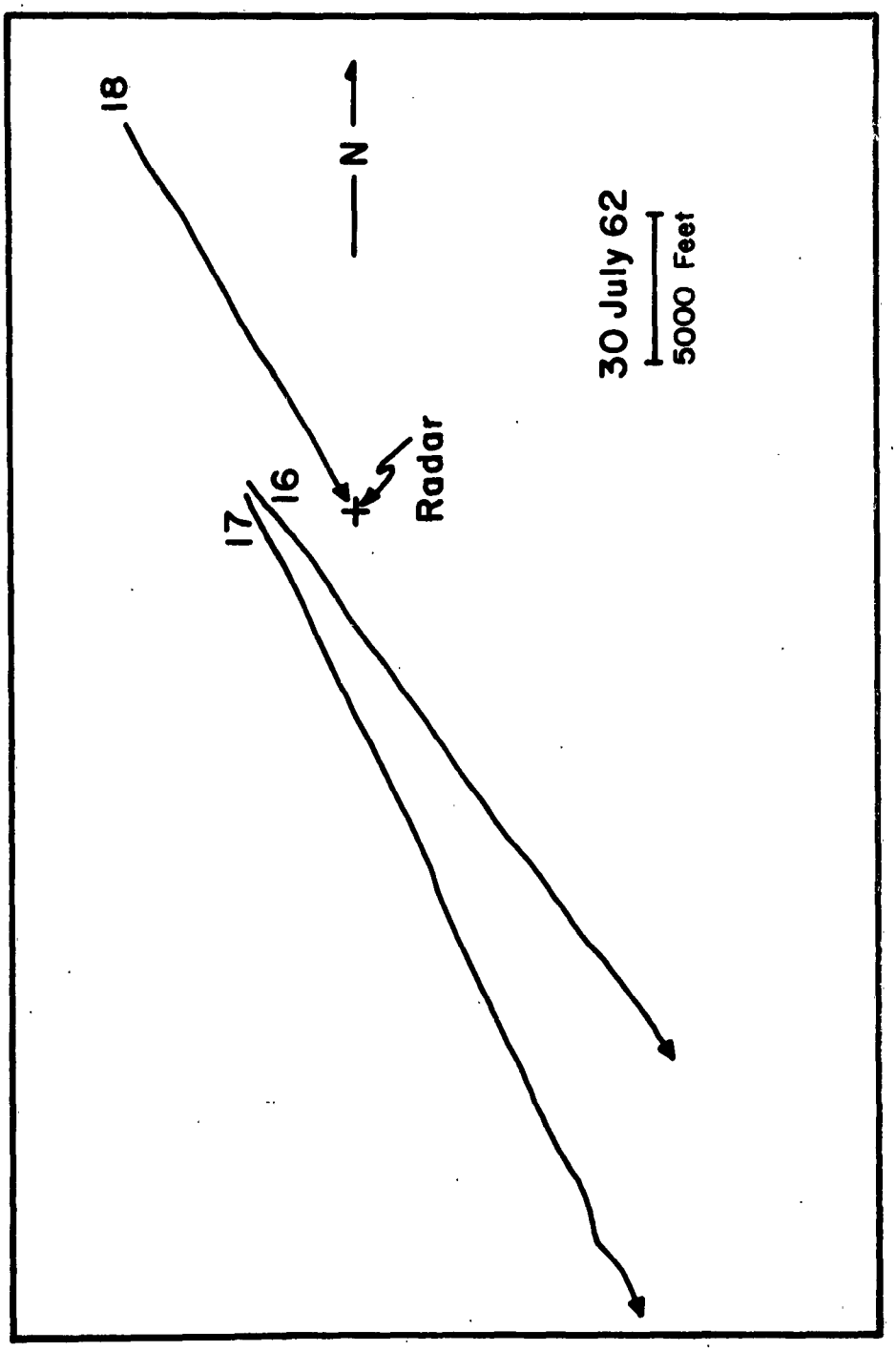

Figure 28

Horizontal Trajectories

Vertical Motion

The following Figures are plots of angel altitude versus time for several days of observation. Note that the time scale is discontinuous so that the true spacing between angel occurrences is not represented graphically.

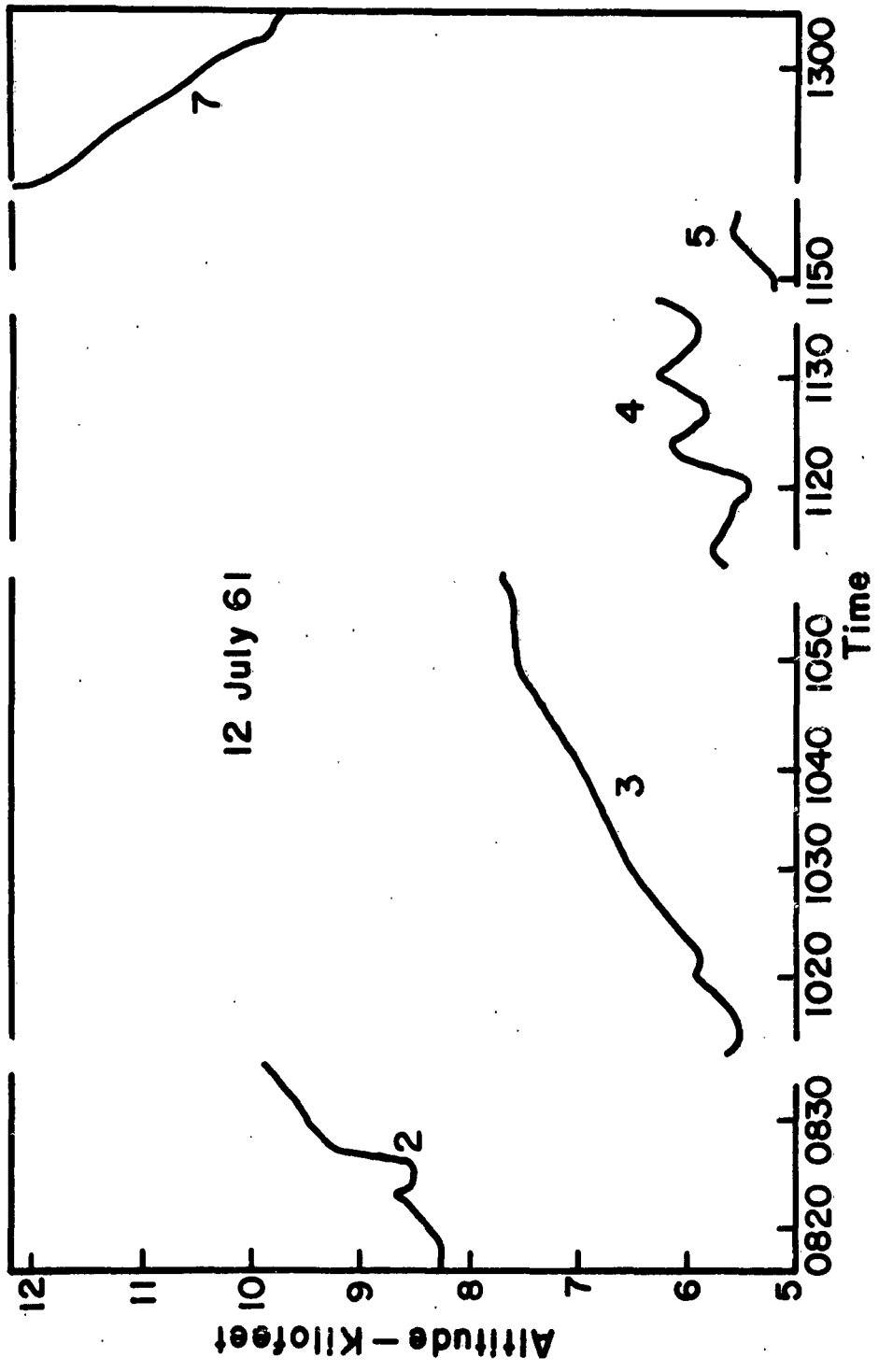

Figure 29

Angel Altitude Versus Time

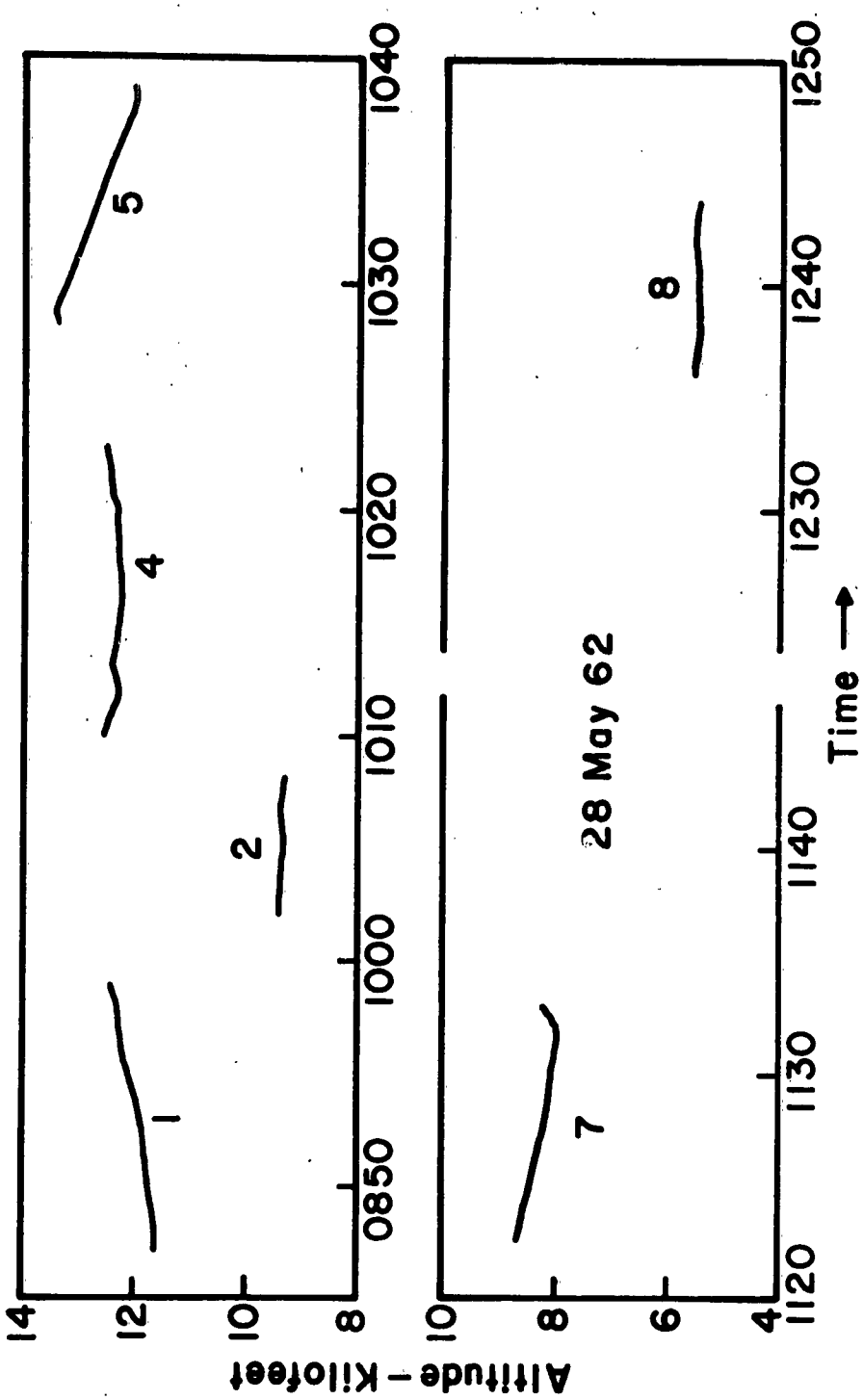

Figure 30

Angel Altitude Versus Time

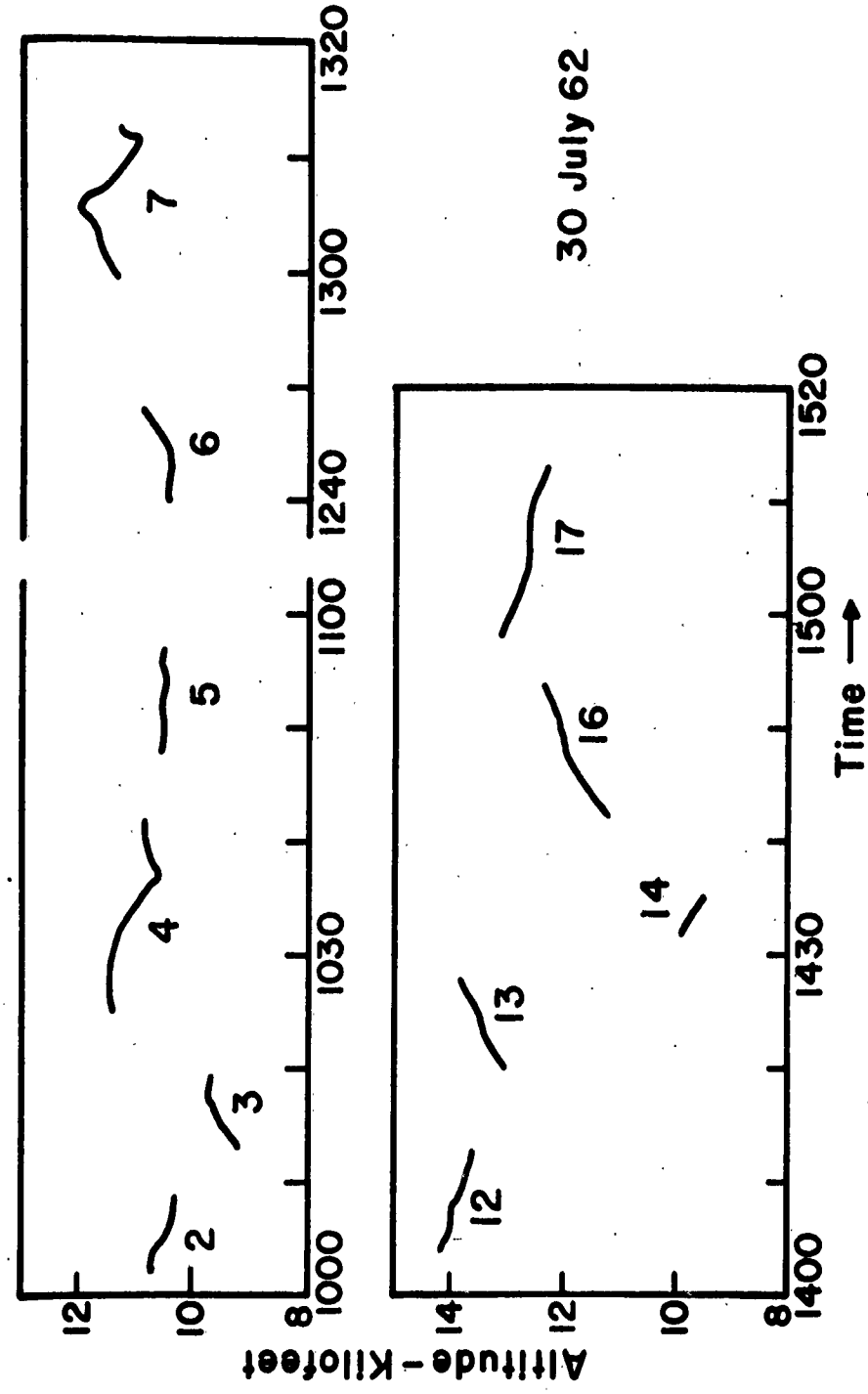

Figure 31

Angel Altitude Versus Time

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