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Applications of the Net Radiometer to Short-Range Fog and Stratus Forecasting at Eugene, Oregon

Leona Yee and Earl Bates

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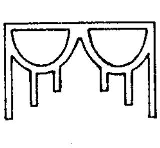

A western Indian symbol for rain. It also symbolizes man's dependence on weather and environment in the West.

U. S. DEPARTMENT OF COMMERCE
ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION
WEATHER BUREAU

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APPLICATIONS OF THE NET RADIOMETER TO SHORT-RANGE FOG AND STRATUS FORECASTING AT EUGENE, OREGON

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WESTERN REGION
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EDITOR'S NOTE

This Technical Memorandum contains results of our continuing study of the use of radiation measurements in operational terminal forecasting. The initial study [1] was undertaken as the result of a suggestion made by Dr. George P. Cressman during a 1965 visit to our Los Angeles forecast office.

Due to difficulty in operating the radiation equipment properly at Los Angeles International airport, and the initiative of Mr. Earl Bates when he was MIC at Eugene, Oregon, the observation site was moved to the Eugene, Oregon airport in 1967.

Study of the data on which this report is based was begun by Mr. Bates. Miss Yee was assigned to collaborate with him in the study during her tour of duty at the Regional Headquarters as a 1969 summer trainee. Miss Yee graduated from Brigham Young University as an honor student in Physics in May 1969. She is currently a graduate student in meteorology at the University of Utah.

L. W. Snellman, Chief
Scientific Services Division
Weather Bureau Western Region

APPLICATIONS OF THE NET RADIOMETER TO SHORT-RANGE FOG AND STRATUS FORECASTING AT EUGENE, OREGON

I. INTRODUCTION

A Thornthwaite miniature net radiometer was placed in operation at the Mahlon Sweet Municipal Airport, Eugene, Oregon, in June 1967 to further explore the instrument's potential as a tool in short-range fog and stratus forecasting. This experiment was a second attempt to determine a correlation of radiative cooling and heating as recorded by the net radiometer with the onset of fog or low stratus. Earlier, a similar experiment was conducted at Los Angeles International Airport with the same instrument and evaluated by Thomas [1]. In addition this paper explores the use of the radiometer in predicting dissipation of fog and/or low stratus.

II. INSTRUMENTATION

The sensor is composed of a small disk containing a thermopile transducer and finished with flat, black paint on the upper and lower surfaces. The disk is mounted parallel to the ground. Two hemispherical polyethylene windows are inflated with dry air to enclose the transducer which measures the temperature difference between its upper and lower surfaces. This temperature difference is proportional to the net radiation and is sensed by the thermopile, the output from which drives a General Electric recorder graduated to indicate a range from -.05 to +2.00 langleys. Further details on the description of the instrument may be found in [1].

In one respect the instrument used in the Eugene experiment differed from that in Los Angeles. Instead of using a chart that moved 3 inches per hour, the recorder was modified to use a chart which moved at the rate of 1 inch per hour. With this slower movement, the slope of the trace was magnified to enable a change in slope to show more plainly. Also, the instrument was exposed in a more favorable location than was possible at Los Angeles so that the problem of obtaining high-quality, reliable data as stated in [1] has been overcome sufficiently to make further study of the use of net radiation observations in short-range forecasting at an airport worthwhile.

Eugene, Oregon airport is located in the southern end of the north-south Willamette Valley, at an elevation of approximately 373 feet and about 53 miles inland from the Pacific Ocean [3]. The center of the valley is about 30 miles from the crest of the Coast Range to the west which has an elevation of 1,500 - 2,500 feet and acts as a barrier to fog and low clouds. To the east, the crest of the Cascade Mountains is about 67 miles away and rises to 6,000 feet with numerous peaks at 10,000 feet. Winds are predominantly from the north or southwest, being affected strongly by the topography of the land. During summer afternoons, up-valley winds are northerly 5-15 knots. Branches of the Willamette River are located 4-5 miles northeast of the airport, while a reservoir (20 square mile surface) is situated 7-8 miles west of the airport.

At the Eugene Airport Station, the sensor is located one meter above the ground in a readily accessible area 200 feet away from the Weather Bureau building. Located west-northwest of the radiometer, this building has a tower on top for a total height of 55 feet. Sharp vertical drops in the radiometer trace around sunset result from the sun setting behind this building. Around the 18"x 18" concrete slab that supported the instrument, the ground was bare for about a radius of 5 feet. Attempts to grow grass had proven unsuccessful. Most of the time, the concrete was kept covered with soil to eliminate heat reflection. A daily dusting of the two polyethylene windows was the only cleaning necessary. For two prolonged periods the instrument was out of service due to leaks in the protecting plastic hemisphere. The cause of one leak was not determined; the other was caused by rain freezing on the sphere.

Waste products from nearby lumber mills cause considerable air pollution. The smoke thus created often reduces visibilities. It is possible that observers may at times confuse the smoke for fog. This problem occurs frequently during the night.

In November, December, and January, the radiation fog that develops at night sometimes thickens and persists during the day. In late spring and early summer, north winds of 6-12 knots blow up the valley, bringing persistent stratus that lasts into the afternoon. This stratus is often found at 400-500 feet above the ground. Such environmental conditions at Eugene must be considered as they could account for some exceptions to the criteria set up in this study to define a fog or low stratus case and trace jumps.

III. PREDICTING FOG AND/OR LOW STRATUS FORMATION

A. Theory and Application.

The net flux of radiative energy, ^{F}N, consists of the difference between downward incoming radiation, ^{F}D, and upward outgoing radiation, ^{F}U. Considering incoming radiation as positive and outgoing radiation as negative, the net flux of radiative energy recorded by the instrument is:

$$F_N = F_D + (-F_U).$$

Incoming radiation is composed of direct and scattered short-wave radiation plus long-wave downward radiation from clouds and carbon dioxide. Outgoing radiation is composed of long-wave terrestrial radiation plus reflected short-wave radiation.

During the day, net radiation is dominated by incoming direct and scattered short-wave plus downward long-wave radiation, while at night this incoming radiation is almost nil, and outgoing long-wave radiation from the earth dominates. Therefore, net radiation is positive during the day and almost always negative at night. For more details on this part of the theory and possible application of the net radiometer, the reader is referred to [1].

On a clear night the earth's surface and the first meter of atmosphere have a net loss of about 6 langleys per hour, which is recorded on the trace at about -.10 langleys on the scale. Increases in atmospheric water vapor and clouds result in an increase in downward long-wave radiation (F_D), which in turn causes the radiometer to record less negative or slightly positive values at night. If a stratus cloud moves over the airport or fog begins to form, the recorder trace shows a change in slope preceding the appearance of stratus or fog. The scale value usually rises .05 or more. These slope changes indicate an increase in moisture and consequent decreases in energy loss from near the earth's surface, and may be used as a warning or predictor of stratus or fog [2]. Following this theory, traces of the net radiometer were examined for such predictors of fog or low stratus, and an attempt was made to establish a quantitative relationship between the two.

B. Preliminary Study.

In the preliminary study done by Bates [2], data for a period of eleven months in 1968 from January through November were examined. Due to the radiometer being out of operation for much of December, no use could be made of data from that month. In defining which specific cases were to be studied with respect to the trace jump (i.e., sharp slope change) criteria were set up using times of beginning and ending of fog from Form WBAN 10 (Airway Observations) for the Eugene, Oregon airport. No consideration was given to actual visibility values. Cases considered included times when stratus existed as a broken or overcast layer at ≤ 1500 feet and/or as low broken stratus with fog. By studying the traces and measuring the time from the point where a trace jump occurred to the point of fog or stratus onset, an average lead time of 2.8 hours was obtained through the eleven-month period [2]. However, some discrepancies were found in this preliminary study, requiring a reevaluation of the traces.

Reevaluation of data in [2] was done in Salt Lake City at Regional Headquarters by Miss Yee, independently of the preliminary study. Criteria established for selection of cases were:

1) Appearance of low stratus (ceiling $\leqslant$1500 feet and more than five-tenths sky coverage) following skies that were clear or with cirrus only for the preceding 3-5 hours, and

2) appearance of fog, ground fog, or haze (visibility $\leqslant$3 miles) under skies that were clear or with cirrus only for the preceding 3-5 hours.

Fog and low stratus occurrences meeting these criteria were labeled "positive" cases. "Negative" cases were characterized by clear skies or cirrus in the evenings but no fog or low stratus as defined above in the morning; or by a trace jump, but no subsequent fog or low stratus.

For the traces examined in the "positive" cases, the following parameters of γ_1, γ_2, and ΔT were measured, where γ_1 is the change in radiation (langleys) for the 4-hour period just preceding fog and/or stratus onset; γ_2 is the slope of the trace jump; and ΔT is the time between the jump and onset of fog or stratus.

On a typical night with clear skies or cirrus with low moisture content and no fog forming the next morning, the radiometer trace read between -.10 and -.05 langleys from evening through the night until sunrise. At sunrise the trace began to rise gradually, reaching a peak reading between .75 and 1.00 langleys on the scale near noon on summer days (see Figure 1). If fog or low stratus formed in early morning, the trace usually showed an increase of about .05 langleys in the form of a strong jump (over an interval of 30 minutes or less) or a moderate jump (over an interval from 1/2 hour to 2 hours). The trace remained nearly level after the jump as well as before. As an example, on January 4, 1968 (Figure 2), a trace jump occurred at 0155 PST and fog began at 0330 PST. Skies were clear in the evening and early portion of the night, then visibility dropped to 1/2 mile as ground fog appeared. In this particular instance a warning time of 1 hour 35 minutes was given before fog onset with $\gamma_1 = .01 \frac{\text{langleys}}{\text{hour}}$ (averaged over a 4-hour period) and $\gamma_2 = .30 \frac{\text{langleys}}{\text{hour}}$. For the 27 such cases, January through November 1968, an average Δ of 3 hours 16 minutes was found with values ranging from 5 minutes to 10 hours. An average γ_1 of .02 langleys/hour (averaged over a 4-hour period) with a range from 0 to .06 langleys/hour and an average γ_2 of .14 langleys/hour with a range from .04 to .46 langleys/hour were found.

Another type of situation studied was that which occurred when the air was initially near saturation under cloudless skies prior to fog formation in the early morning hours. The trace for a case of this type is shown in Figure 3 where there is a gradual rise during the night with only a very slight jump before fog onset. Sometimes there may be only the gradual rise. For the 8 cases of this type $\overline{\gamma_1} = 0.02$ langleys/hour (averaged over a 4-hour period), $\overline{\gamma_2} = 0.31$ langleys/hour and $\overline{\Delta T} = 3$ hours 18 minutes with ranges of .00 to .05 langleys/hour, .02 to .54 langleys/hour, and 1 hour 5 minutes to 5 hours 30 minutes, respectively. A rising trace without a jump did not necessarily mean fog or low stratus formed, for there were some occurrences with just a rising trace. A forecaster should be alerted in such a circumstance.

Although the cases described above were the principal ones, others included a category for traces which seemingly had two discontinuities or warnings before fog onset; a category for smoke before fog onset; a category for ΔT greater than 4 hours; a category for higher stratus clouds (1,500 - 6,000 feet) ending around 4 hours before fog or low stratus onset; and a category for fog overlapping ground fog cases.

About 55 "negative" (no fog or low stratus formation) examples were found during the period of interest. Theoretically the traces should remain level at -.05 langleys until sunrise as in Figure 1, even with smoke present. However, 17 cases showed the trace rising very gently probably due to an increase in moisture during the night. But an example of the "negative" cases which were especially deceptive is illustrated in Figure 4, where favorable conditions of a small temperature-dewpoint spread (2°F.), a light wind (5 knots), high relative humidity (93%), and cirrus existed the night before. At about 0140 PST a trace rise occurred but no fog or low stratus appeared in the morning. No explanation could be offered for the failure of fog to appear when the warning was given, and the conditions were favorable.

C. Results.

Table 1 presents results of Miss Yee's evaluation. It is seen in the "positive" cases that there are 50 instances where any kind of trace jump preceded fog or low stratus onset as opposed to 3 instances where no trace jump preceded onset. In the "negative" cases there are 23 instances where jumps or rises existed, but no fog or low stratus as defined earlier occurred as opposed to 32 instances where there was no trace jump and no fog or low stratus found.

Analysis of the value of trace jumps as predictors of fog is given in Tables 2A and 2B. Using all jumps, it is seen that forecasts of fog or low stratus were followed by the occurrence of fog or low stratus 68% of the time, while occurrences of fog or low stratus were correctly indicated in advance 94% of the time. On the basis of just strong and moderate jumps, it is seen that forecasts of fog or low stratus were followed by the occurrence of fog or low stratus 88% of the time (post-agreement), while occurrences of fog or low stratus were correctly indicated in advance 79% of the time (prefigurance). These figures indicate underforecasting of fog using all the jumps. The percent correct of forecasted cases was 76% using all jumps and 84% using only strong or moderate jumps. The threat score was also higher using only strong or moderate jumps as predictors.

From preliminary study, radiometer trace jumps appear to be worthwhile predictors of fog and low stratus especially if the jumps are strong or moderate. An average warning time of 3 hours 16 minutes can be expected.

D. Further Investigation.

The two authors conferred in Eugene during July 1969 to discuss further steps to be taken in the radiometer study. These discussions considered new criteria upon which to forecast fog and low stratus, encompassing five more parameters of temperature-dewpoint spread, relative humidity, observer's remarks, wind speed and direction at time of and prior to fog formation, and new definitions of a radiometer trace jump. These parameters were considered in attempting to account for any inconsistencies among developmental cases. They were also employed later subjectively to determine whether or not a forecast should be issued on the basis of trace jumps in the test data.

Criteria for selection of fog or low stratus cases were also redetermined. Cases were divided in fog or stratus and no fog or stratus cases. In Group A cases were defined as fog with visibility ≤ 6 miles and/or low stratus with the ceiling ≤ 1500 feet and antecedent conditions of clear skies or cirrus from 1900 PST to time of fog or low stratus appearance. After traces for these selected cases were reexamined, Group A was subdivided into two groups--A_1 and A_2. Group A_1 contained cases with trace jumps while Group A_2 contained cases without trace jumps. Note was taken of cases where smoke or subfreezing temperature existed. Group B cases were defined as no fog (visibility >6 miles) and/or no low stratus (ceiling >1500 feet) formation with antecedent conditions of clear skies or cirrus from 1900 PST to sunrise. After traces for these cases were examined, Group B was subdivided into Groups B_1 and B_2 where the former included cases with trace jumps and the latter included cases with no trace jumps.

After defining the groups and subgroups as above, radiometer traces were reexamined, and four categories were formed for Groups A_1 and A_2 and for Groups B_1 and B_2. Characteristics of the traces were reclassified as either a strong jump, a moderate jump, an indeterminate rise, or no jump. In further redefining these characteristics, a strong jump had to raise the trace at least .03 langleys over a time span of 30 minutes or less, and be fairly smooth and level before and after the jump (see Figure 2). A moderate jump had to raise the trace at least .03 langleys, have a time span greater than 30 minutes but less than 1-1/2 hours, and be fairly smooth and level before and after the jump. (See Figure 5.) The indeterminate rise category included traces that had a very tiny jump or a definite rise, or traces with a jump and decreases or dips following (see Figure 6). In the first two categories, a forecaster could be pretty certain that fog or low stratus would occur providing the conditions were otherwise favorable, i.e., clear skies, high relative humidity $\geq 83\%$, light winds ≤ 10 knots, and low temperature-dewpoint spread $\leq 4°$. The no-jump cases had essentially flat traces.

E. Results of Further Investigation.

Table 3 presents the new classification of radiometer trace jumps under two main groups. The average ΔT obtained for Group A_1 cases was 3 hours 13 minutes, while γ_1, and γ_2 averaged .014 langleys/hour (averaged over a 4-hour period) and .08 langleys/hour, respectively. Values for the range of ΔT were from 10 minutes to 6 hours 45 minutes (see Figure 7); for $\gamma 1$, values were from 0 to .03 langleys/hour and for $\gamma 2$, values were from .01 to .32 langleys/hour.

It should be noted that only 2 out of the 11 indeterminate rise cases had a pronounced enough jump to be measured. In distinguishing ΔT between the 10 strong and 17 moderate jump cases, an average value of 2 hours 52 minutes (range from 10 minutes to 6 hours and 45 minutes) was obtained for the former, and an average value of 3 hours 28 minutes (range from 55 minutes to 5 hours 25 minutes) was obtained for the latter (see Figures 8 and 9).

Some study was done to determine why at times a moderate jump appeared rather than a strong jump, when prior surface conditions appeared to be similar for both categories. It was noticed that for the five 1968 jump cases, visibility went down to an average of 3/8 miles in the morning while it only went down to an average of 2-1/2 miles for the 15 moderate jump cases. Ranges for these cases were 1/4 - 1/2 mile and 1/4 - 8 miles, respectively. One possibility is that the moisture gradient in the atmosphere may be a factor.1/

Of the 30 Group B_2 cases, ten had slightly increasing traces or uneven fluctuations. However, by checking surface observations for these cases, the forecaster would probably not have predicted fog as other factors favoring fog formation were not present.

In Group B_1 cases there was a jump although no fog occurred. Some of these B_1 strong jump cases very closely resembled A_1 cases as far as the trace was concerned (see Figures 4 and 10). Six such cases of close resemblance were found but considering other factors, a forecaster should be able to make a reasonably accurate prediction despite the deceptive trace jump. Figure 11 reveals that for the 10 B_1 cases with definite jumps, 80% had visibilities of 15 miles or greater at the last observation recorded before the trace jump occurred, while Figure 12 shows for the 29 A_1 cases with definite jumps, only 50% had visibilities of 15 miles or greater at the last observation recorded before the trace jump occurred. The range of temperature-dewpoint spreads for the B_1 cases was from 3°F. to 20°F. while for the A_1 cases, the temperature-dewpoint spread ranged from 1°F. to 7°F. No relationship could be found between wind speed and wind direction for the two cases. Since a trace jump is not necessarily followed by fog or low stratus, it appears the forecaster can sometimes avoid issuing an erroneous forecast by considering surface conditions at the time of the jump along with the jump. For fog or low stratus formation preceded by a trace jump, visibility tends to be lower and temperature-dewpoint spread smaller at the last observation before the trace jump than for cases when no fog or no low stratus follows a trace jump. No relationship could be found between time of jump and subsequent occurrence or nonoccurrence of fog or low stratus.

1/ Personal communication with Mr. Leonard Snellman.

Contingency Tables 4A and 4B indicate the value of the radiometer trace jump as a forecast tool for fog or low stratus as used on developmental data. Using all jumps, it is seen that forecasts of fog or low stratus were followed by occurrence of fog or low stratus 72% of the time (post-agreement), while occurrences of fog or low stratus were correctly indicated in advance 74% of the time (prefigurance). On the basis of just strong and moderate jumps, it is seen that forecasts of fog or low stratus were followed by occurrence of fog or low stratus 82% of the time, while occurrences of fog or low stratus were correctly indicated in advance 51% of the time. These figures indicate underforecasting of fog using trace jumps. The percent correct of forecasted cases were 70% using all jumps and 67% using only strong or moderate jumps. Threat scores were 57% using all trace jumps and 46% using only strong or moderate jumps.

To test the success of the radiometer as a forecast tool, traces from January through May 1969 were used. Without knowing beforehand the dates on which fog or low stratus did appear, two meteorologists with no experience in forecasting for Eugene, individually examined the traces, simulating a real-time operation, just as if the traces were coming off the radiometer. In other words, the eye could not see ahead of each hour's length of trace being considered at the time. If any jumps or suspicious rises appeared, their times were recorded. For the dates and times where these jumps occurred, surface observations were obtained, summarized from three hours before and one hour after time of recorded jump or suspicious rise. The information presented was temperature-dewpoint spread, relative humidity, wind speed, wind direction, ceiling, and visibility, while any data on obstructions to visibility were withheld from the test participants. On the basis of the trace and summarized surface observations, the test meteorologists issued subjective forecasts for occurrence or nonoccurrence of "fog or low stratus" for each date. Eugene hourly and special observations were used to verify the forecasts. Table 5 summarizes results obtained for these predictions. It is seen that forecasts of fog or low stratus (as made by the meteorologists under simulated conditions) were followed by the occurrence of fog or low stratus 81% of the time (post-agreement), while occurrence of fog or low stratus was correctly indicated in advance 57% of the time (prefigurance). These figures indicate underforecasting of fog with trace jumps. The percent correct of forecasted cases was 70% for the test data, and threat score was 50%. It can be seen that there is skill in the predictions.

In making predictions of fog or low stratus, the average ΔT of 3 hours 13 minutes found under further investigations was added to the time the meteorologists recorded for their trace jump or rise. The time thus obtained was the expected time of onset of fog or low stratus. In some cases fog or low stratus occurred after the expected time of onset and in some cases, before the expected time. A statistical analysis showed that for cases where fog or low stratus was forecasted and did occur, the average time lapse between the expected time of onset and actual time of onset was 2 hours 21 minutes with a range from 2 minutes to 7 hours 25 minutes. Average deviation for the time lapse was 1 hour 8 minutes.

Tables 6A and 6B show results obtained from the 1969 test data with the meteorologists making forecasts of fog or low stratus using only the occurrence of trace jumps as a basis, without relying on other parameters or on their experience. It is seen that in using all types of radiometer trace jumps, forecasts of fog or low stratus were followed by the occurrence of fog or low stratus 58% of the time (post-agreement). If only strong or moderate jumps are used, forecasts of fog or low stratus were followed by the occurrence of low stratus 56% of the time (post-agreement). Thus, at this point, the net radiometer works more successfully as a fog forecasting tool when its jumps are considered subjectively in relation to other parameters at the time of the jump.

F. Conclusions.

The net radiometer serves best as a predictor of fog or low stratus formation with clear skies or cirrus for four or more hours before fog or low stratus onset. Qualitatively the radiometer trace is apparently able to indicate a substantial increase condensed moisture not visible to observers which frequently precedes fog formation. Under cloudy skies, the trace becomes useless with too many fluctuations. There is a definite relationship between trace jumps and occurrences of fog, but there are also many cases that yield wrong predictions, i.e., trace jump and no fog occurring or no trace jump and fog occurring. Further study should include a larger number of cases and more detailed observations at the time of all trace jumps.

So far the net radiometer data have been evaluated and tested as a subjective forecast tool where the forecaster's knowledge and the existing surface conditions must be employed in addition to the radiometer trace jump in making a prediction. As was seen in the results of the test data, the exact time of fog or low stratus onset cannot be forecasted although the deviation is within a couple of hours.

Further work should be done in developing the net radiometer as an objective tool in fog and low stratus forecasting. Other parameters of relative humidity, temperature-dewpoint spread and wind speed and direction can be obtained for a certain time of the day, (i.e., 2100 or at the time of the trace jump) and be plotted in scatter diagrams with the trace jump as one parameter. Thus one can arrive objectively at a probability of occurrence-type graphical analysis with the above factors, or radiometer trace readings can be punched on cards and run through a computer to fit a multiple regression model which could in turn produce a forecast. Another area worthy of study is the stratification of fog and low stratus cases as to the time of year of occurrence to examine the value of the trace jump as a predictor from this aspect. For Eugene, Oregon, stratification would be useful in view of environmental factors. With more cases, the number of correct forecasts made with the trace jump can be correlated with the type or intensity of the jump. Results from this analysis could be used in establishing a probability of occurrence-type method for forecasting with different radiometer trace jumps.

It should be noted that this study applies only to the Eugene Airport where two years of continuous radiometer data were available. On a wide-scale application, forecasters would have to develop net radiometer method for their own locations, as either a subjective or objective tool because of varied environmental conditions and problems unique to each area.

IV. PREDICTING FOG AND/OR LOW STRATUS DISSIPATION

A. Theory.

After sunrise, incoming short-wave solar radiation increases gradually to dominate outgoing long-wave radiation from the earth's surface. A typical net radiometer trace reads -.05 langleys shortly before and after sunrise, rises to zero langleys, then reads increasingly positive values until noon. (See Figure 13.) Typical radiation fogs are quite shallow and dissolve readily as a result of diurnal heating [4]. If radiation fog or low stratus has not dissipated by sunrise, the slope of the radiometer trace from sunrise to the time at which the trace reads zero langleys may be used as a tool in predicting dissipation time. If the average number of energy units needed to dissipate fog or low stratus under the trace from sunrise is known (1 energy unit = a rectangle .05 langleys high and 30 minutes wide on the trace graph, as shaded in Figure 13), then extension of the trace's slope from where the trace crosses zero langleys after sunrise until the necessary number of energy units is obtained under the entire line (including the portion between sunrise and the point the trace crosses zero langleys) gives a time at which fog or low stratus is forecast to dissipate.

If fog or low stratus begins in the morning and persists through most of the day before dissipating in the afternoon, or persists through the night before dissipating next morning, the net radiometer trace cannot be applied in predicting a dissipation time. Cases of persistent fog or low stratus in Eugene are common in late fall and winter, and are usually associated with a cold earth relative to ambient air temperature or by north winds bringing upslope fog. In winter, incident solar radiation during the day is at a minimum, nights are longer, and stronger inversions form. As a result, fogs require more energy and time to dissipate. Shorter nights, more incident solar radiation during the day, and weaker inversions characterize summer; consequently, fogs tend to be more shallow and less solar energy and time are required for dissipation than in winter. Thus, the number of energy units needed to dissipate fog or low stratus is expected to decrease as spring and summer progress and increase as autumn and winter progress. Figure 14 shows the schematic relationship between number of energy units needed for dissipation and month of year, taking into consideration soil moisture and surface temperatures [2].

B. Application.

Criteria established were based on a need for surface conditions to be better than absolute IFR aircraft minima. Fog and low stratus cases from February-November 1968 were used as developmental data. Fog cases had to have minimum visibilities ≤ 1 mile with no alto or higher stratus (>1500 feet) clouds moving in above the fog. Low stratus (≤ 1500 feet) cases had to go below 700 feet, broken to overcast, with no alto or higher stratus (>1500 feet) clouds moving in above the low stratus. Fog with clear skies or cirrus above was considered dissipated when visibility was greater than one mile. Fog which lifted to a stratus deck between 300 and 700 feet broken or overcast, and stratus between 1200 and 300 feet broken or overcast that lowered to form fog were considered dissipated when the stratus deck lifted to 700 feet scattered, broken, or overcast or when the stratus deck completely dissolved (whichever occurred first); and when visibility was greater than one mile. The method of extrapolation from sunrise to dissipation does not apply to fog or low stratus cases ending before the trace reaches zero langleys.

Net radiometer traces for selected fog and low stratus cases were examined for the number of energy units needed for dissipation. Times of sunrise were taken from the U. S. Naval Observatory's table of sunrise and sunset at Eugene, Oregon, PST. Although there is an average delay time of about 10 minutes from the time the sun appears above the sea-level horizon (given as sunrise in this table) and the actual time that the sun shines on Eugene, due to the mountains to the east this delay time was not considered, as it did not show up as a large difference on the recorder chart. A straight line was drawn from time of sunrise to time of fog or stratus dissipation such that the areas above and below the trace were equal (see Figure 15). The area under this straight line is proportional to the total energy required for fog or low stratus dissipation.

$$E = \frac{y \cdot x}{2}$$

Where E is the number of energy units; x is the number of 1/2-hour intervals under the trace; and y is the number of .05 spacings along the y axis.

C. Results.

In Table 7 for January - November 1968 data for the 22 fog cases with clear skies, cirrus or low stratus deck above, an average of 25.8 energy units were needed for dissipation. In separating the two types of fog cases, the eight cases with clear skies or cirrus above took an average of 16.2 energy units for dissipation, while the 14 cases extending from or into a stratus deck took an average of 31.2 energy units for dissipation.

Only two low stratus cases were found, and an average of 14.6 energy units were required for dissipation.

Combining both fog and low stratus cases gives an average of 24.8 energy units for dissipation. Table 7 also shows results obtained when fog or low stratus formed after sunrise. For the five fog cases, an average of 31.0 energy units were required while for the one low stratus case 18.4 energy units were required. Combining fog and low stratus cases occurring after sunrise gives an average of 28.9 energy units. It may be noted that more energy units are needed for dissipation of fogs beginning after sunrise than before sunrise. This is contrary to what would be expected from theory. It was believed that fogs beginning after sunrise would be shallower and be composed of more sparse droplets, and therefore be easier to dissipate. However, this discrepancy may be due to cold air advection in the layer below the inversion or simply due to small sample size. A larger sample of cases of this type is needed to resolve this apparent contradiction.

Table 8 stratifies results by months and seasons of the year and by types of cases. The general trend of fewer energy units for dissipation in the warm season and of more energy units for dissipation in the cold season is evident. Figure 16 presents histograms of energy units needed for fog and low stratus dissipation stratified by seasons. Figure 17 is a histogram of energy units for all January-November 1968 developmental cases.

In further analyzing results, inversion heights from Salem radiosonde soundings for January-November 1968 were considered. An important factor in forecasting fog or low stratus dissipation is depth of fog or thickness of low stratus. This information is usually not known precisely. Deeper fog or low stratus would require a larger number of energy units to dissipate. In this study it was assumed the fog or stratus top would be as high as the top of the first inversion layer. A correlation was then attempted between height of the top of the inversion and number of energy units needed for dissipation. However, due to a limited number of developmental dissipation cases, no relationship could be found.

Data from January-May 1969 were used as test data. Restrictions were needed in applying dissipation techniques to test data. If fog began and visibility went below one mile before sunrise with no higher stratus clouds appearing or rain occurring, then the technique was applied after sunrise when the trace reached zero langleys. If fog began before sunrise but visibility did not reach below one mile before the trace reached zero langleys, the tool was used only if visibility appeared to be steadily dropping to one mile. If a minimum visibility below one mile was not reached, the case was not included in the test. If fog dissipated before sunrise or during the time the trace climbed to zero langleys, the method could not be employed. If fog began and visibility went below one mile any time after sunrise, with no alto or higher stratus clouds appearing or rain occurring, then the technique was applied using the slope of the trace based on the interval between sunrise and the time when the trace crossed zero langleys. If fog began after sunrise but visibility was still greater than a mile at the time the trace crossed zero langleys, a dissipation time was predicted assuming visibility would continue to drop below a mile. If later in the morning, lowest visibility was found to be greater than a mile, the case was not used.

Above restrictions also applied to low stratus cases with the condition that the ceiling had to drop below 700 feet instead of visibility dropping below a mile.

For the six test cases on which restrictions permitted the dissipation technique to be used, expected times of dissipation were calculated by extending the slope of the trace (over the interval from sunrise to where the trace crossed zero langleys) and by extrapolating the number of energy units still needed for dissipation (see Table 9). When compared with actual times of dissipation, forecast times were found to be off 1 hour 4 minutes on the average with a range from 20 minutes early to 2 hours 45 minutes late. Average bias between expected and observed times of dissipation was +42 minutes.

This positive bias in test cases was caused by a bias introduced during development of technique. This bias was caused by errors in estimating from a short section of trace (sunrise until trace reached zero langleys) the long period trace rise. Reworking the development data to account for the difference between projected and observed trace rise led to determination of a bias of +41 minutes for forecast minus observed ending time. Correction for this bias on the six test cases resulted in the errors shown in the last column of Table 9.

Table 10 presents results of the six test cases where stratified units needed for dissipation, taken from Table 7, were used--i.e., for fogs with clear skies or cirrus above, 16.2 energy units were used; and for fogs extending from or into a stratus deck above, 31.2 energy units were used. It is seen that the lapse between expected and observed dissipation times is reduced considerably in five out of six cases. Between expected and actual ending times, the average time lapse was 43 minutes with a range from -5 minutes to +1 hour 55 minutes, and a bias of +42 minutes. Application of the 41 minutes correction determined from the developmental data gives the unbiased result shown in the last column of Table 10.

An overall relationship between net radiation and visibility during fog formation and dissipation at Eugene, Oregon, airport for September 7, 1968, is seen in Figure 18. A rapid decrease in visibility at and following the time of the jump on the radiometer trace can be seen. The trace jump came between 0030 PST and 0040 PST. A secondary jump occurred just after 0330 PST and fog began at 0515 PST, when visibility decreased rapidly. Sunrise was at 0550 PST, so a net increase in energy was seen after 0600 PST. Visibility continued variable until fog dissipated at 1000 PST [2].

D. Conclusions.

Further study on dissipation of fog or low stratus with more data should yield more conclusive results. Results in this limited study show the promise of the net radiometer as a tool in short-term forecasting of fog or low stratus dissipation. With a greater number of cases, correlation between number of energy units needed for dissipation and inversion height or correlation between number of energy units and ground temperatures could be done.

Further stratification of more cases by seasons is needed, as is stratification of fog or low stratus cases before or after sunrise. Months may be placed into seasons by energy units rather than by astronomical methods, while ground fog cases may be separated from fog cases to make the study more useful.

Other areas of study that would prove useful to aircraft operations would be finding the number of energy units to lift fog into a stratus deck or the energy required to increase visibility under fog from 1/2 mile to 3 miles.

Further evaluation is needed both at Eugene and at other airports where there is interest in developing the net radiometer as an objective short-term forecasting tool for fog or low stratus.

V. ACKNOWLEDGMENTS

The writers are grateful to Ronald A. Surface, L. C. Jones, and other members of the staff of the Weather Bureau Office, Eugene, Oregon, for supplying radiation data and surface observations used in this study. Appreciation goes to L. W. Snellman, P. Williams, Jr., W. W. Dickey, and R. P. Augulis of the Weather Bureau Western Region Headquarters for comments and suggestions during preparation of this paper. We recognize Miss Eva Mallock for efforts in making original evaluations of the radiometer trace.

VI. REFERENCES

[1] F. Thomas, "Applications of Net Radiometer Measurements to Short-Range Fog and Stratus Forecasting at Los Angeles," Western Region Technical Memorandum, No. 14, September 1966.

[2] E. Bates, "Net Radiation as a Possible Prediction of Beginning and Ending of Fog or Stratus," June 1969, unpublished.

[3] P. Williams, Jr., "Station Descriptions of Local Effects on Synoptic Weather Patterns," Western Region Technical Memorandum, No. 5, April 1966.

[4] S. Petterssen, Weather Analysis and Forecasting, Volume II, Weather and Weather Systems, McGraw Hill Book Company, Inc., 1956, pp. 111-122.

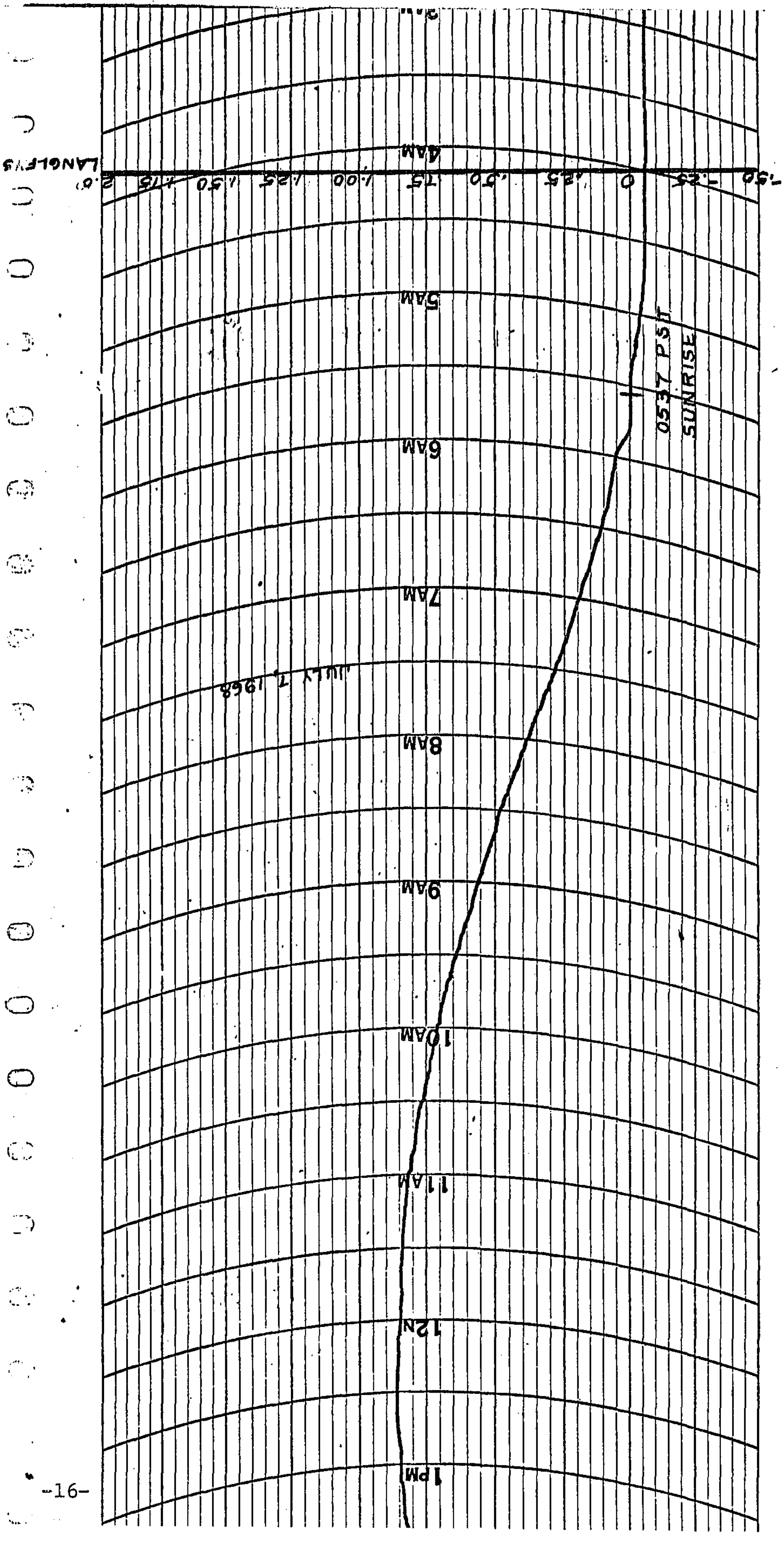


FIGURE I - NET RADIOMETER TRACE FOR EUGENE, OREGON, JULY 7, 1968

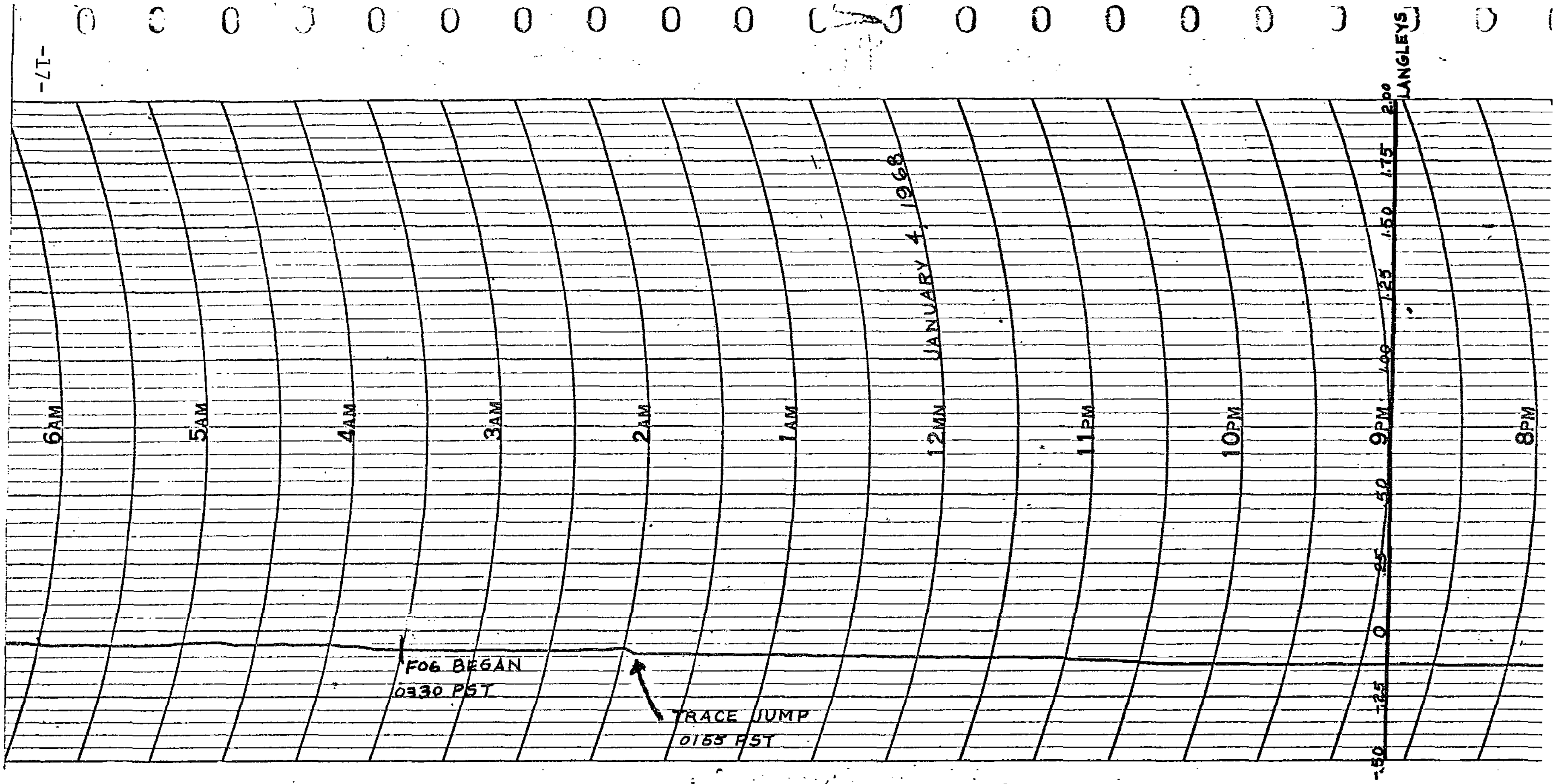


FIGURE 2 - NET RADIOMETER TRACE FOR EUGENE, OREGON, JANUARY 4, 1968

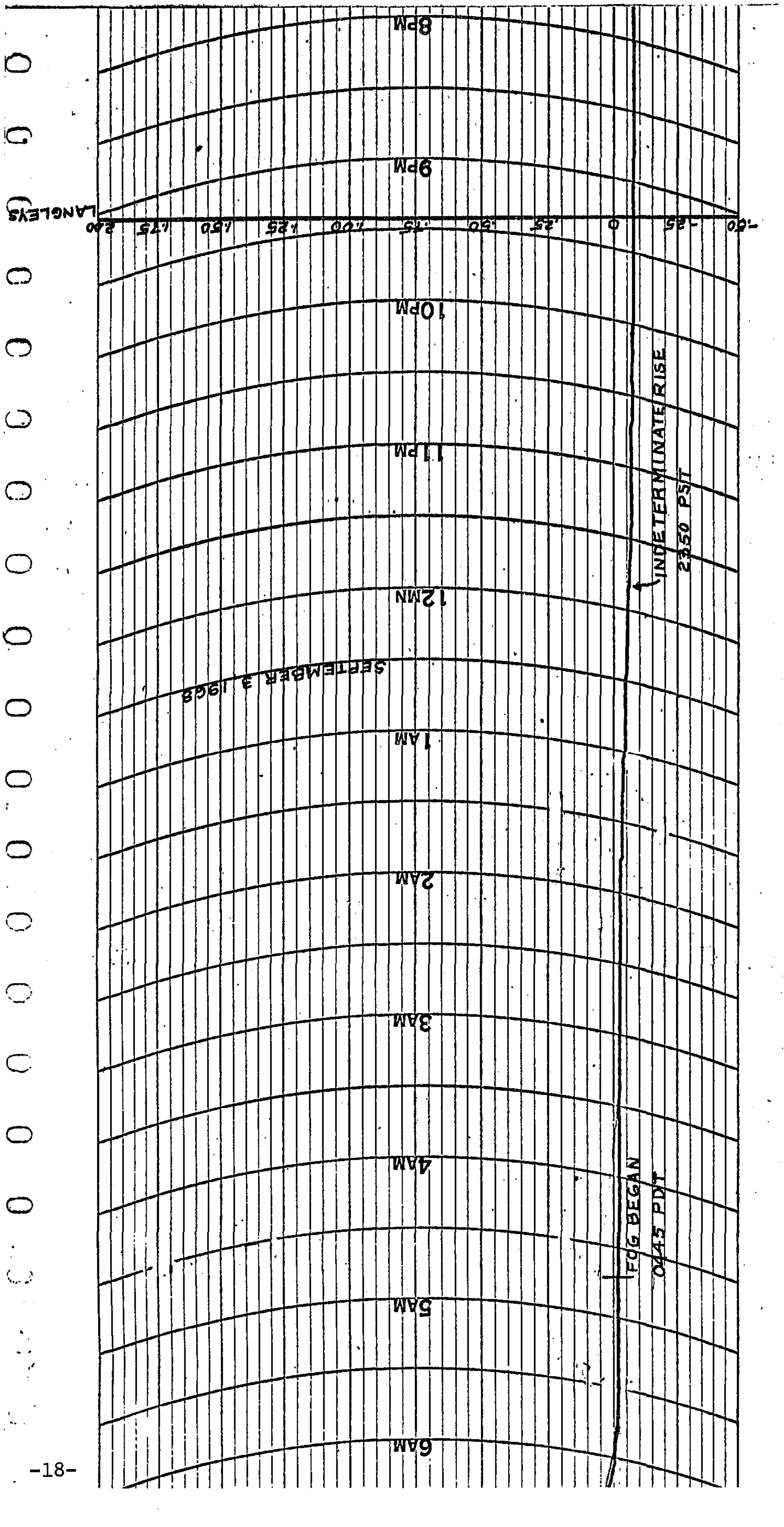


FIGURE 3 - NET RADIOMETER TRACE FOR EUGENE, OREGON, SEPTEMBER 3, 1968

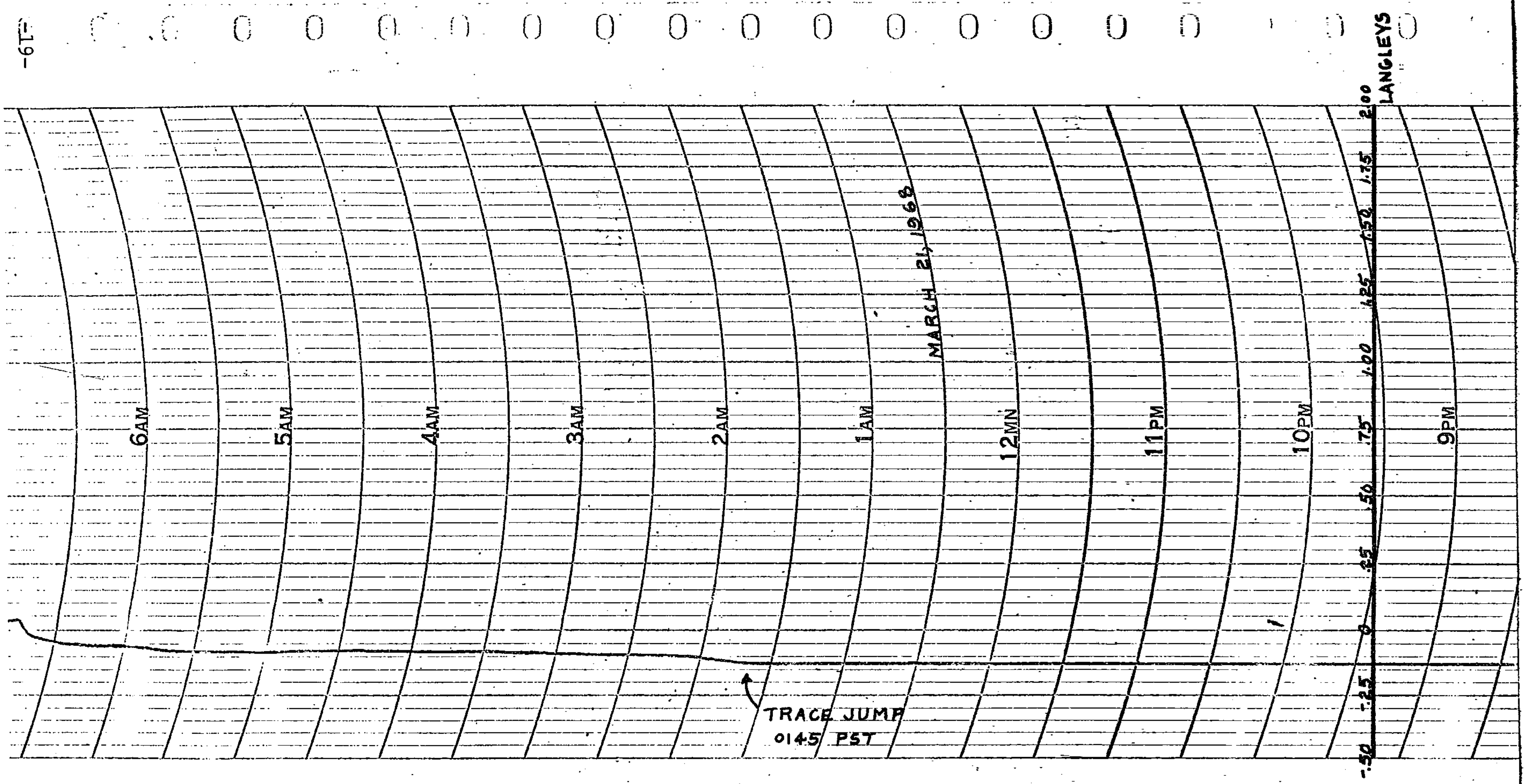


FIGURE 4 - NET RADIOMETER TRACE FOR EUGENE, OREGON, MARCH 21, 1968

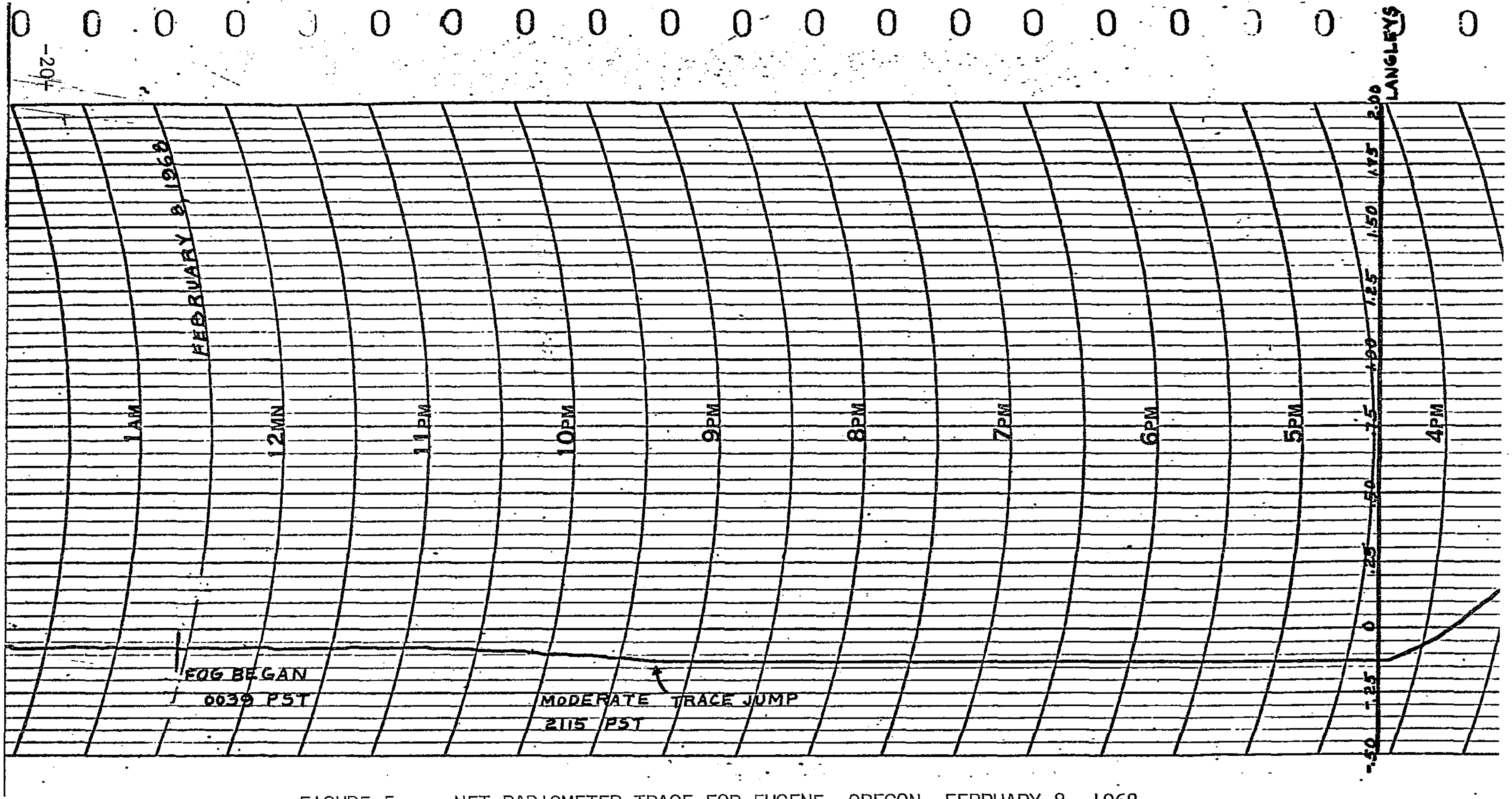


FIGURE 5 - NET RADIOMETER TRACE FOR EUGENE, OREGON, FEBRUARY 8, 1968

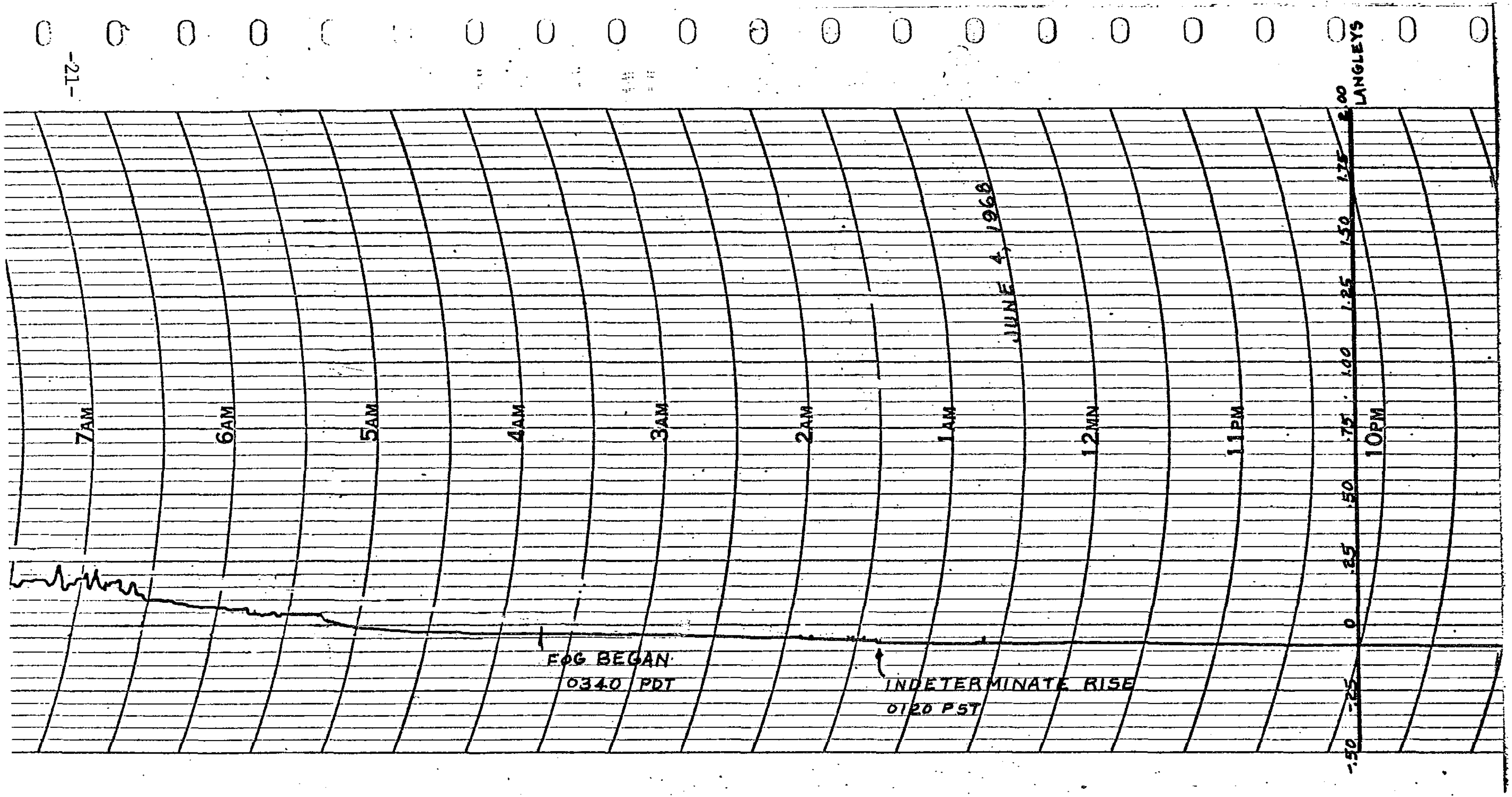
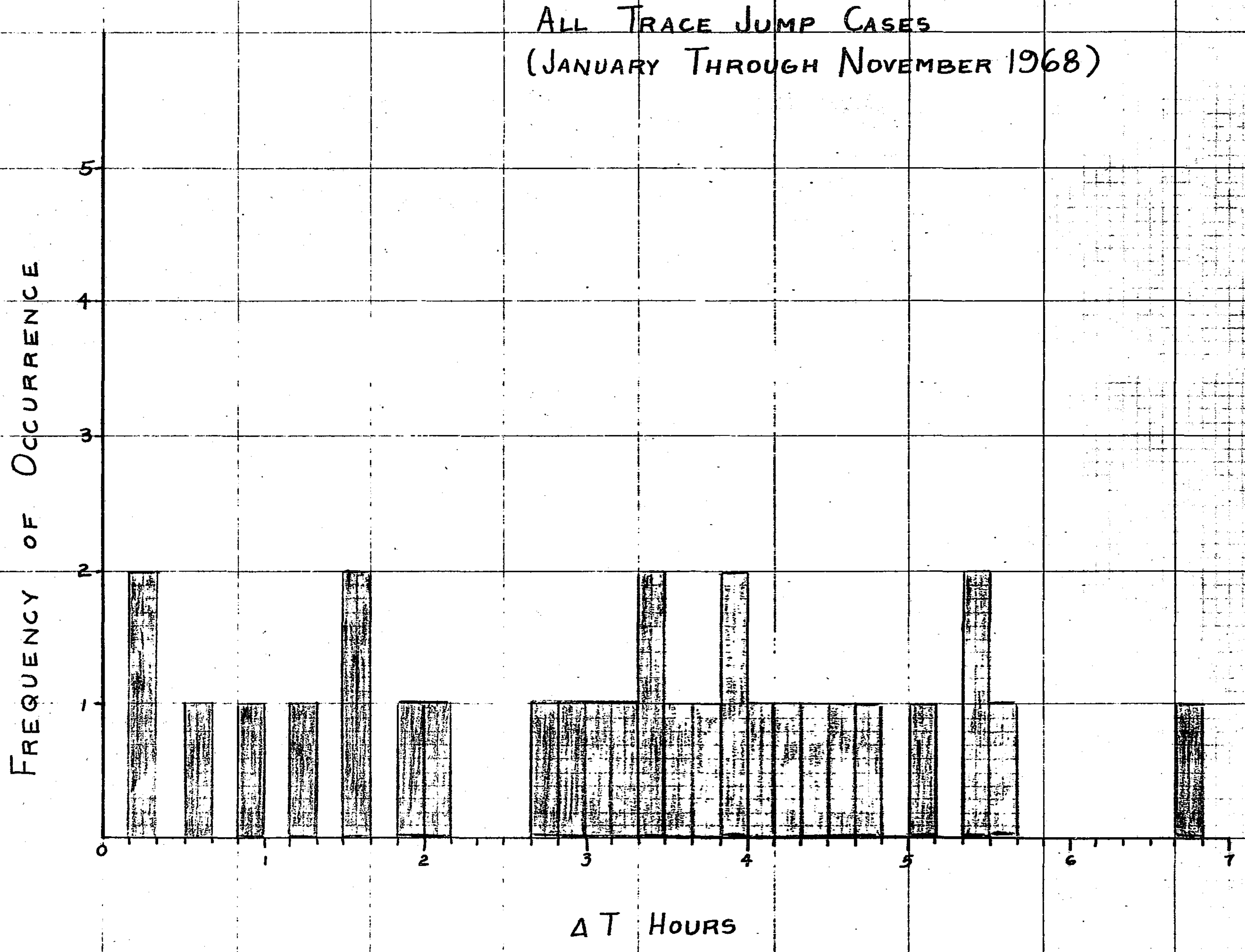


FIGURE 6 - NET RADIOMETER TRACE FOR EUGENE, OREGON, JUNE 4, 1968

FIGURE 7 - HISTOGRAM OF ΔT FOR ALL TRACE JUMP CASES (JANUARY THROUGH NOVEMBER 1968)



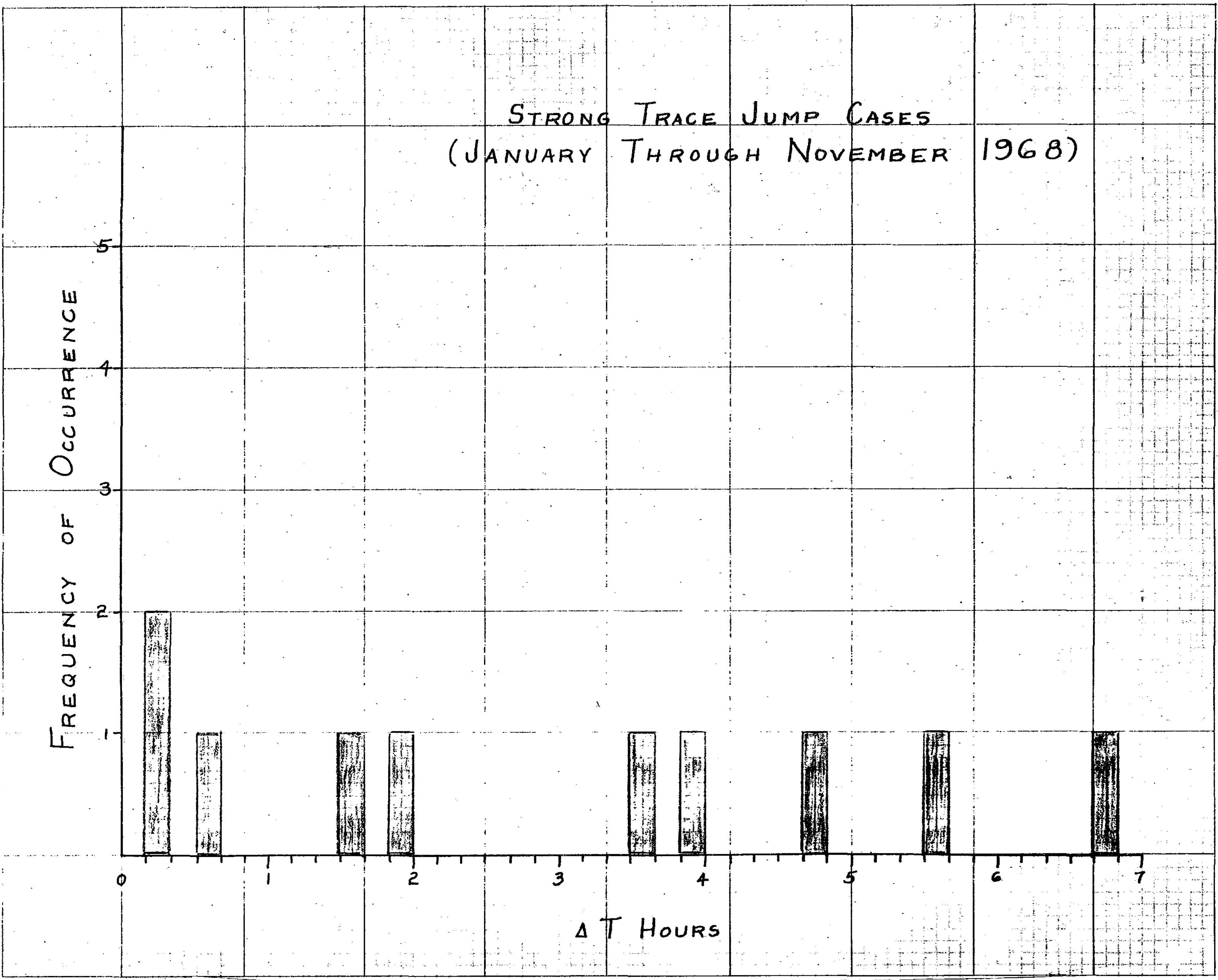
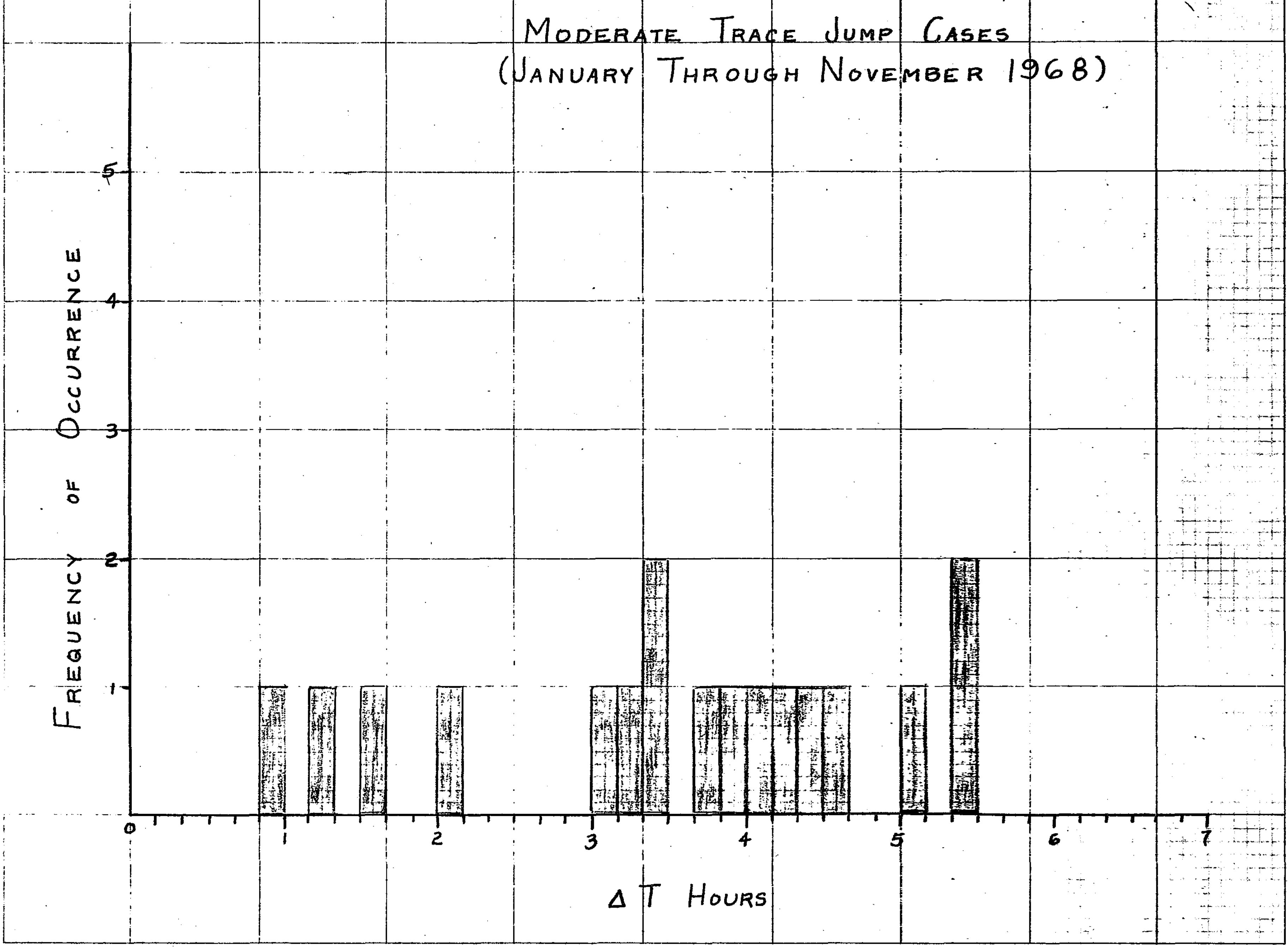


FIGURE 8 - HISTOGRAM OF ΔT FOR STRONG TRACE JUMP CASES (JANUARY THROUGH NOVEMBER 1968)

FIGURE 9 - HISTOGRAM OF ΔT FOR MODERATE TRACE JUMP CASES (JANUARY THROUGH NOVEMBER 1968)



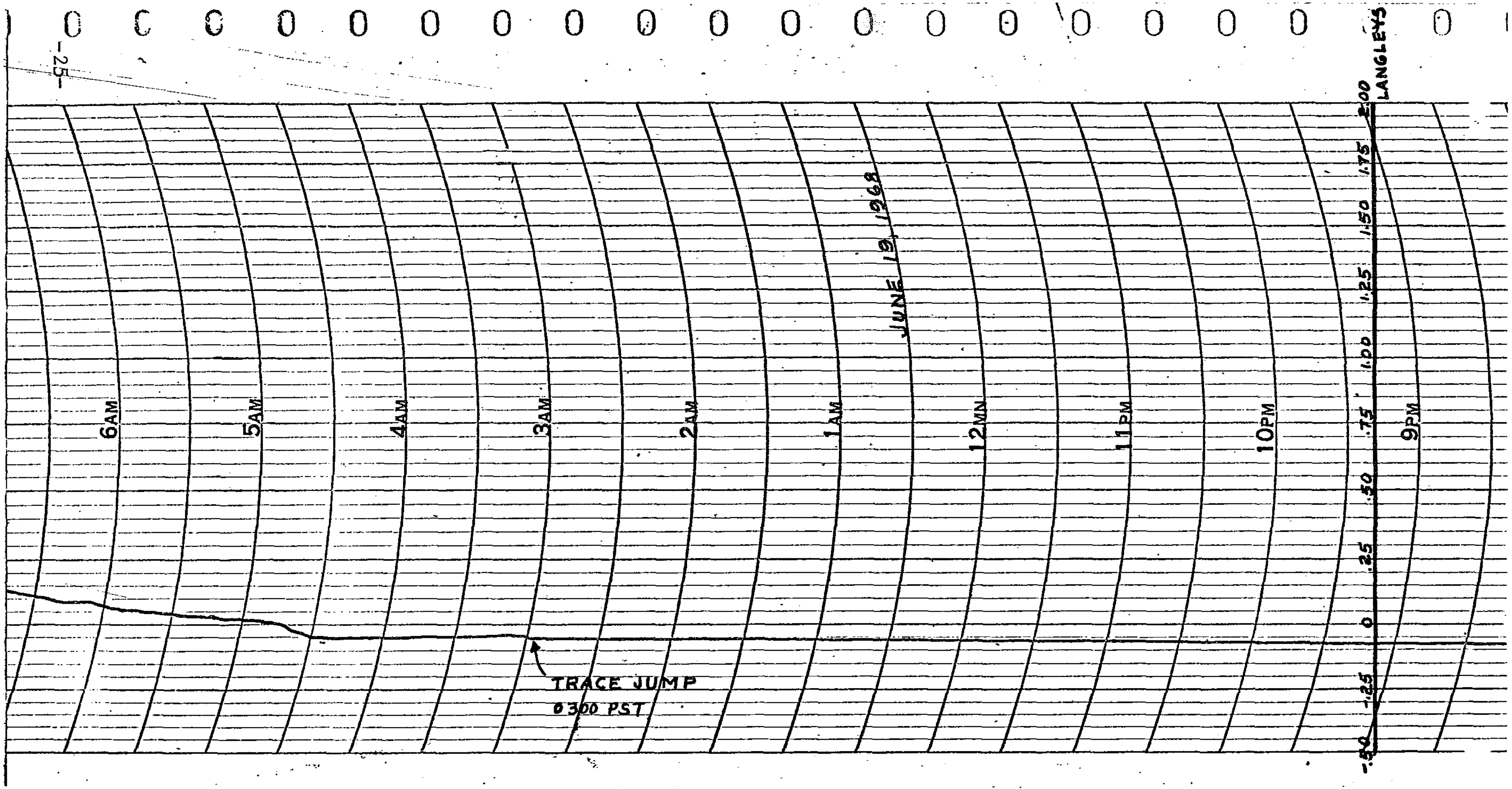
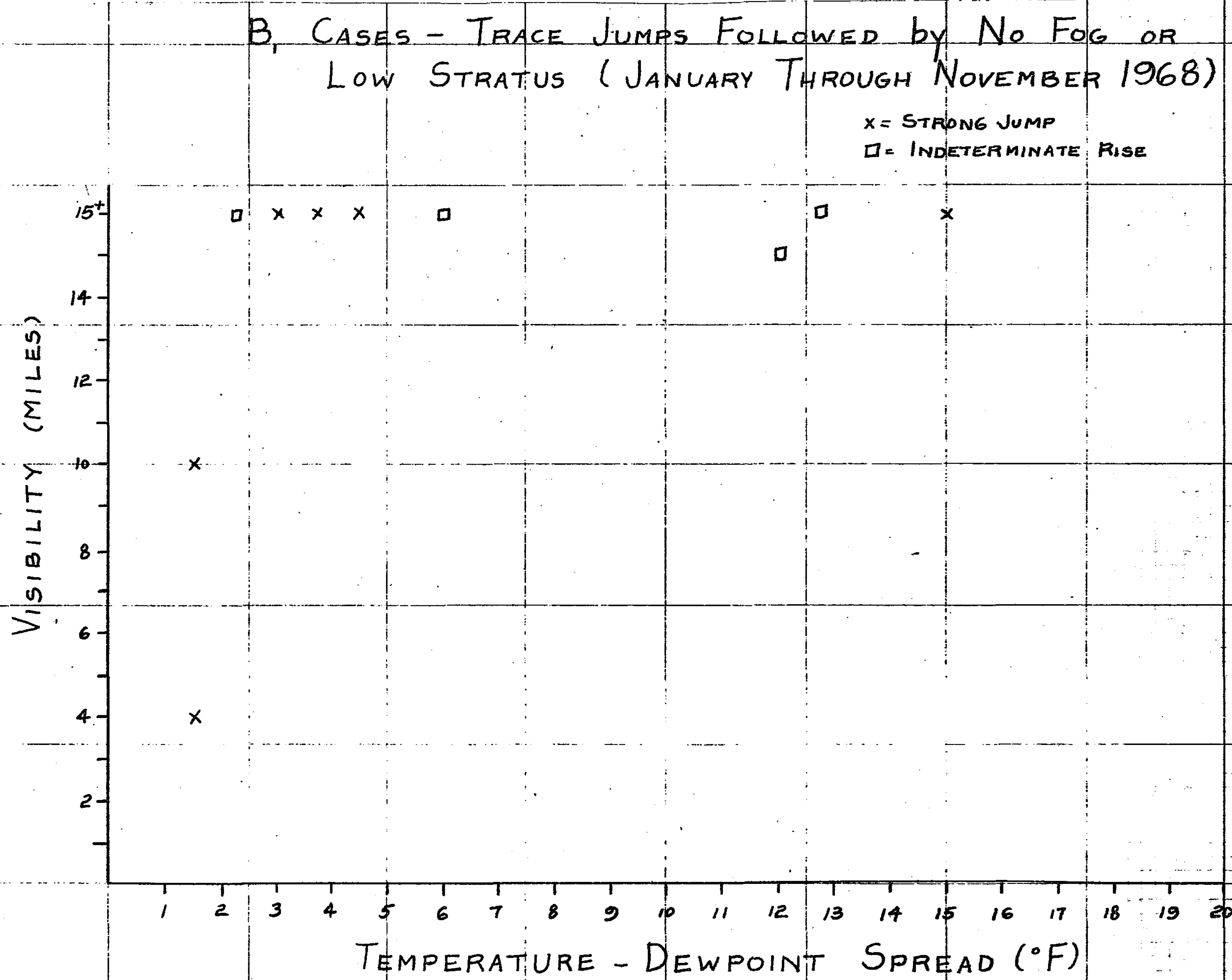


FIGURE 10 - NET RADIOMETER TRACE FOR EUGENE, OREGON, JUNE 19, 1968

FIGURE 11 - SCATTER DIAGRAM OF B_1 CASES SHOWING RELATIONSHIP OF VISIBILITY TO TEMPERATURE-DEWPOINT SPREAD FROM LAST OBSERVATIONS TAKEN PRIOR TO TRACE JUMP.



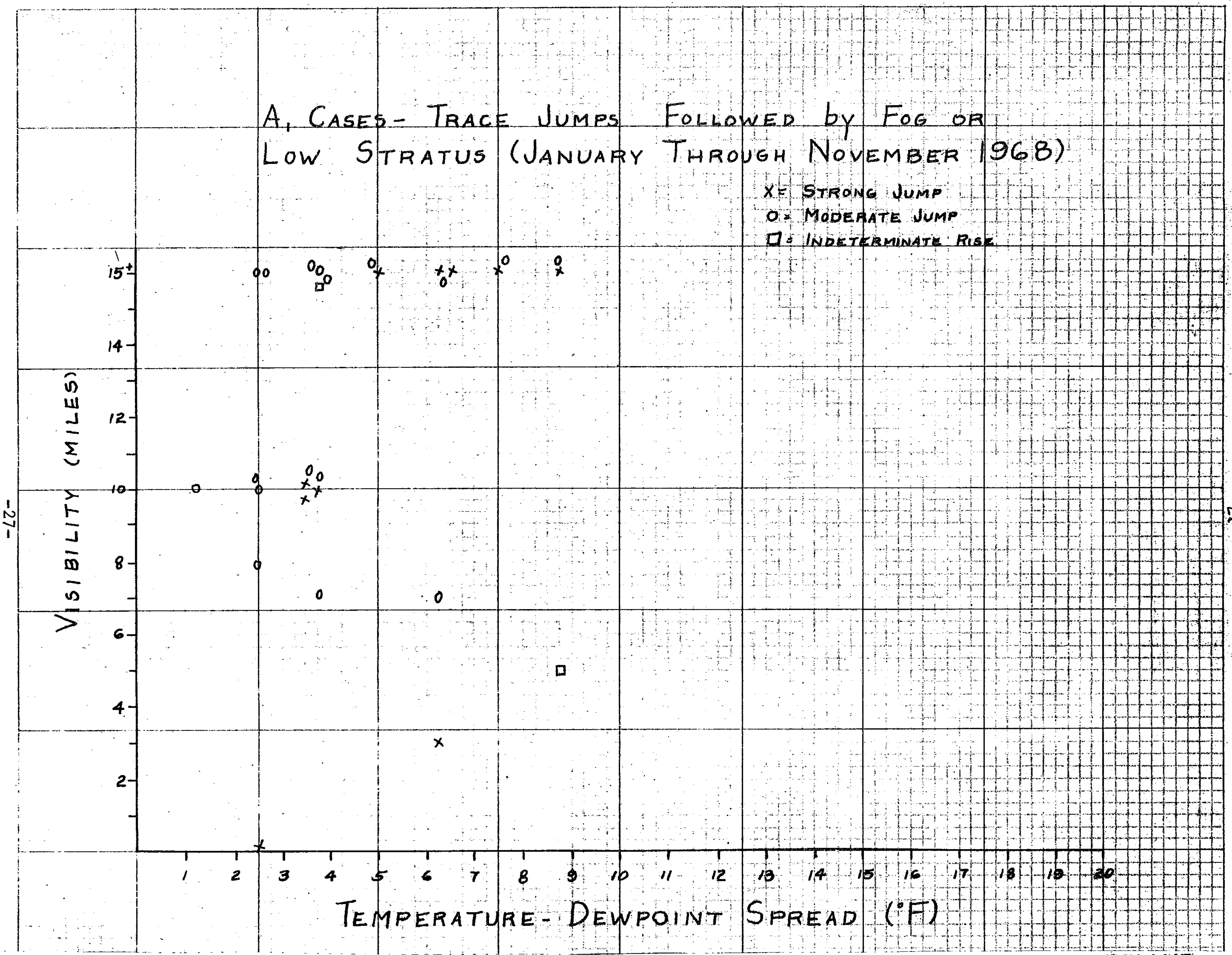


FIGURE 12 - SCATTER DIAGRAM OF A1 CASES SHOWING RELATIONSHIP OF VISIBILITY TO TEMPERATURE-DEWPOINT SPREAD FROM LAST OBSERVATIONS TAKEN PRIOR TO TRACE JUMP.

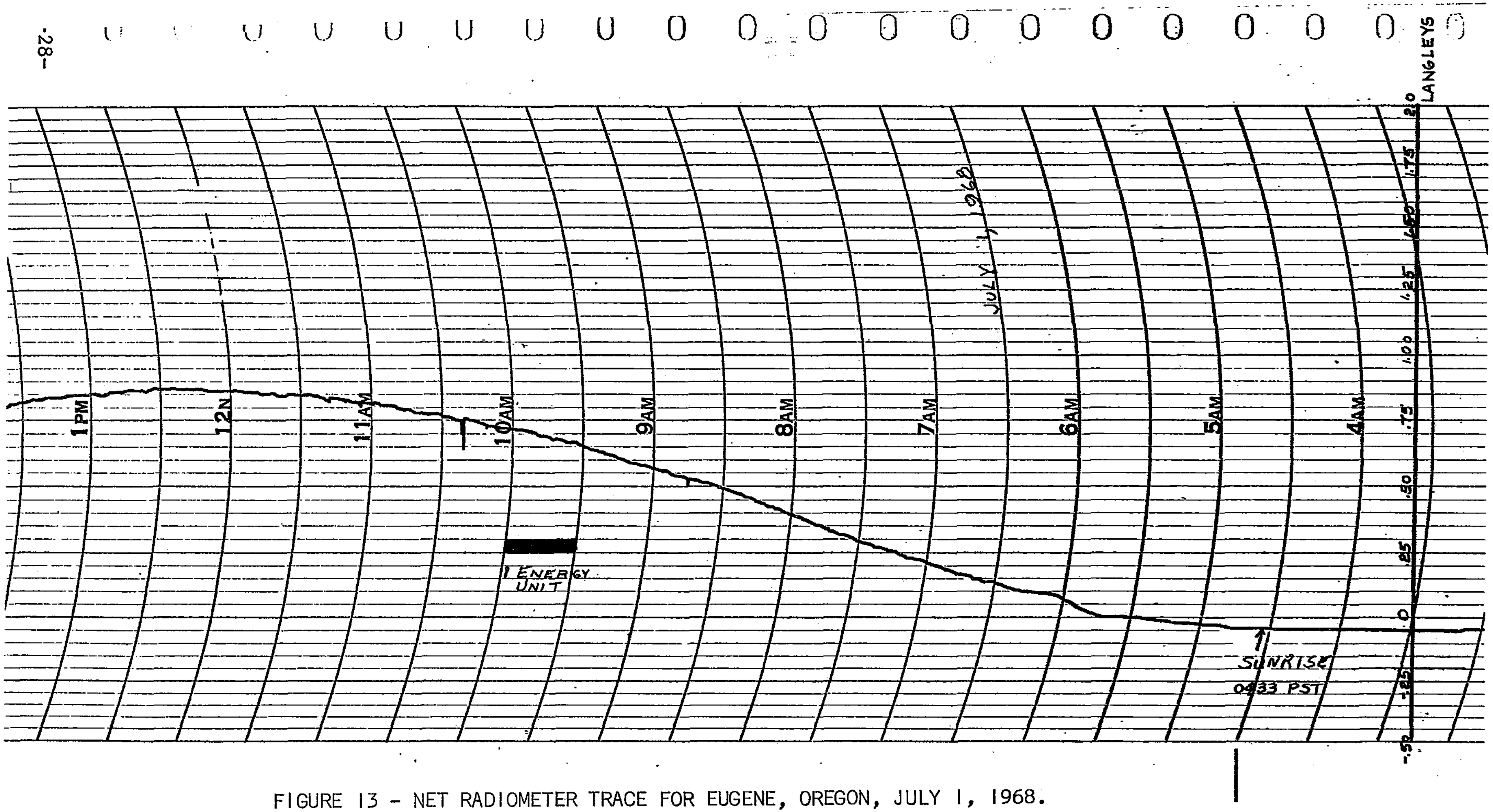


FIGURE 13 - NET RADIOMETER TRACE FOR EUGENE, OREGON, JULY 1, 1968.

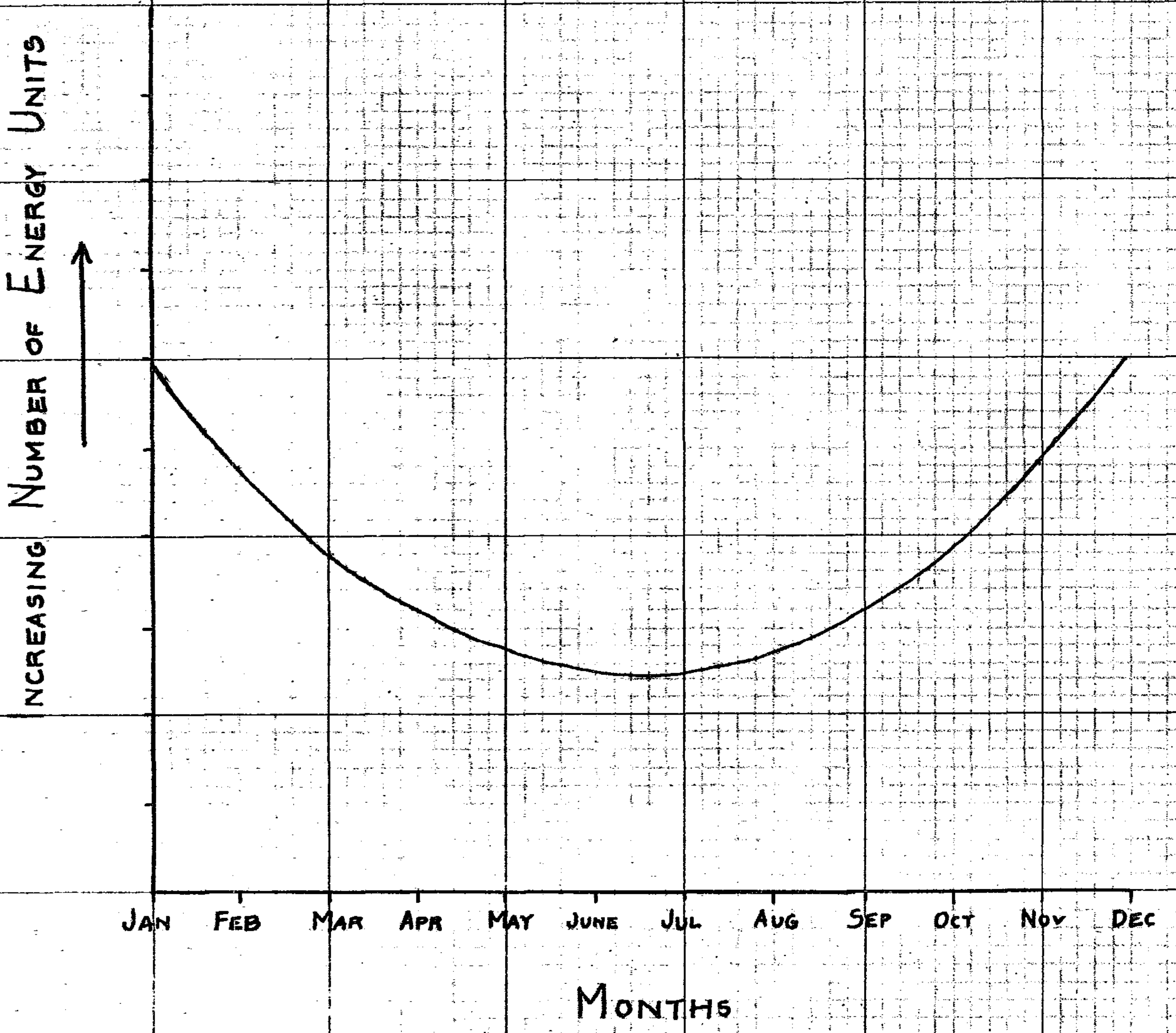


FIGURE 14 - SCHEMATIC RELATIONSHIP OF ENERGY UNITS NEEDED FOR DISSIPATION TO MONTHS OF THE YEAR.

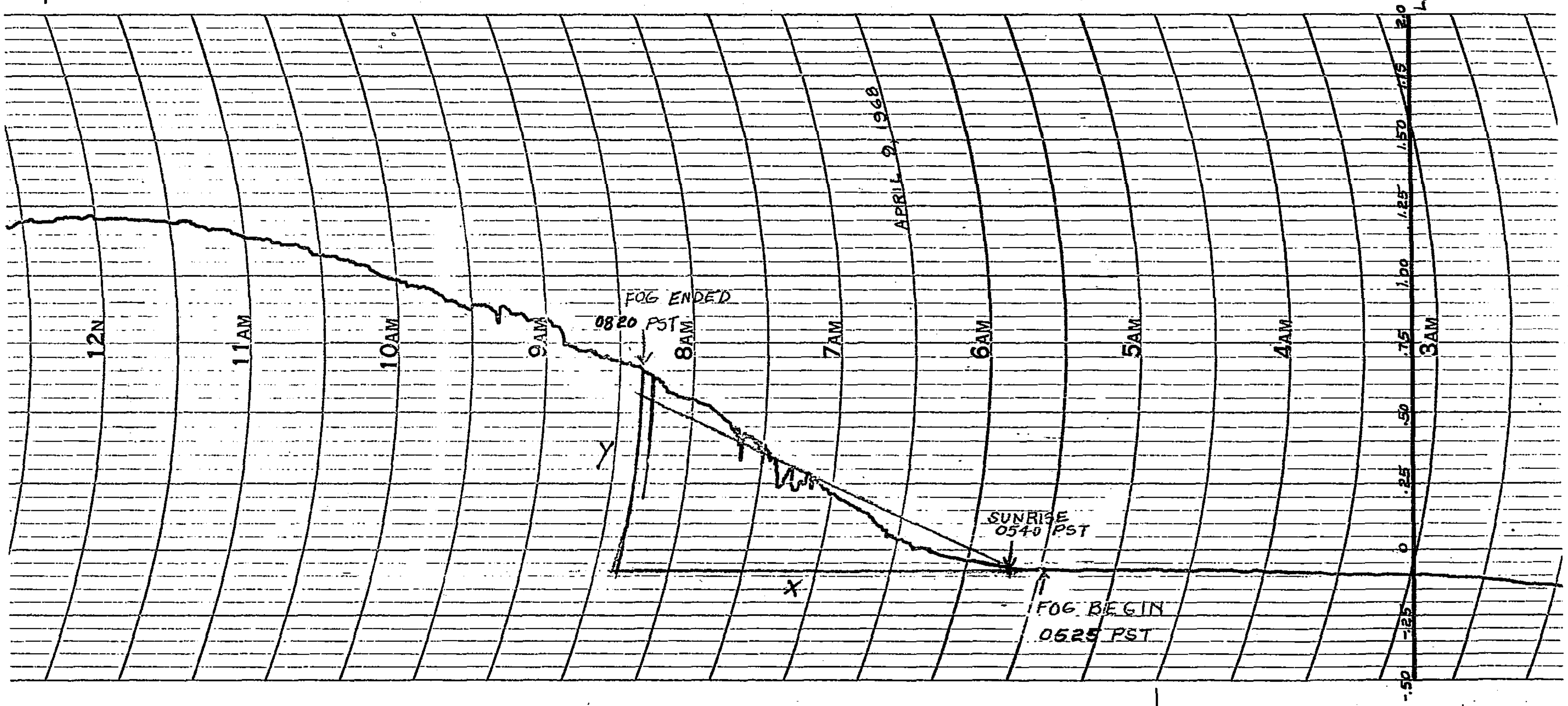


FIGURE 15 - NET RADIOMETER TRACE FOR EUGENE, OREGON, APRIL 9, 1968.

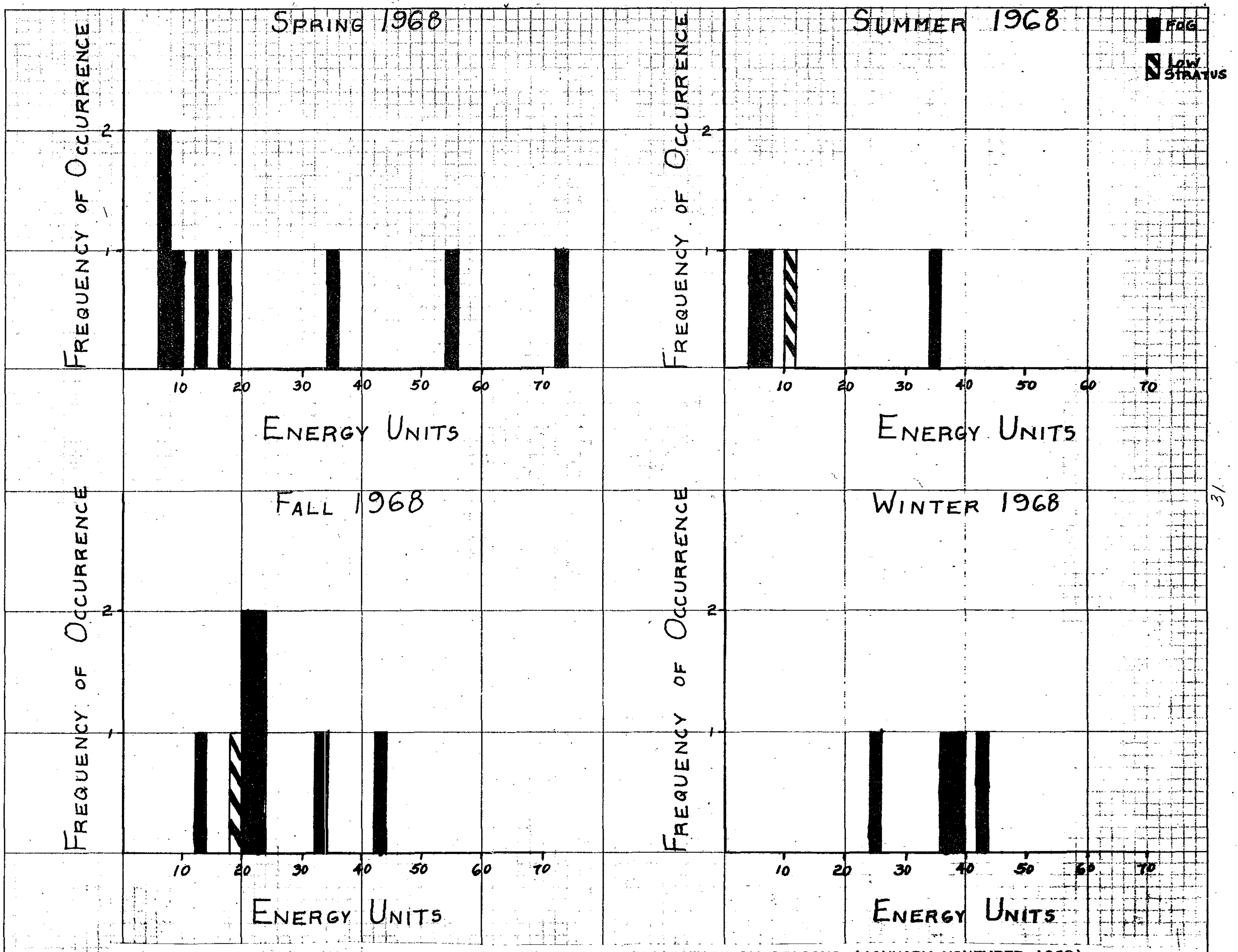


FIGURE 16 - HISTOGRAM OF ENERGY UNITS NEEDED FOR DISSIPATION BY SEASONS ~~(JANUARY-NOVEMBER 1968)~~.

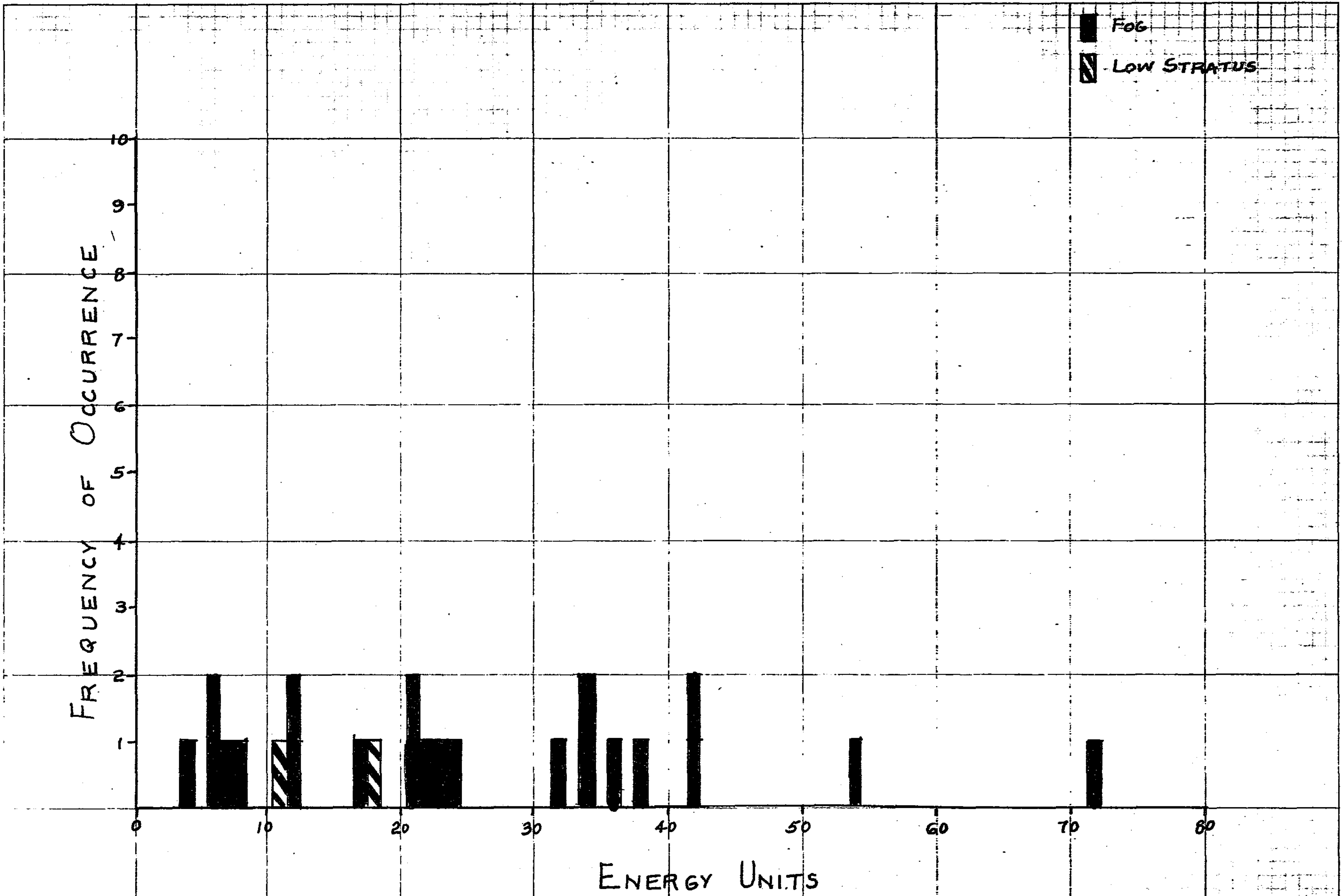


FIGURE 17 - HISTOGRAM OF ENERGY UNITS NEEDED FOR DISSIPATION FOR ALL CASES (JANUARY-NOVEMBER 1968).

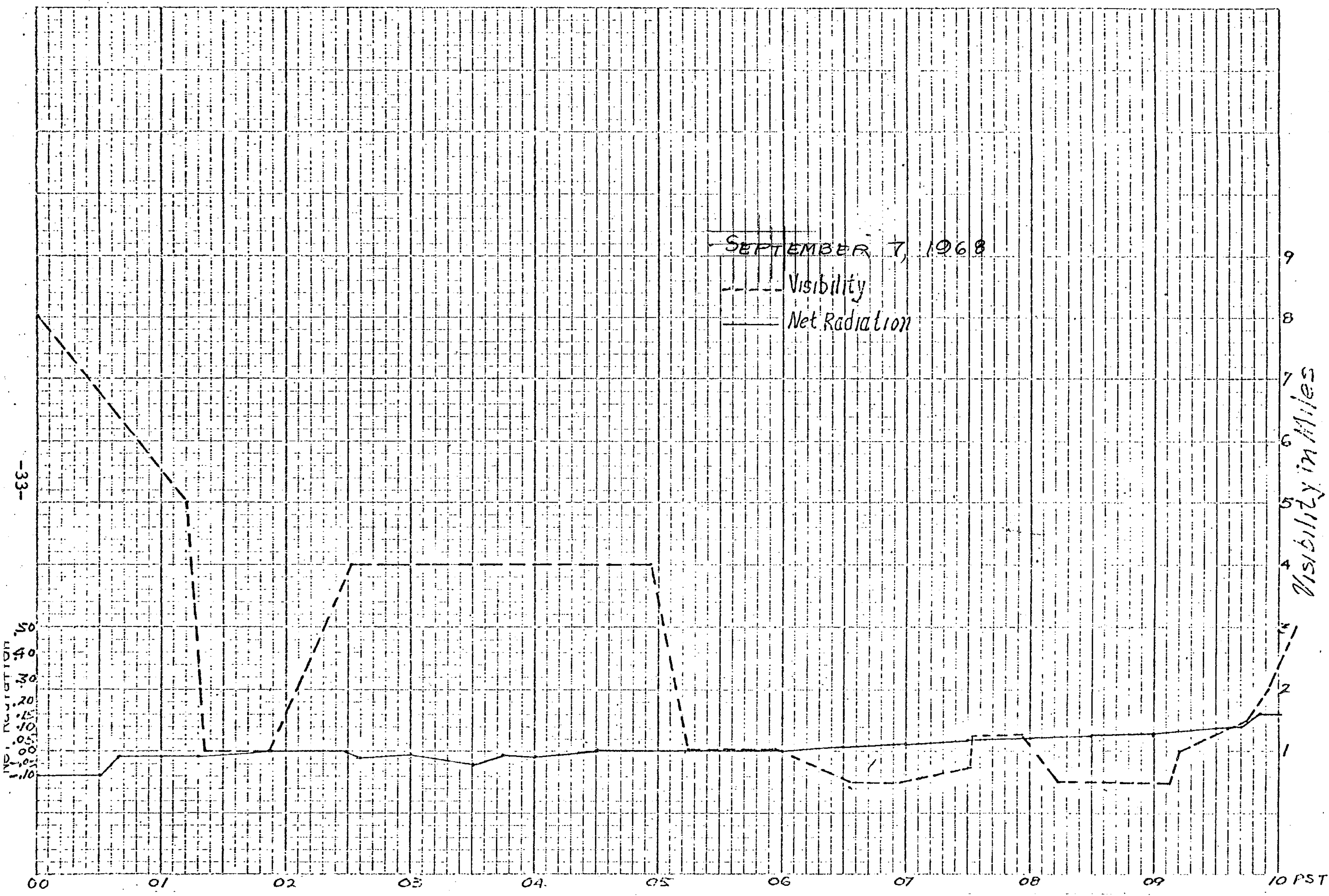


FIGURE 18 - RELATIONSHIP OF NET RADIATION AND VISIBILITY FOR EUGENE, OREGON, SEPTEMBER 7, 1968.

TABLE I

GROUPING OF RADIOMETER TRACE JUMPS
(JANUARY THROUGH NOVEMBER 1968)

"Positive" Cases: Fog or Low Stratus

Trace Jump		No Trace Jump	
(1) Strong Jump	13	(1) No Jumps	3
(2) Moderate Jump	29		
(3) Rise	8		
Total	50	Total	3

"Negative" Cases: No Fog or Low Stratus

Trace Jump		No Trace Jump	
(1) Strong Jump	5	(1) No Jumps	32
(2) Moderate Jump	1		
(3) Rise	17		
Total	23	Total	32

TABLE 2A

RESULTS OF SALT LAKE CITY REEVALUATION

FORECASTS OF FOG OR LOW STRATUS MADE ON BASIS OF ALL TYPES OF RADIOMETER TRACE JUMPS (JANUARY THROUGH NOVEMBER 1968)

		Forecast		
		Fog	No Fog	Total
Observed	Fog	50	3	53
	No Fog	23	32	55
	Total	73	35	108

Prefigurance - $\frac{50}{53}$ = .94

Post Agreement - $\frac{50}{73}$ = .68

Threat Score - $\frac{50}{76}$ = .66

Percent Correct - $\frac{82}{108}$ = .76

TABLE 2B

RESULTS OF SALT LAKE CITY REEVALUATION

FORECASTS OF FOG OR LOW STRATUS MADE ON BASIS OF STRONG OR MODERATE RADIOMETER TRACE JUMPS (JANUARY THROUGH NOVEMBER 1968)

		Forecast		
		Fog	No Fog	Total
Observed	Fog	42	11	53
	No Fog	6	49	55
	Total	48	60	108

Prefigurance - $\frac{42}{53}$ = .79

Post Agreement - $\frac{42}{48}$ = .88

Threat Score - $\frac{42}{59}$ = .71

Percent Correct - $\frac{91}{108}$ = .84

TABLE 3

GROUPING OF RADIOMETER TRACE JUMPS FROM FURTHER INVESTIGATION (JANUARY THROUGH NOVEMBER 1968)

GROUP A: Fog or Low Stratus Cases

A_1 - TRACE JUMP		A_2 - NO TRACE JUMP	
(1) Strong Jump	10	(1) No Jump	14
(2) Moderate Jump	17		
(3) Indeterminate Rise	12		
Total	39	Total	14

GROUP B: No Fog or Low Stratus Cases

B_1 - TRACE JUMP		B_2 - NO TRACE JUMP	
(1) Strong Jump	6	(1) No Jump	30
(2) Moderate Jump	0		
(3) Indeterminate Rise	9		
Total	15	Total	30

TABLE 4A

RESULTS OF FURTHER INVESTIGATION
FORECASTS OF FOG OR LOW STRATUS MADE ON BASIS OF ALL TYPES OF RADIOMETER TRACE JUMPS (JANUARY THROUGH NOVEMBER 1968)

Forecast

Observed

	Fog	No Fog	Total
Fog	39	14	53
No Fog	15	30	45
Total	54	44	98

Prefigurance - $\frac{39}{53} = .74$

Post Agreement - $\frac{39}{54} = .72$

Threat Score - $\frac{39}{68} = .57$

Percent Correct - $\frac{69}{98} = .70$

TABLE 4B

RESULTS OF FURTHER INVESTIGATION

FORECASTS OF FOG OR LOW STRATUS ON BASIS OF STRONG OR MODERATE RADIOMETER TRACE JUMPS (JANUARY THROUGH NOVEMBER 1968)

Forecast

Observed

	Fog	No Fog	Total
Fog	27	26	53
No Fog	6	39	45
Total	33	65	98

Prefigurance - $\frac{27}{53} = .51$

Post Agreement - $\frac{27}{33} = .82$

Threat Score - $\frac{27}{59} = .46$

Percent Correct - $\frac{66}{98} = .67$

TABLE 5

CONTINGENCY TABLE OF TEST DATA RESULTS (JANUARY THROUGH MAY 1969)

		Forecast		
		Fog	No Fog	Total
Observed	Fog	21	16	37
	No Fog	5	27	32
	Total	26	43	69

Prefigurance - $\frac{21}{37}$ .57

Post Agreement - $\frac{21}{26}$ .81

Threat Score - $\frac{21}{42} = .50$

Percent Correct - $\frac{48}{69} = .70$

TABLE 6A

TEST DATA RESULTS - FORECASTS OF FOG OR LOW STRATUS MADE ON BASIS OF ALL TYPES OF RADIOMETER TRACE JUMPS (JANUARY THROUGH MAY 1969)

		Forecast
		Fog
Observed	Fog	38
	no Fog	27
	Total	65

Post agreement = $\frac{38}{65}$ = .58

TABLE 6B

TEST DATA RESULTS - FORECASTS OF FOG OR LOW STRATUS MADE ON BASIS OF STRONG OR MODERATE RADIOMETER TRACE JUMPS (JANUARY THROUGH MAY 1969)

		Forecast
		Fog
Observed	Fog	24
	no fog	19
	Total	43

Post agreement = $\frac{24}{43}$ = .56

TABLE 7

ENERGY UNITS NEEDED FOR DISSIPATION OF FOG AND LOW STRATUS (JANUARY THROUGH NOVEMBER 1968)

Cases	$\overline{E}$ (Energy Units)	Range	Number of Cases
Fog (All Types)	25.8	4.5 to 72	22
Clear Above	16.2	4.5 to 35.8	8
Stratus Type	31.2	6.5 to 72	14
Low Stratus	14.6	10.8 to 18.4	2
Fog and Low Stratus Combined	24.8	4.5 to 72	24

Fog Starting After Sunrise	31.0	11.8 to 72	5
Clear Above	12.2		1
Stratus Type	35.8	11.8 to 72	4
Low Stratus Starting After Sunrise	18.4		1
Fog and Low Stratus Combined	28.9	11.8 to 72	6

TABLE 8

STRATIFICATION OF ENERGY UNITS NEEDED FOR DISSIPATION BY SEASONS (JANUARY -NOVEMBER 1968)

Month	All Fog			Clear Above			With Stratus			Low Stratus			Fog and Low Stratus Combined		
	No.	$\overline{E}$	Range	No.	$\overline{E}$	Range	No.	$\overline{E}$	Range	No.	$\overline{E}$	Range	No.	$\overline{E}$	Range
January	0									0			0		
February	4	35.1	24 to 42.5	1	35.8		3	34.8	24 to 42.5	0			4	35.1	24 to 42.5
Winter	4	35.1	24 to 42.5	1	35.8		3	34.8	24 to 42.5	0			4	35.1	24 to 42.5
March	4	27.0	6.9 to 72	2	9.6	6.9 to 12.2	2	44.4	16.7 to 72	0			4	27.0	6.9 to 72
April	3	32	7.5 to 54.4	2	20.8	7.5 to 34	1	54.4		0			3	32	7.5 to 54.4
May	1	6.4		1	6.4					0			1	6.4	
Spring	8	26.3	6.4 to 72	5	13.4	6.4 to 34	3	47.7	16.7 72	0			8	26.3	6.4 to 72
June	2	19.2	4.5 to 33.8	1	4.5		1	33.8		0			2	19.2	4.5 to 33.8
July	0									1	10.8		1	10.8	
August	1	6.5					1	6.5		0			1	6.5	
Summer	3	15.0	4.5 to 33.8	1	4.5		2	20.2	6.5 to 33.8	1	10.8		4	14.0	4.5 to 33.8
September	5	28.2	21 to 42.5	1	23.0		4	29.5	21.0 42.5	1	18.4		6	26.6	18.4 to 42.5
October	2	16.2	11.8 to 20.5				2	16.2	11.8 to 20.5	0			2	16.2	11.8 to 20.5
November	0									0			0		
Fall	7	24.8	11.8 to 42.5	1	23.0		6	25.1	11.8 to 42.5	1	18.4		8	24.0	11.8 to 42.5

TABLE 9 - RESULTS OF TEST DATA USING AVERAGED ENERGY UNITS OF ALL FOG CASES (JANUARY THROUGH MAY 1969)

Cases	T_E Expected Time of Dissipation PST	T_D Actual Time of Dissipation PST	Time Lapse $T_E - T_D$ (Minutes)	**Time Lapse (Minutes) with 41 Minutes Correction**
March 4	1020	0930	+50	**+9**
March 8	1025	1045	-20	**-61**
March 27	1005	0720	+165	**+124**
May 4	0900	0746	+74	**+33**
May 10	0950	1035	-45	**-86**
May 21	0820	0750	+30	**-11**
		Average Error	64	**54**
		Bias	+42	**-1**

TABLE 10

RESULTS OF TEST DATA USING AVERAGED STRATIFIED ENERGY UNITS FOR CASES (JANUARY THROUGH MAY 1969)

Cases	T_E Expected Time of Dissipation	T_D Actual Time of Dissipation	Time Lapse $T_E - T_D$ (Minutes)	Time Lapse (Minutes) With 41 Minutes Correction
March 4 (cirrus above)	0940	0930	+10	-31
March 8 (stratus deck)	1040	1045	-5	-46
March 27 (cirrus above)	0915	0720	+115	+74
May 4 (clear above)	0805	0746	+19	-22
May 10 (stratus deck)	1045	1035	+10	-31
May 21 (stratus deck)	0930	0750	+100	+59
		Average Error	43	4
		Bias	+42	0

Western Region Technical Memoranda: (Continued)

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