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FINAL REPORT

REMOTE SENSING OF ATMOSPHERIC INVERSIONS
PROJECT No. 3-164-2 CONTRACT No. 022

Submitted To The California Air Resources Board

By

SIDNEY R. FRANK

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FINAL REPORT

REMOTE SENSING OF ATMOSPHERIC INVERSIONS
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ABSTRACT

The program was conducted in two parts: 1. The calibration of the atmospheric ducting of television signals over the ocean in terms of temperature inversion base heights and, 2. The calibration of anomalous propagation as exhibited by radar surface return over land during periods of temperature inversion base heights. The former, 1, was conducted measuring the signal strength of San Diego television station, Channel 10, at a receiver at the Sidney R. Frank...Group office at the Santa Barbara Airport, and the latter, 2, was conducted by analyzing 3.5 years of almost continuous time-lapse filming of the radarscope of the National Weather Service's WSR/57 weather radar at Sacramento. Both phases of the program were successful in that highly useful atmospheric information for air pollution control was obtained by means other than the "normal" meteorological sensors. In addition, under almost all circumstances, the data were more valuable and more economically derived than those obtained by the standard methods used today. The conclusion was that these remote sensing techniques be expanded to other Basins in California and, ultimately, throughout the nation.

1.0 Review

As this Final Report includes a Fourth Quarter Progress Report (an extension of time without additional funds), more data were acquired and analyzed than originally anticipated. Hence, while not all scheduled areas were examined for television signal ducting as originally planned, the use and results from the unplanned (unscheduled) radar data, and the additional Southern California ducting data provided further documentation of the applicability of atmospheric ducting. As will be seen, the conclusions reached open an entirely new means of providing the Air Pollution Control Officer with real time atmospheric data without adding significantly to his operational budget.

1.1 Phase One - Atmospheric ducting of television signals over Southern California Bay between San Diego and Santa Barbara.

The initial investigation of the program was designed to re-examine and quantify the relationship between the strength of the 193.25 MH signal from Channel 10, television station in San Diego, as received at the Santa Barbara Airport, Goleta, and the measured inversion base heights as determined by radiosonde stations located along coastal Southern California.

To accomplish this task, the SIGNAL STRENGTH values at radiosonde times were extracted from the continuous monitoring system installed at the offices of the Sidney R. Frank...Group.

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The system consists of a 20 DB gain antenna specifically designed for the Channel 10 frequency band, a television receiver, and a matched Leeds & Northrup Speedomax H. analog recorder. Calibrations were made periodically with a Sencore FS 134 Field Strength Meter. The desirability of having a continuous monitoring system instead of spot samples at specific times was further substantiated when it became necessary to synchronize the "irregular" timing of the LAX (Los Angeles International Airport), NTD (Pt. Mugu), and NSI (San Nicholas Island) radiosondes for measured INVERSION BASE HEIGHTS with SIGNAL STRENGTH data. It can be seen from the radiosonde location map, Figure 1, that the two stations closest to the beam path are NTD and LAX with LAX being the closest to midpoint between SBA (Santa Barbara Airport, Goleta) and the Channel 10 transmitter. Hence the first testing of the technique was scheduled to involve correlations of signal strength with the LAX inversion base height. Actual correlation calculations were deferred until an adequate sample size was obtained. By the end of 1971, it was evident that highly useful data had been obtained during the period of August 25, through November 30, 1971. Consequently, Progress Report #2 and the subsequent reports documented the results obtained throughout 1972, in a manner similar to that of the original period's analysis. These will be presented in Section 2.0, as the "Fourth Quarterly Progress Report".

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1.2 Phase Two - Atmospheric ducting of radar signals emanating from the NWS WSR/57 radar located at Sacramento, California.

To determine the optimum period for testing the Remote Sensing Technique in the Sacramento Valley, a study was initiated of film made of the Sacramento NWS WSR/57 radar scope during the period July 1964 to May 1968. The reason for using this particular period was that the film consisted of a continuous series of individual frames exposed at a rate of nominally one every 15 minutes. The hypothesis leading to the study was that Anomalous Propagation (AP), recognizable on the scope as an anomalous ground return area, would occur under atmospheric conditions identical to those causing ducting and, hence, would involve the same parameters as those defining inversions.

The results of the study from June 1966 to May 1968 exceeded expectations in that not only did a distinct "climatology" by months emerge but a diurnal "climatology" as well. The correspondence of the monthly AP "climatology" to the ducting at Oakland (as defined by the difference in refractive index between the surface and 1 Km above the surface, Figure 2) was particularly striking since it implied similarity of air masses encompassing the Bay Region and Sacramento. Another parameter, the magnitude of the reflected signal measured off Sutter Buttes, Pr, was tested to see if it exhibited any monthly or seasonal variation. A similar pattern to that of the AP frequency was found and, by making the distinction between Pr values at times of AP and those times without evidence of AP,

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the curves assume an identical phase relationship. Considering that only one measurement per day was made (between 0000 and 0300), it provided additional qualitative support to the basic hypothesis.

A frame by frame examination of the radar scope film for evidence of Anomalous Propagation using a counting procedure of calling any portion of an hour with AP an "AP hour" produced a finite seasonal and diurnal variation. A reduction to a percentage of total hours in each month and plotted on axes, 24 hour by serial month (from June 1965 through May 1968), produced the patterns as shown on Figures 3 and 4. Of note are the late summer high percentage values and the consistent few (or no) early afternoon occurrences of AP. The relatively high values of April 1968 is in direct contrast with that of April 1967 emphasizing the fact that the AP, being a function of the ducting characteristics of the atmosphere, is subject to the natural variability of those characteristics.

A composite was made of the analyzed 3.5 years, January 1965 through May 1968. Figure 5 shows this composite by months and hours. As expected, the August maximum remained as the dominant feature and the Summer-Fall pattern extended to the AM hours reflecting the April 1968 high values.

Referring back to Figure 2(a), the composite by months shows three curves: the average percentage hours/month of AP, the OAK 6 year average of refractive index gradient between surface

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signal strength data and additional correlations of inversion base heights with signal strength. That made possible analyses of a complete year's data plus an additional 3 month data comprising the Fall Quarter of 1972.

A review of the total Sacramento AP data coupled with air quality in terms of monthly oxidant values produced an in-phase annual trend. Those values, plus a special test in cooperation with the Sacramento weather radar team, will be expanded upon in Section 2.2.

2.1 Phase One - Atmospheric ducting of television signals SAN to SBA.

The main thrust in acquiring additional signal strength data was to complete a full year's test of the basic hypothesis. The Supplement to Progress Report #2 completed the seasonal analysis of the diurnal variation of signal strength $\geq$ 300 uV through May 1972, as can be seen in Figures 6, 7, 8 and 9. The number, 300 microvolts, was chosen as a limiting factor in the correlation calculations since any higher value of signal strength indicated an average inversion base of less than 1000 feet (see correlation chart, Figure 10).

The additional data was used to produce Figure 11, the Summer of 1972 which, again, showed the highest frequency of low inversions at midday - although the high frequency began earlier in the day than during other seasons. The 3 months rolling mean of the yearly composite, Figure 12, covering the period

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25 August 1971 to 31 August 1972 differs from the three season composite, Figure 9, by the increased frequency of low inversions earlier in the day as would be expected by the Summer, 1972 addition.

Time permitted calculations of the Fall, 1972 diurnal frequency, as shown in Figure 13. The major difference between that and the Fall, 1971 distribution was the high frequency of low inversions in the evening. Here, again, we see evidence of the variability from year to year of a meteorological parameter basic to ambient air pollution concentrations calculations. Another means of showing the yearly and monthly variability of meteorological parameters is by plotting correlation coefficients of signal strength vs inversion base heights. It was shown in earlier reports that the correlations were highest during summer and early fall. With the subsidence inversion extending over the entire Southern California Bay, the fairly uniform distribution of the ducting parameters along the beam path during that period would account for the higher correlation coefficients while the discontinuities of these parameters along the beam paths during winter and early spring would be ample cause for lower correlation coefficients. Accordingly, the monthly values were plotted with the correlation coefficients derived in terms of the log signal strength vs log inversion base heights for LAX, Figure 14; Pt. Mugu, NTD, Figure 15; for the average of the two (when the RAOBs were

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taken simultaneously), Figure 16; and finally a comparative of the 3 month rolling mean, Figure 17.

Examining the four charts in order, we see that Figures 14, 15 and 16 show the monthly curves in phase (with the one exception that LAX has a June maximum instead of May) but differing in amplitude. On the other hand, the LAX calculations were made with a larger number of samples, N, thereby providing a somewhat higher confidence level. The relatively high values of correlation coefficient in January, 1972, for both LAX and NTD can be ascribed to the fact that no storms passed through the area during that month and hence the dominant meteorological situation was that of extended periods of high pressure cells and their corresponding subsidence inversions. The comparison of 3 month rolling means, Figure 17, is interesting in that the minimum indicated at LAX in November, 1971, is displaced to February, 1972, for the average $\overline{\text{LAX + NTD}}$, and to March, 1972, for NTD. Essentially, the displacement is due to the relatively small sample size and the fact that the RAOBs at both LAX and NTD represent <u>singular points in time and place</u> whereas the signal received at the Santa Barbara Airport represents a <u>mean of the entire beam path</u>. The fact that the highest correlations exist during the smog season actually provides a measure of confidence in the concept that RAOBs during the smog season can be considered representative of a greater area than the singular point in

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space (though not, of course, for a greater period than the singular point in time).

From Progress Report #2, a sample of the analog trace recorded on August 26, 1971, from 1400 - 1600 PDT, shows an irregular trace. The interpretation of that trace was that the inversion surface itself was irregular and that the undulations were reflected in the trace as the inversion surface moved across the beam path. Another possibility is that the inversion surface was stationary and the undulations were due to wave action along the surface. In either case, the high correlations that were obtained conceivably would have been even higher had it been possible to run continual measurements of the inversion surface at the half-way point.

2.1.1 Conclusions

It has been illustrated by measurements throughout a full year's period that the strength of a television signal measured at a trans-horizon point constitutes a relative measure of the height of the temperature inversion base. Although it is known that the ducting is a function of both temperature inversions and moisture discontinuities the fact that correlations exist with temperature inversions alone is probably due to the way in which the RAOBs are interpreted. In actual RAOB practice, the point at which the temperature inversion begins is normally considered by the technicians as the same point at which the moisture discontinuity is placed even

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though they are not measured simultaneously! Hence, our attempts at correlating signal strength and large changes in the vertical distribution of refractive index ($\triangle N \geq 4.5$) provided no better correlation coefficients than that with temperature inversions alone. It would be of great interest to test the signal strength versus the refractive index change (say, with instrumented aircraft) as it would have greater meaning in terms of mixing depth. Previous investigations (Edinger, et. al.) have shown the penetration of moisture through the temperature inversion and, hence, the possibility of penetration by pollutants by the same mechanism. However, since all mathematical models assume the mixing depth is equivalent to the height of the base of the temperature inversion alone, we suggest that, since the signal strength equivalent of mixing depth is probably more representative of <u>actual</u> mixing depth than that "measured" from the RAOBs, the signal strength equivalent be tested as the mixing depth in-put for concentration calculations.

2.2 Phase Two - Analysis of radarscope films from the NWS WSR/57 weather radar at Sacramento.

With the highly encouraging results of the analysis of 3.5 years of radar films, it was decided to test the results by operating the radar at the same specific times as the aircraft soundings (APOBs) currently being flown twice daily at Sacramento. Mr. Roger Pappas, chief weather radar operator, agreed

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to make the tests during June and August, 1972. The tests consisted of operating the radar at 0° elevation, filming the radarscope, and measuring the reflected power from Sutter Buttes and Mt. Tamalpais at 0400 and 1400, the APOB times.

Following the same analytical technique of the 3.5 year analysis, the percentage of the hours of the month that AP was noted for each specific hour was tabulated and the results plotted on Figure 19 (from Figure 2, Progress Report #3). It can be seen that the results of the test fall closely within the iso-percentage line "climatology" of AP as derived from the June, 1966 - May, 1968 radarscope films. The deviation of the 1972, 0400 point from the actual value of the August 3% line is due, of course, to the difference in meteorological conditions, but the fact that the values were remarkably close during the height of the smog season lends strong support to the use of this technique as a valuable tool for the Air Pollution Control Officer.

The attempt at quantification of inversion heights versus AP by timing the radar tests with the APOBs was unsuccessful due to crudeness of the APOB data. It was hoped that <u>actual</u> inversion base heights would be defined by the APOBs. Instead, as the APOBs read the outside air temperature at every 500 foot interval, it was impossible to know the height of the inversion base with any exactitude. What is really needed is a RAOB in association with the radar - even with the inherent

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errors of the RAOB, it would provide useable data for correlation calculations. If aircraft is to be used, it should be instrumented to provide continuous measurements of temperature and moisture and/or refractive index. As described in 2.1.1, the vertical distribution of refractive index would provide the optimum data for correlation with ducting effects on signal strength. Since AP is also a function of vertical distribution of refractive index, an interesting and valuable study could be made using aircraft so instrumented during periods of AP.

2.2.1 Conclusion

At the very least, the occurrence of AP on any radarscope is an indication of a low level inversion. This type of information provides the Air Pollution Control Officer continuous information as to the existence of inversion over hundreds of square miles surrounding his area of interest. Considering that most large cities have radars at their airports, it is feasible to consider incorporating AP information as an input to APCD offices. In that way, the existence of inversions would be instantly known to the Control Officer. Even in a qualitative sense, such information becomes a real time, economical, areal coverage, of one of the basic parameters in air pollution concentration calculations - the mixing depth. When made quantitative, the information would be invaluable.

3.0 Summary

Over the contract period it has been shown that the ducting

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of electromagnetic signals by large vertical changes in the refractive index ($\Delta N \geq 4.5$) can be used in the calculations of mixing depth. Using both active (radar) and passive (receiver only) electronic instrumentation, we have been able to establish statistical relationships between thickness of the surface based ducting layer and the mixing depth. In the passive case, the strength of a trans-horizon television signal, it was possible to obtain relatively high correlation values between the signal strength and height of the base of the temperature inversion. As explained above, the signal strength is probably a better indicator of true mixing depth than the base of the temperature inversion since it reflects sharp vertical changes of <u>both</u> temperature and moisture. Hence, the correlation coefficients would actually be higher if the refractive indices could be obtained along the beam path.

In the active case, radarscope indications of Anomalous Propagation, the same basic premise holds - namely, that sharp vertical changes in refractive index will be indicated by greater reflected signal from greater distances than at times of "normal" lapse rate of refractive index. While it was possible to qualitatively identify the smog season by the percentage of the months exhibiting AP, it was suggested that a program be initiated wherein quantitative evaluations could be made of true mixing depth and used as inputs in mathematical models of transport and diffusion.

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In our analyses of ducting throughout the year it was found that the strngest values occurred during the same periods that maximum oxidant values were found both in the South Coast Basin and Sacramento. As mixing depth is a prime parameter in all concentration calculations, this was no surprise, but it was interesting to see the extent to which a single meteorological parameter apparently influences the ambient air quality values. Figure 20 shows a plot of percent of total possible hours of AP versus monthly averages of daily maximum hours of oxidant at the 13th and J air quality station in Sacramento. The two curves are in phase giving a correlation coefficient of 0.79. It does seem that the quantification of mixing depth plus the transport and diffusion data would provide the Air Pollution Control Officer with practically all he would need for his atmospheric monitoring.

In a similar manner, except that we used the maximum hourly oxidant values from the entire South Coast Basin instead of a single station, a plot was made of the maximum signal strength versus the maximum oxidant value. Figure 21 shows the two curves generally in phase giving a slightly lower correlation coefficient of 0.70. Here again we note the importance of the single meteorological parameter in the total air quality concentration calculations. Since we had quantitative values of mixing depth from our signal strength calibrations we were able to run correlations between the signal strength and Basin oxidant maximum (as well as calculated afternoon maximum

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mixing depth from the 0600 RAOB) and noted the annual trend by plotting monthly values. Figure 22 shows the maximum correlation coefficients during the smog season with the signal strength values, as indicated, proving to be more highly correlated than the calculated maximum inversion base height. In conclusion, then, it has been shown that highly useful meteorological information can be derived from electromagnetic ducting effects of the atmosphere. The application of this information to air pollution control has been amply demonstrated throughout the contract period. It is, therefore, recommended, in fact, urged, that the techniques described undergo the refinements in calibration as suggested, but, pending that, that the basic techniques be implemented in other Basins in California.

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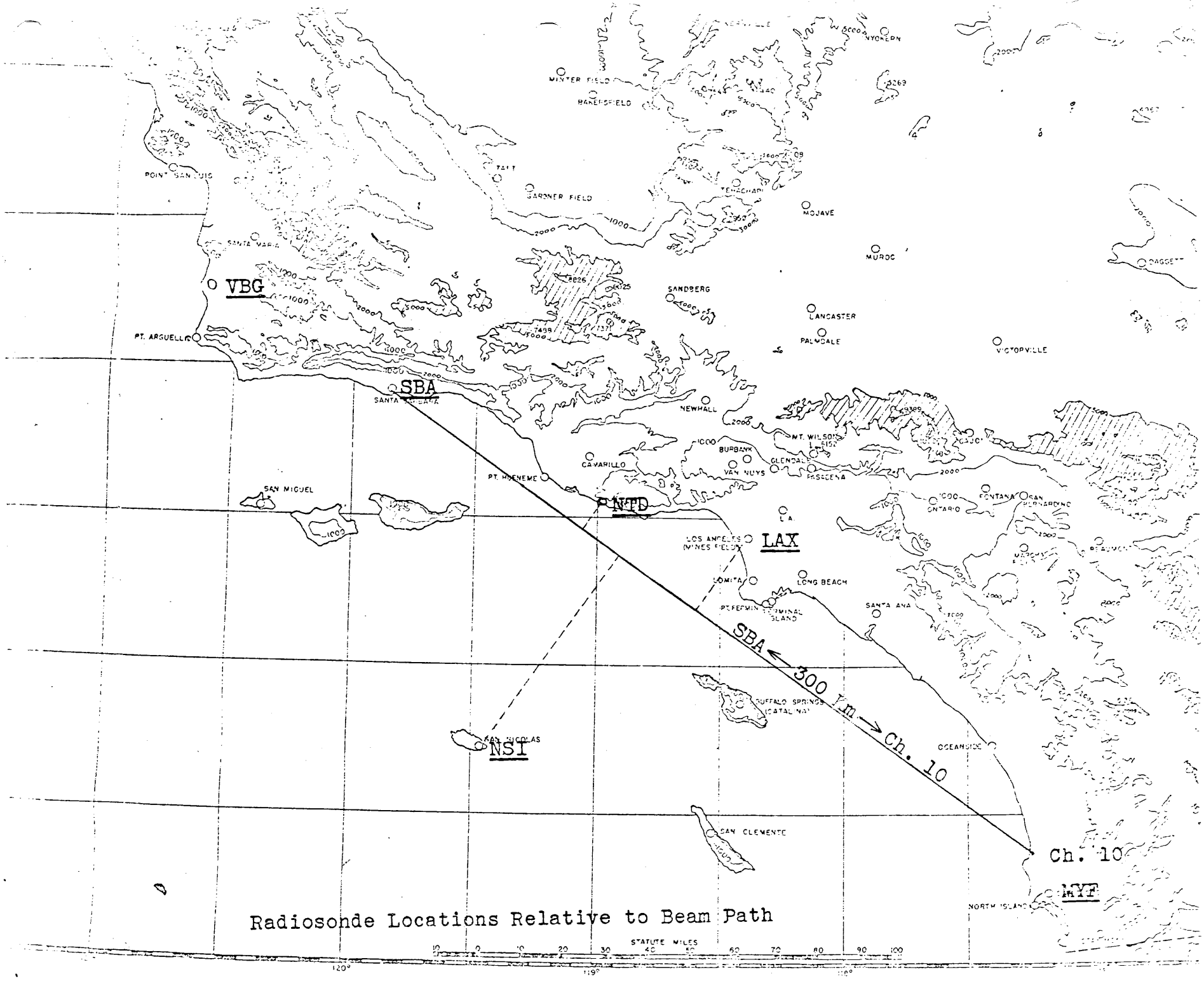

Radiosonde Locations Relative to Beam Path

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Figure 1

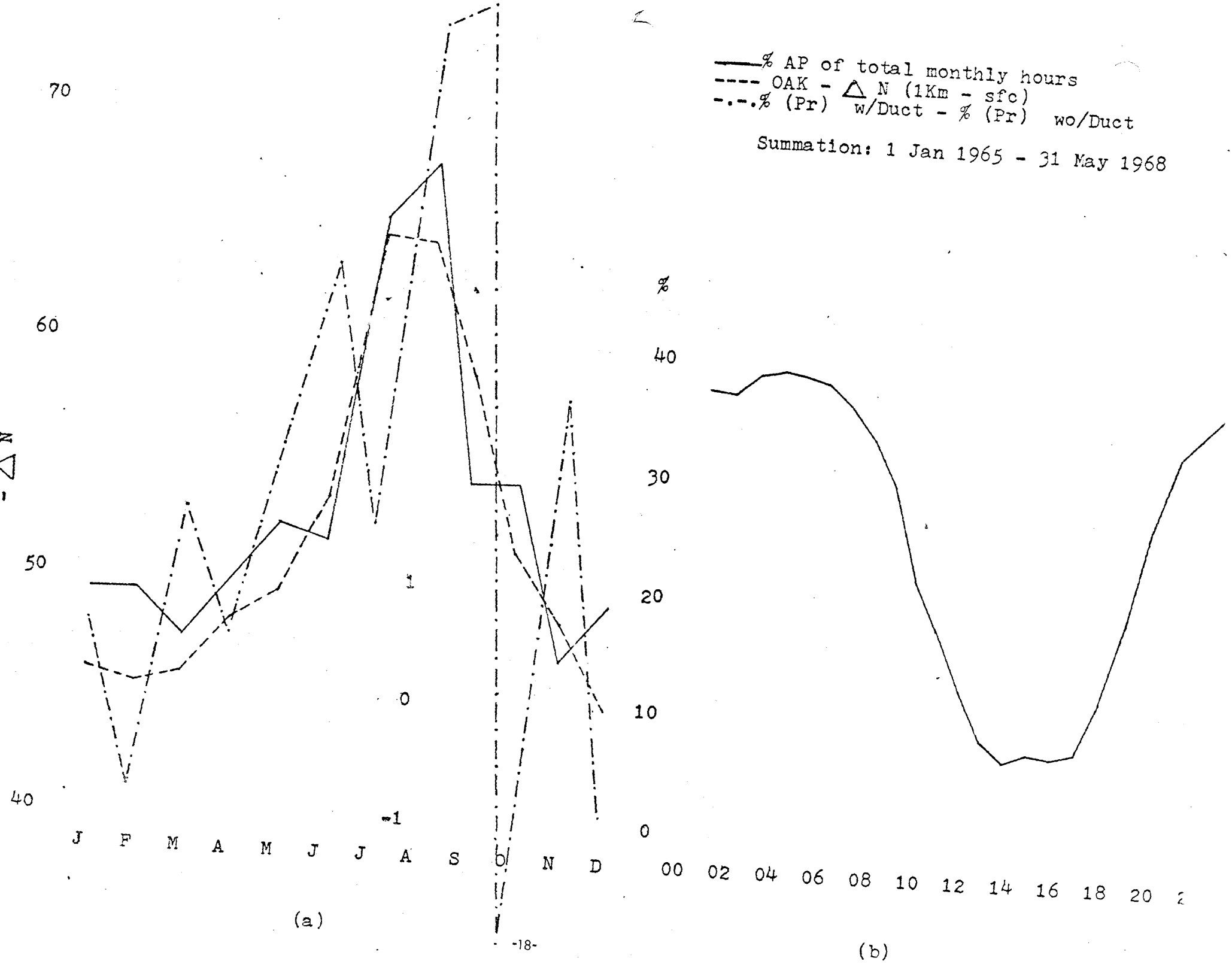
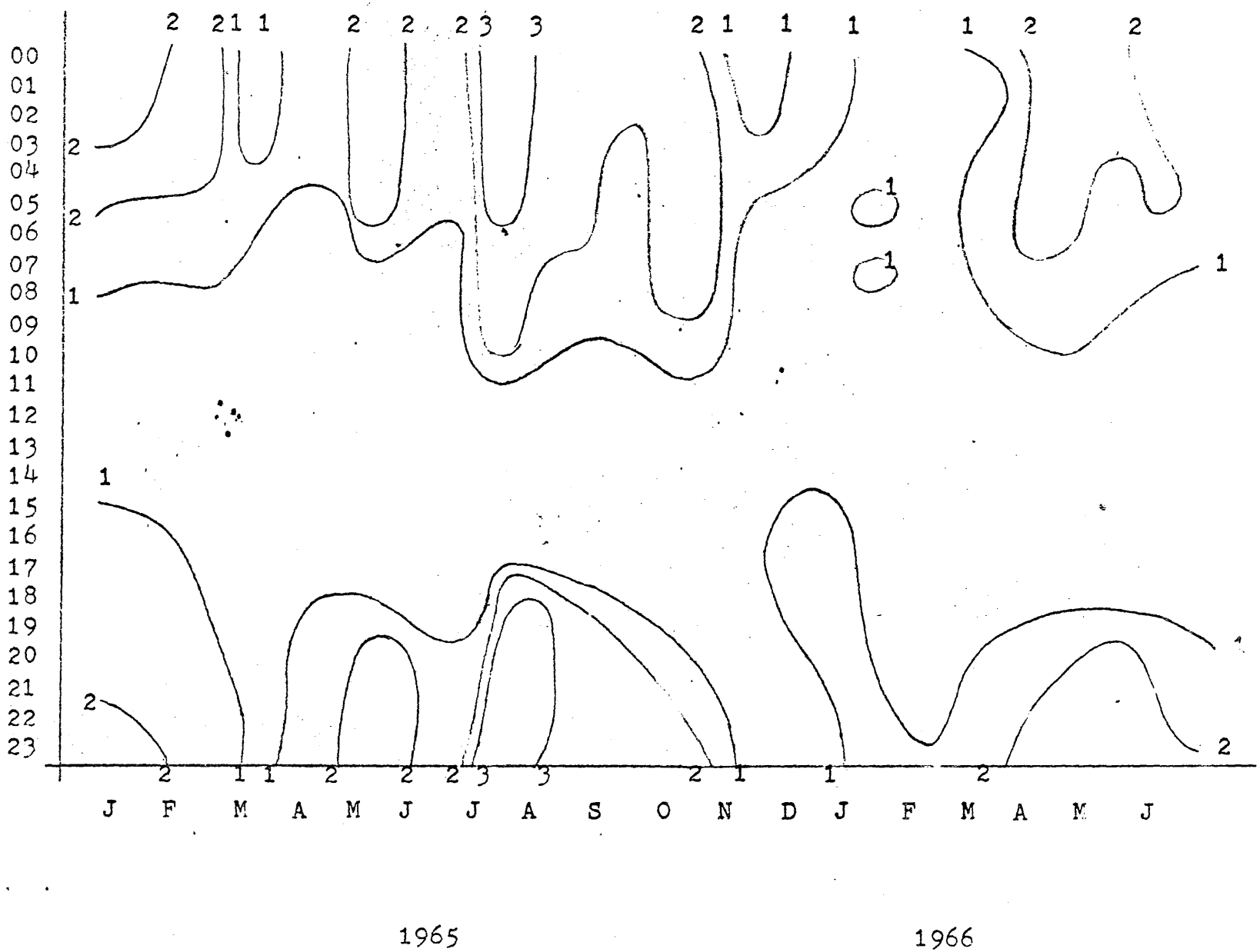

% AP of total monthly hours
OAK - △ N (1Km - sfc)
% (Pr) w/Duct - % (Pr) wo/Duct
Summation: 1 Jan 1965 - 31 May 1968
70
60
50
40
- △ N
1
0
-1
J F M A M J J A S O N D
(a)
%
40
30
20
10
0
00 02 04 06 08 10 12 14 16 18 20
(b)

Figure 2



DUCTING OCCURRENCE - Percent of Total Monthly Hours

Figure 3

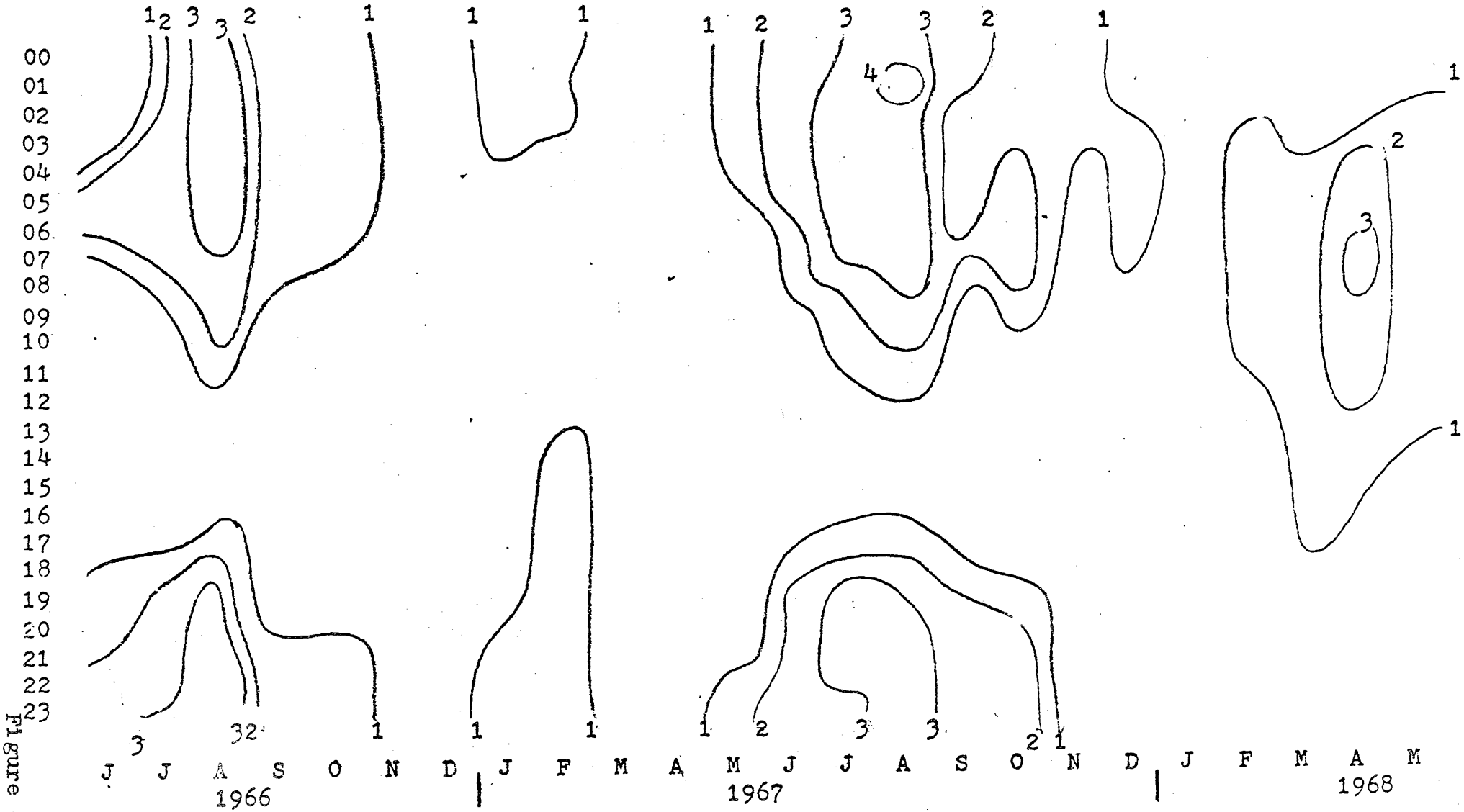
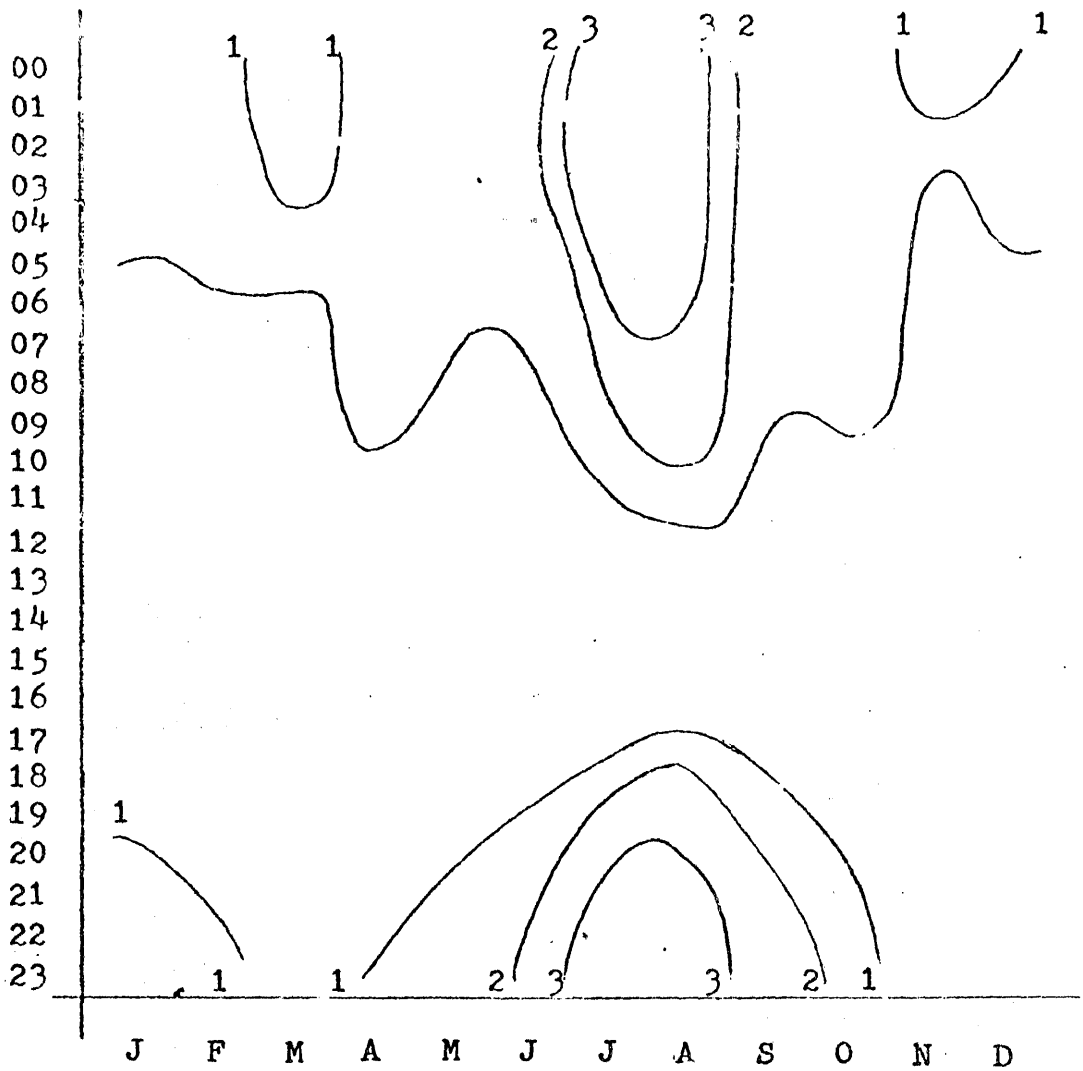


Figure 4

DUCTING OCCURRENCE - Percent of Total Monthly Hours



DUCTING OCCURRENCE
Percent of Total Monthly Hours

Average of Period Jan. 1965 - May 1968

Figure 5

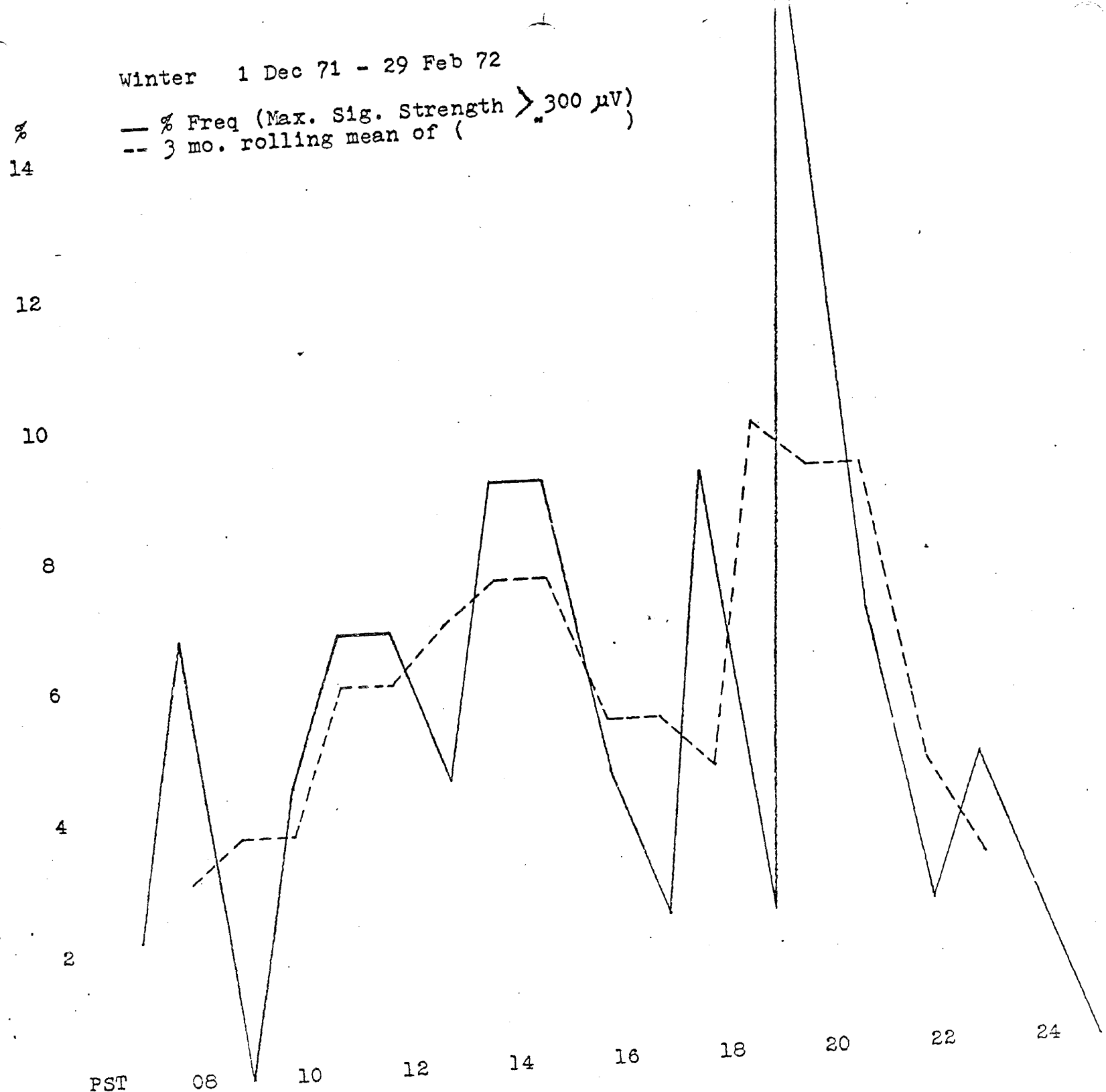

Winter 1 Dec 71 - 29 Feb 72
— % Freq (Max. Sig. Strength > 300 μV)
-- 3 mo. rolling mean of ( )
%
14
12
10
8
6
4
2
PST
08
10
12
14
16
18
20
22
24

Figure 7

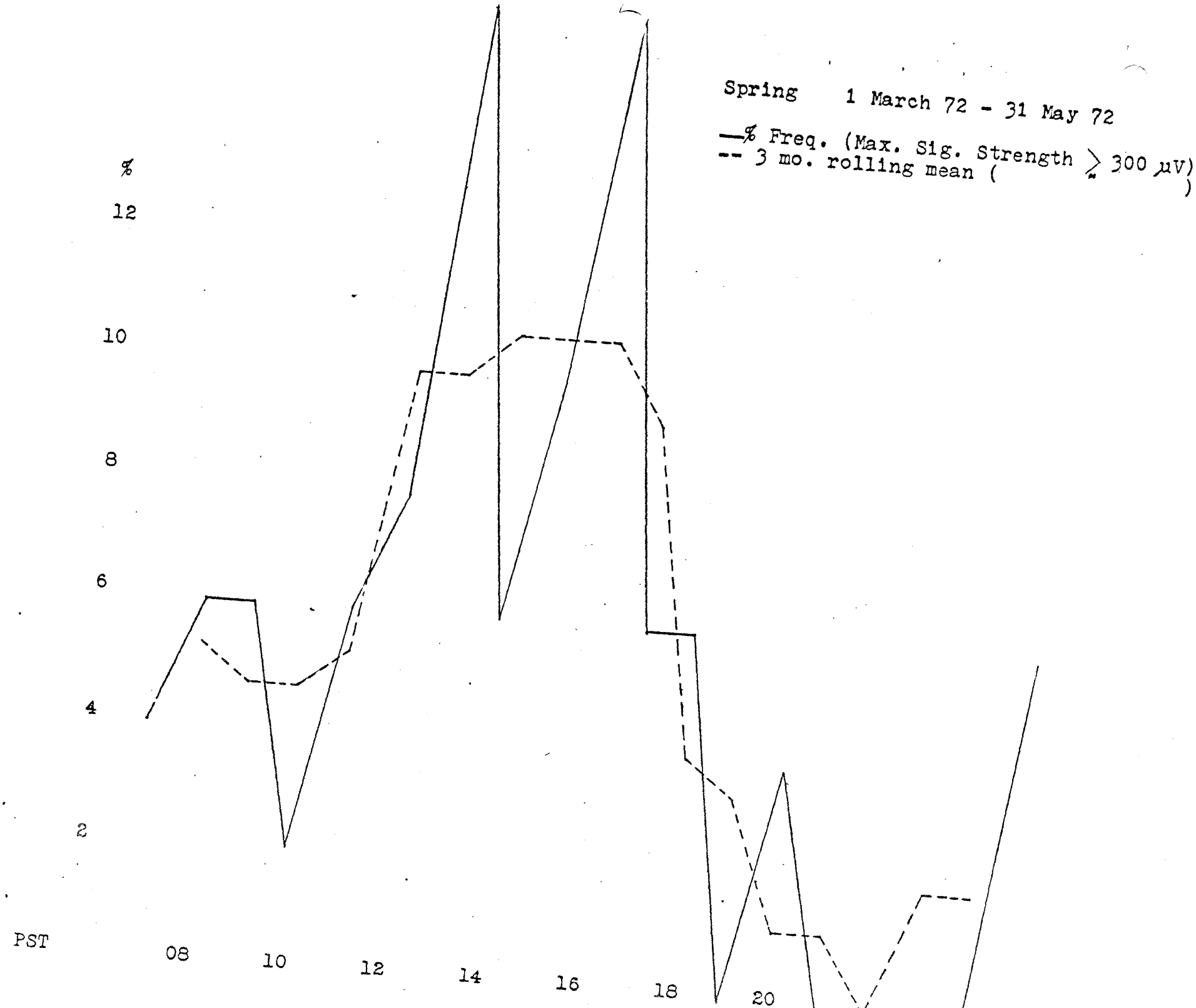

Spring 1 March 72 - 31 May 72
—% Freq. (Max. Sig. Strength ≥ 300 μV)
-- 3 mo. rolling mean ( )
%
12
10
8
6
4
2
PST
08
10
12
14
16
18
20

Figure 9

Composite Fall, Winter, Spring
25 Aug 71 - 31 May 72

—% Freq (Max. Sig. Strength > 300 μV)
-- 3 mo. rolling mean (")

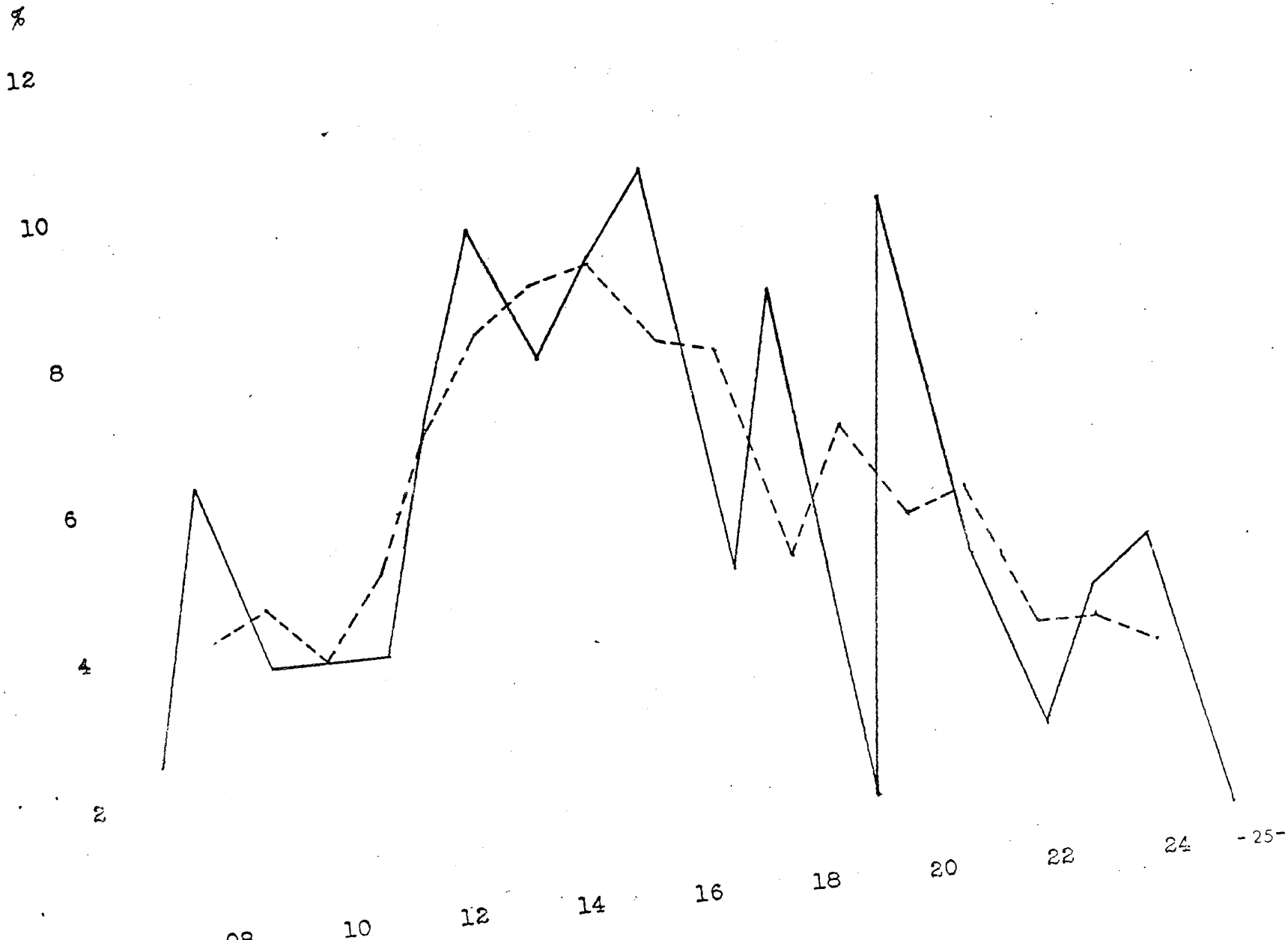
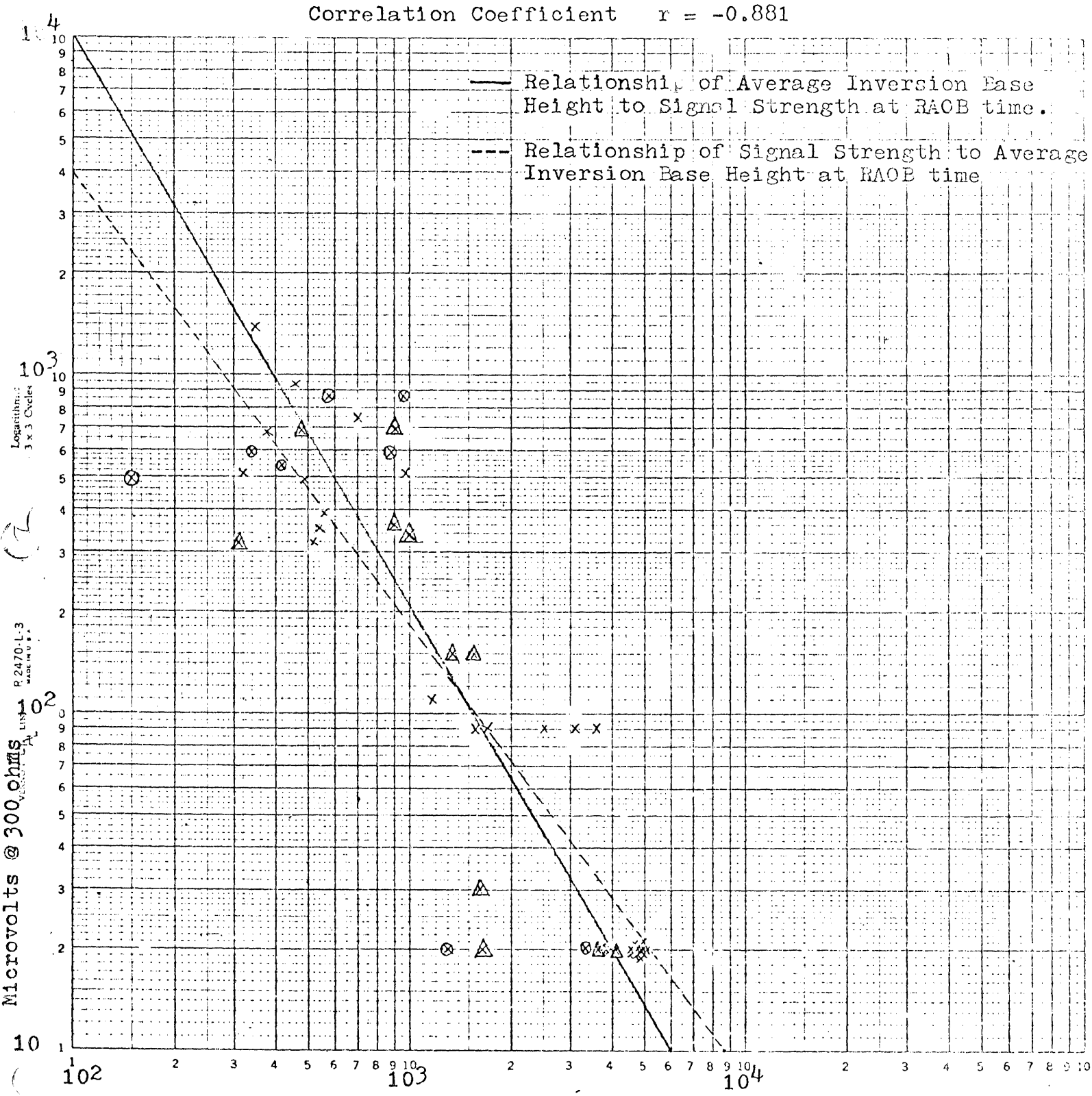


Figure 9

RELATIONSHIP OF SIGNAL STRENGTH AT SANTA BARBARA
TO AVERAGE INVERSION BASE HEIGHT ($\overline{NTD + LAX}$)



Average Inversion Base Height ($\overline{NTD + LAX}$) Feet MSL
x = August 25 - September 30, 1971
⊗ = October, 1971
△ = November, 1971

Figure 10

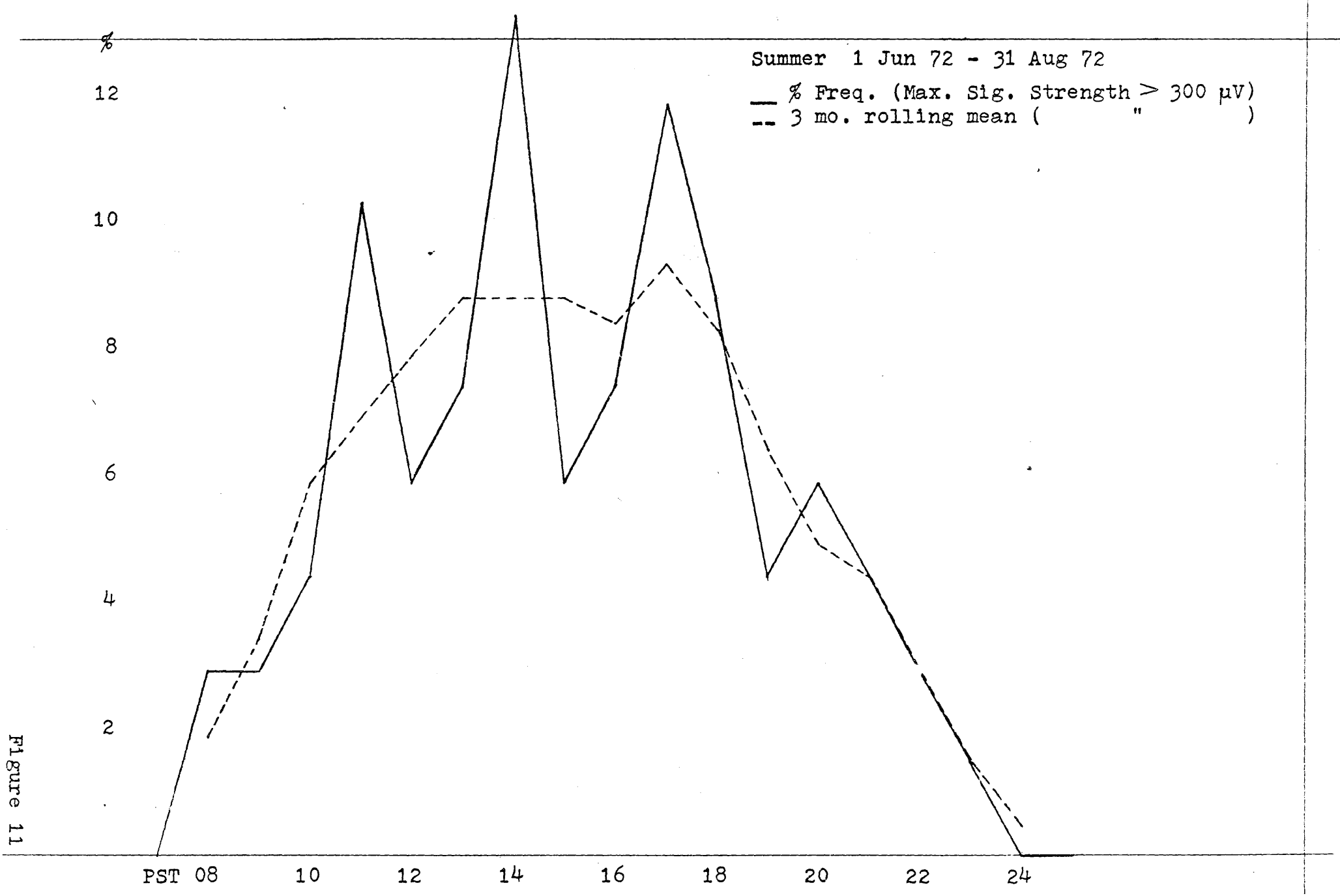

Summer 1 Jun 72 - 31 Aug 72
% Freq. (Max. Sig. Strength > 300 μV)
3 mo. rolling mean (")
%
12
10
8
6
4
2
PST 08
10
12
14
16
18
20
22
24

Figure 11

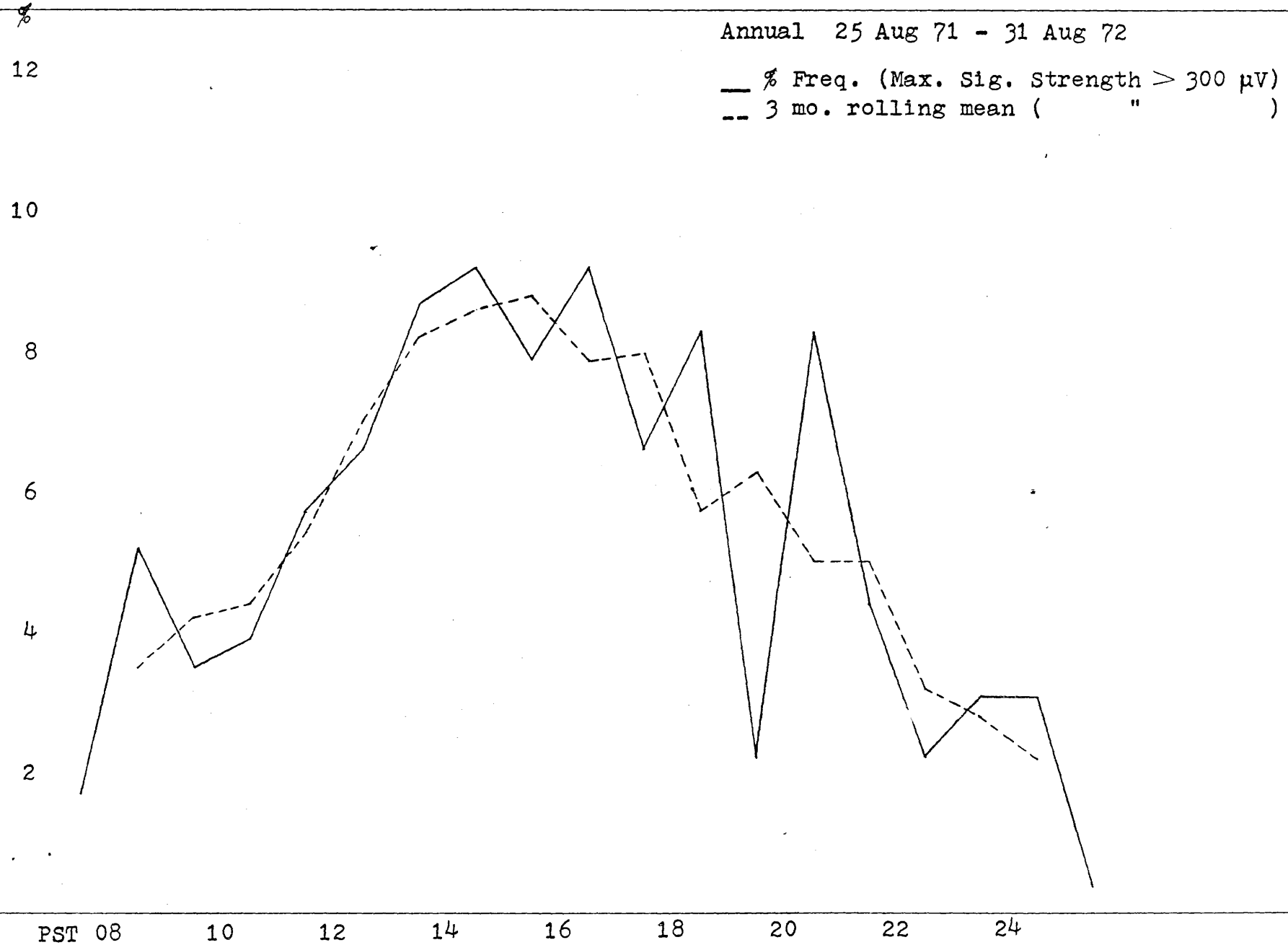

%
12
10
8
6
4
2
Annual 25 Aug 71 - 31 Aug 72
% Freq. (Max. Sig. Strength > 300 μV)
3 mo. rolling mean (")
PST 08
10
12
14
16
18
20
22
24

Figure 12

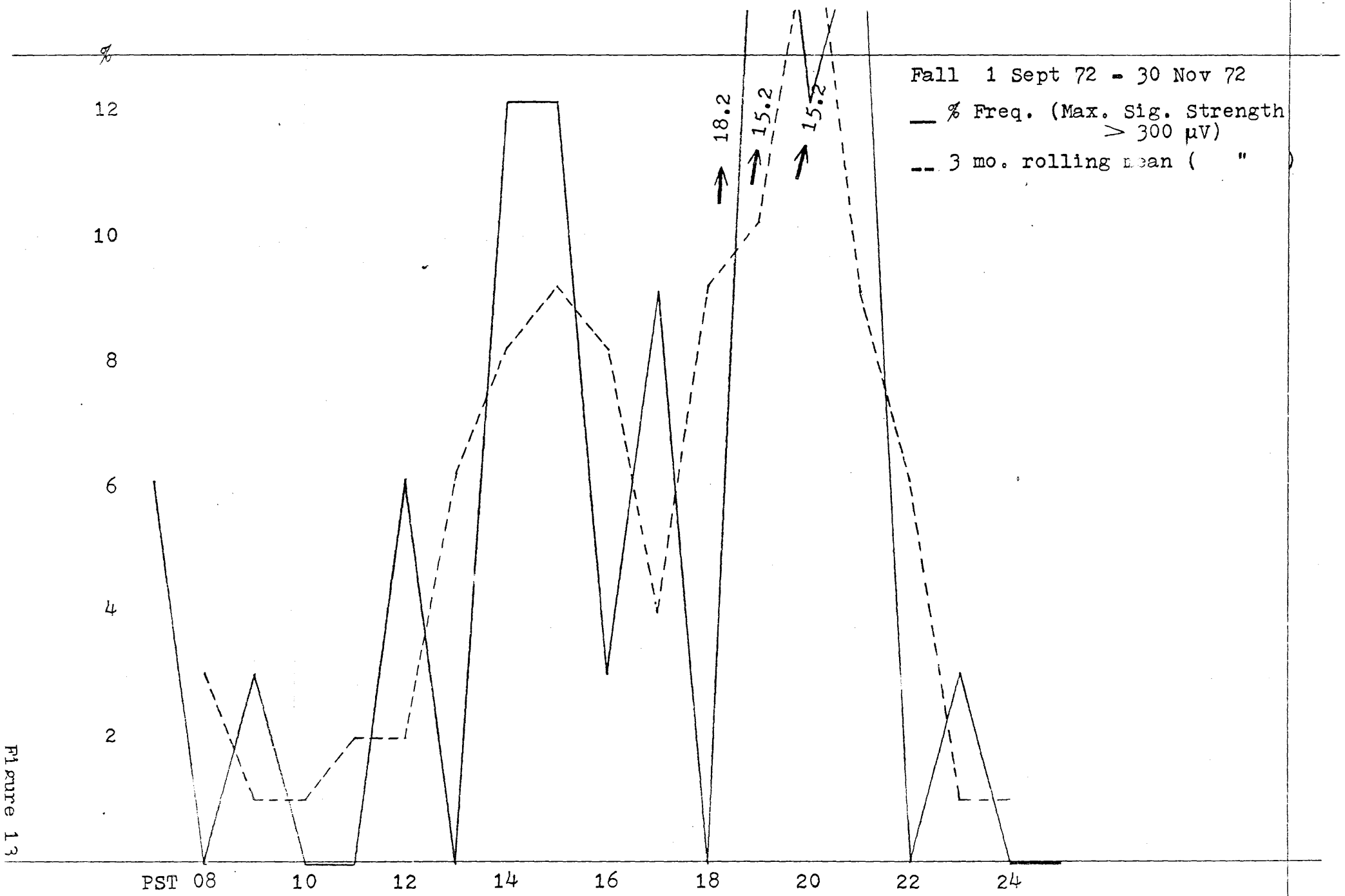

%
12
10
8
6
4
2
PST 08
10
12
14
16
18
20
22
24
18.2
15.2
15.2
Fall 1 Sept 72 - 30 Nov 72
% Freq. (Max. Sig. Strength > 300 μV)
3 mo. rolling mean (")

Figure 13

Monthly Trend of Correlation Coefficients

log microvolt signal vs. log inversion base height

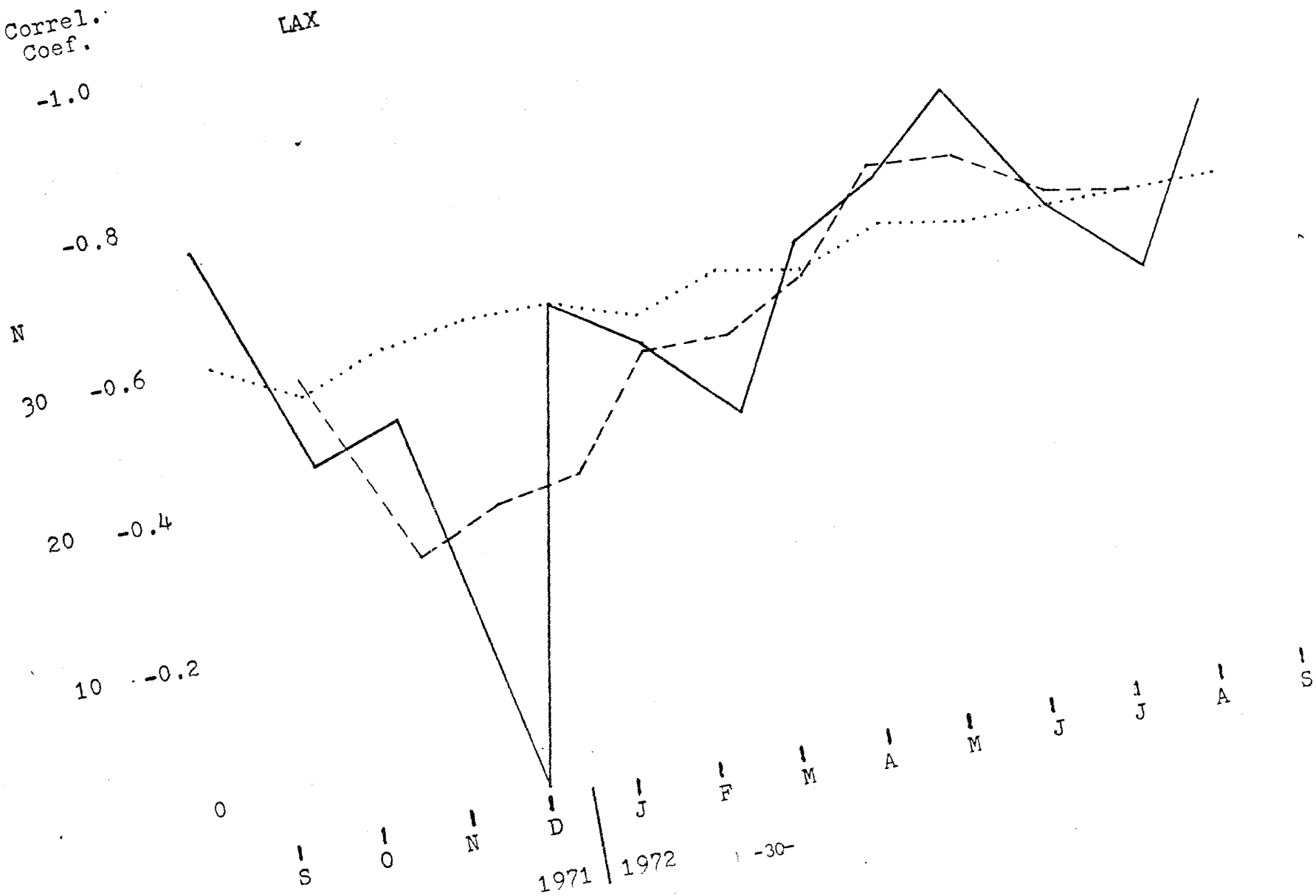


Figure 14

Monthly Trend of Correlation Coefficients

log microvolt signal vs. log inversion base height

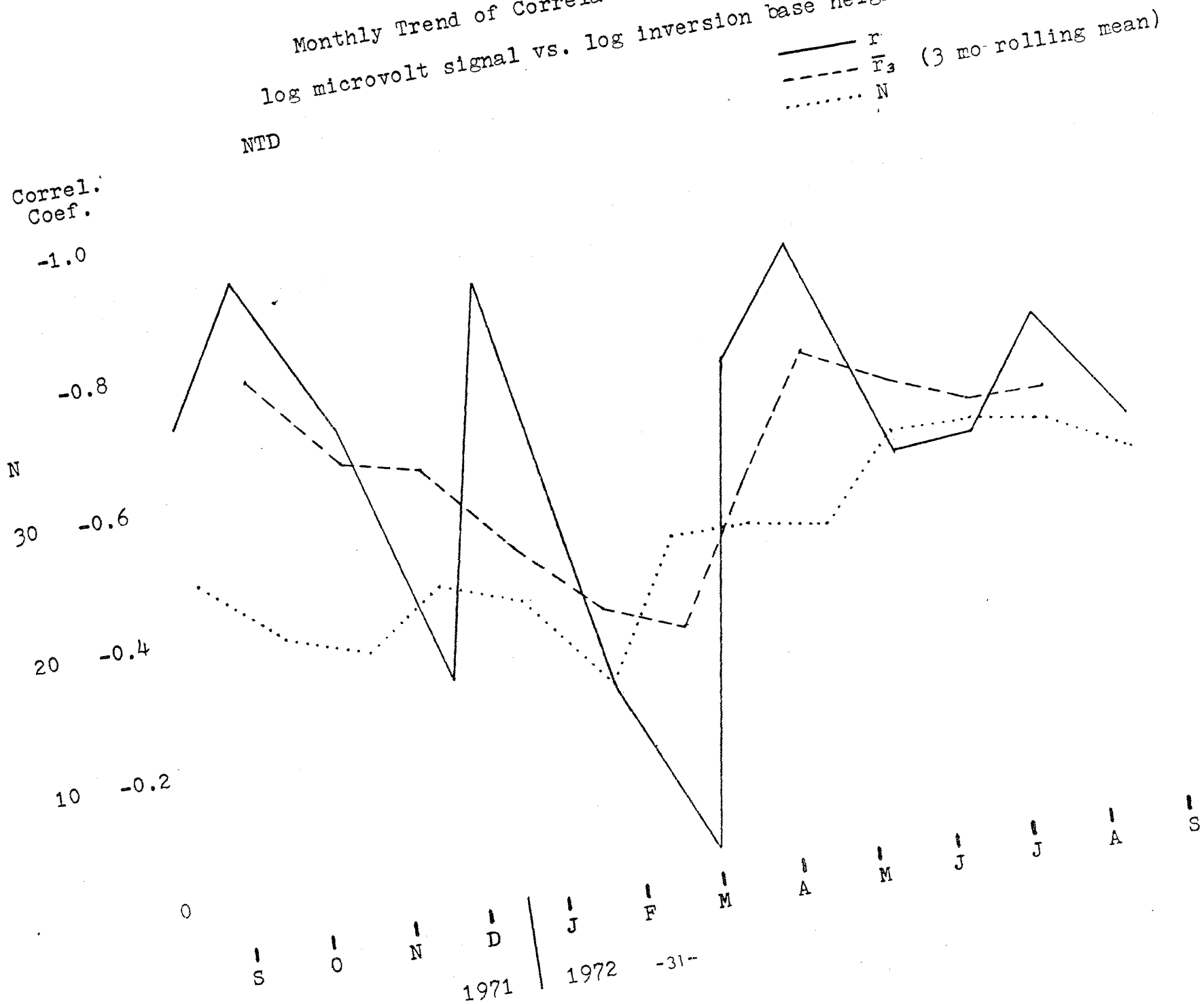


Figure 15

Monthly Trend of Correlation Coefficients

log microvolt signal vs. log inversion base height

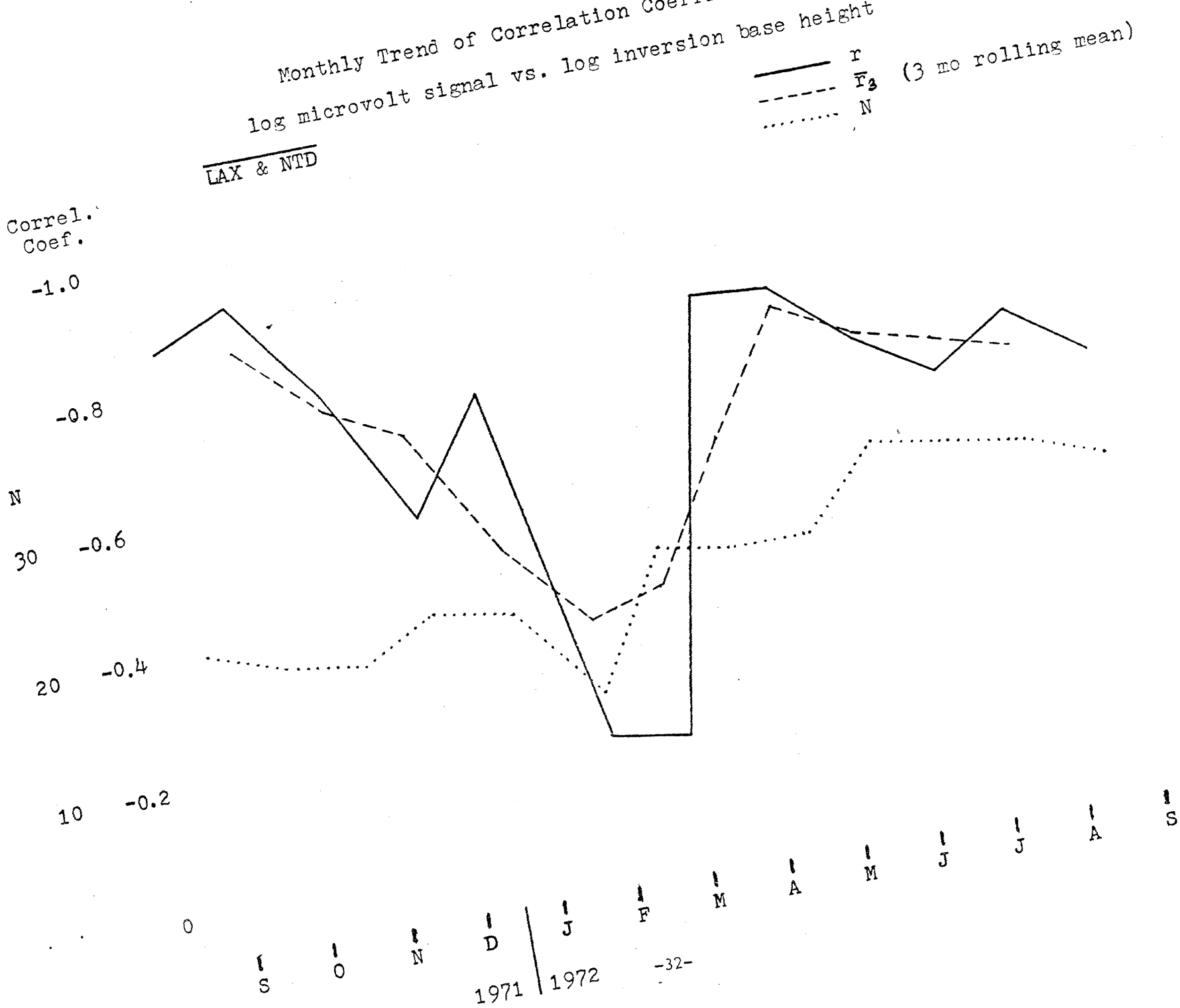


Figure 16

Monthly Trend of Correlation Coefficients

log microvolt signal vs. log inversion base height

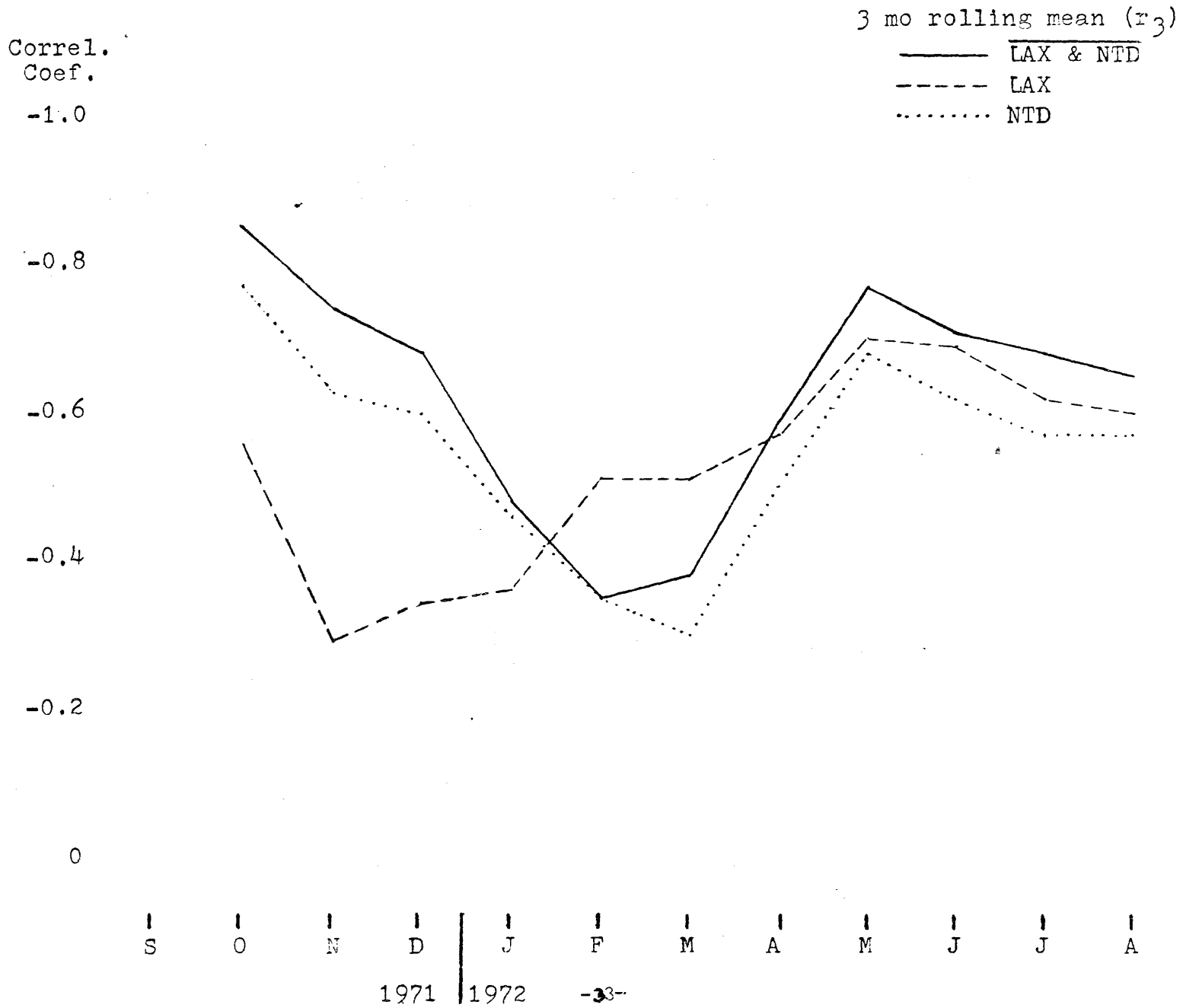


Figure 17

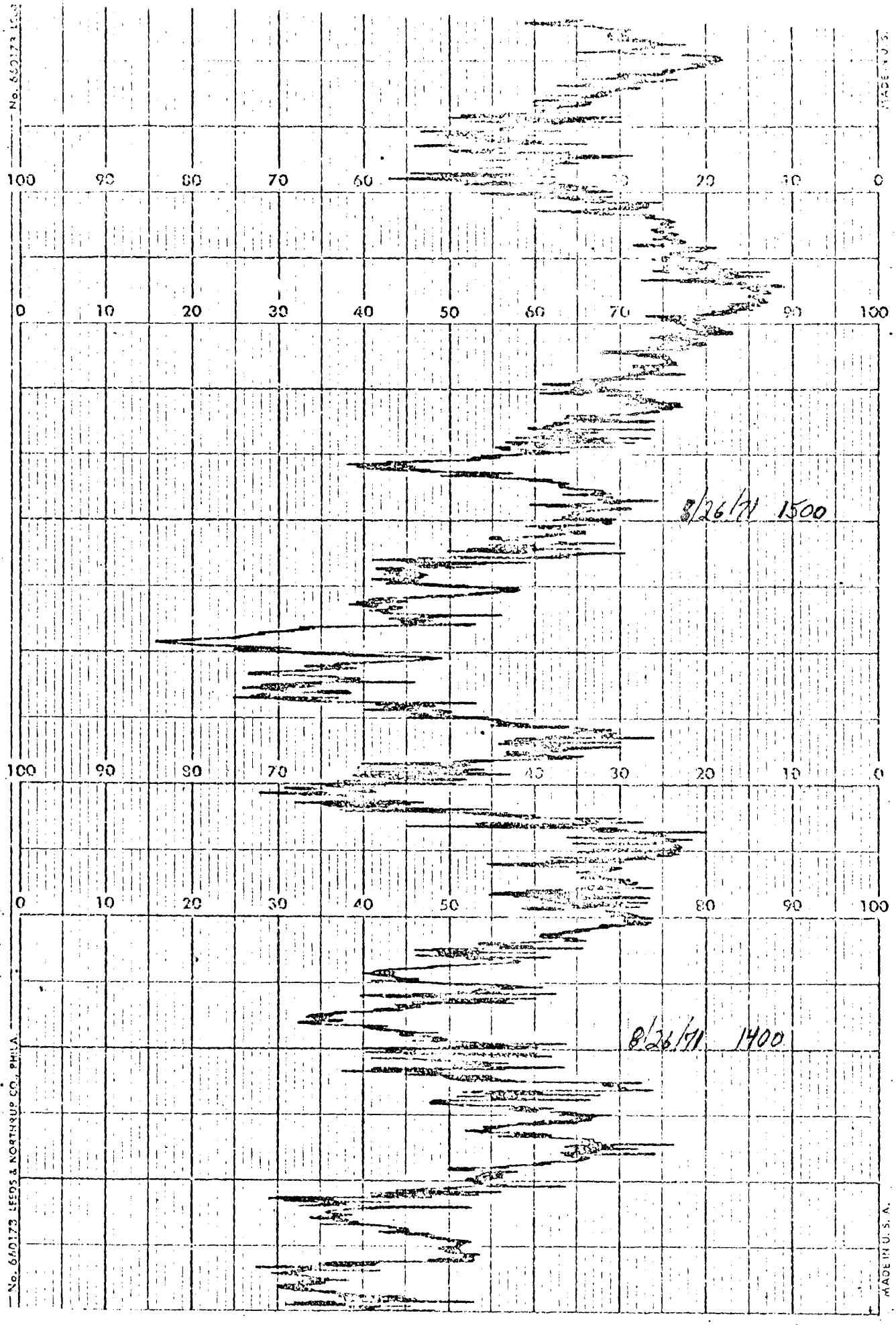


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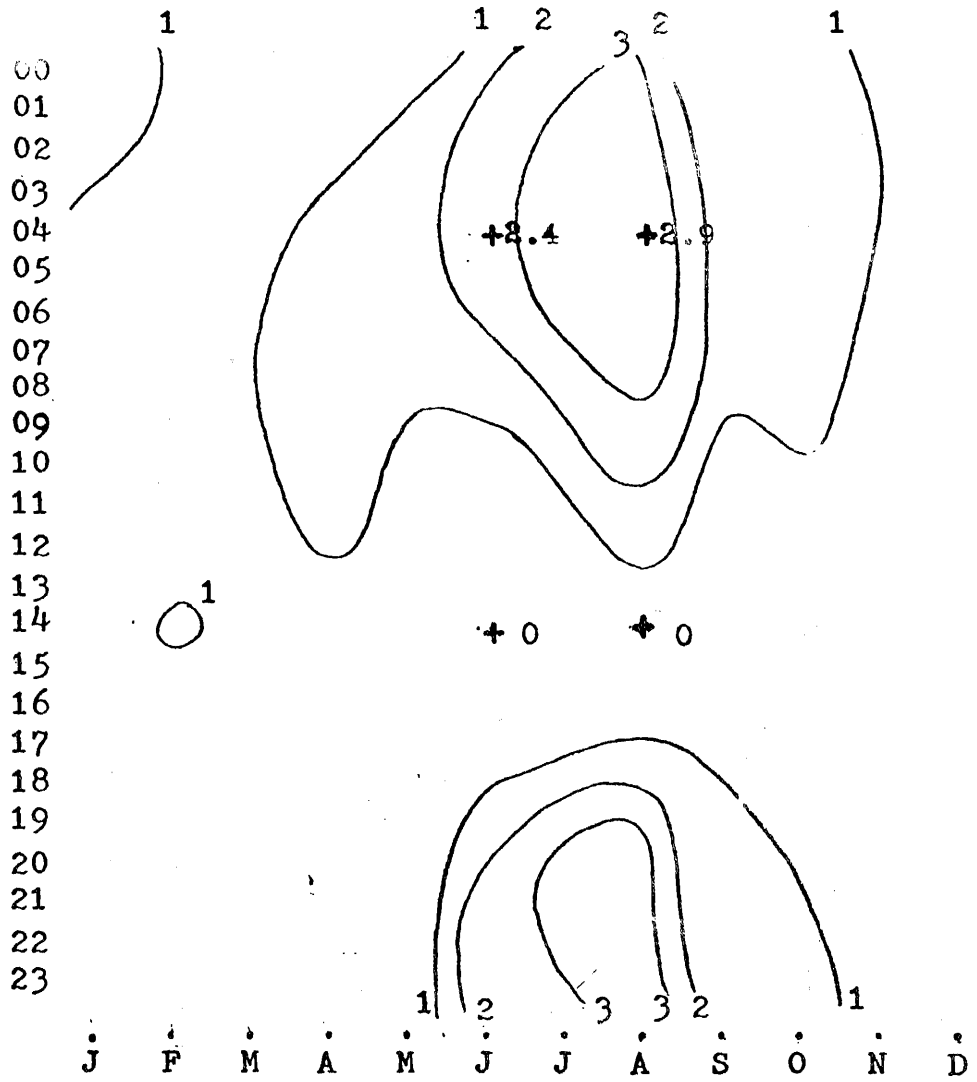
Figure 18



DUCTING OCCURRENCE
Percent of Total Monthly Hours

Average of Period June 1966 - May 1968

Figure 19

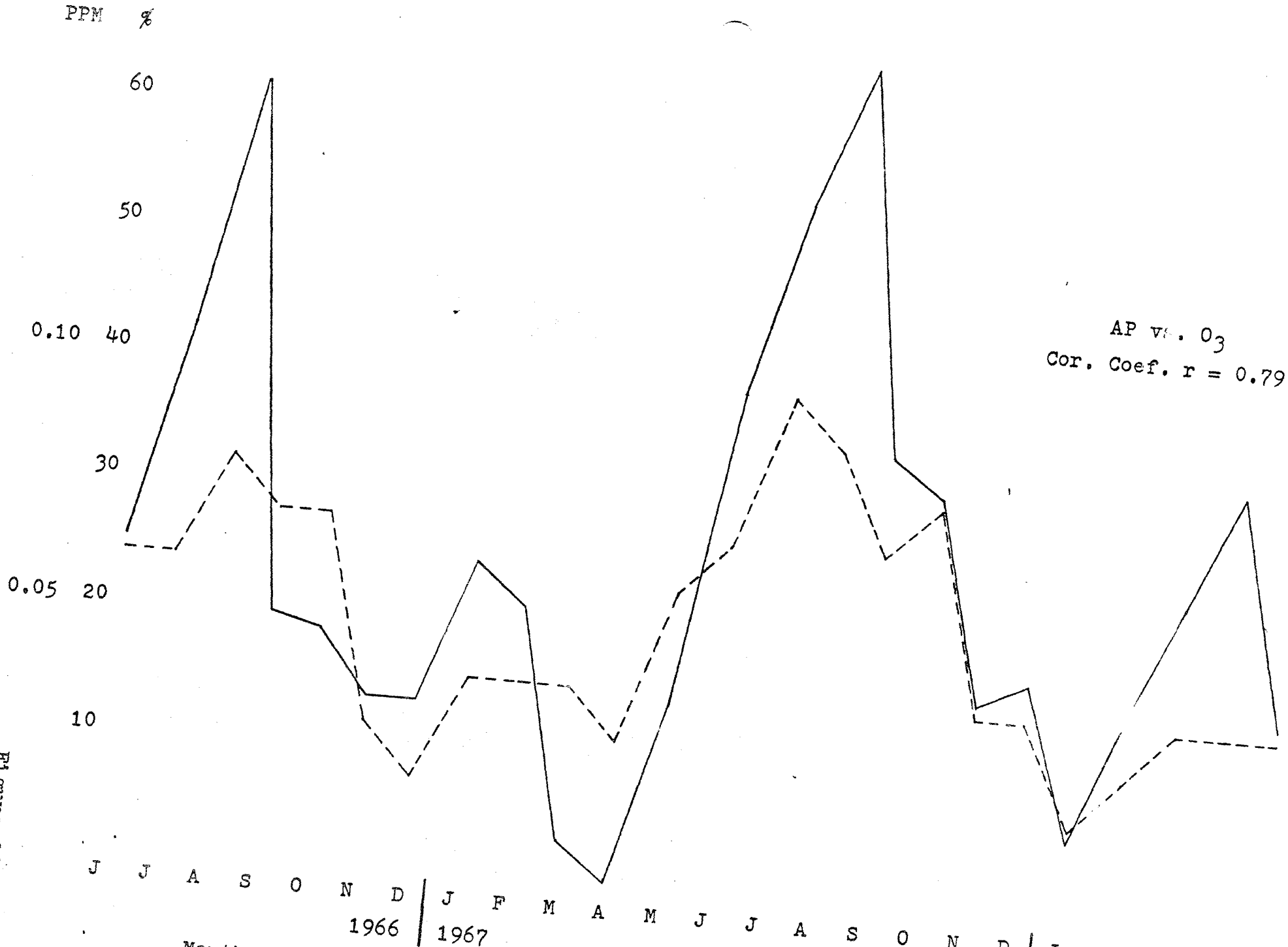
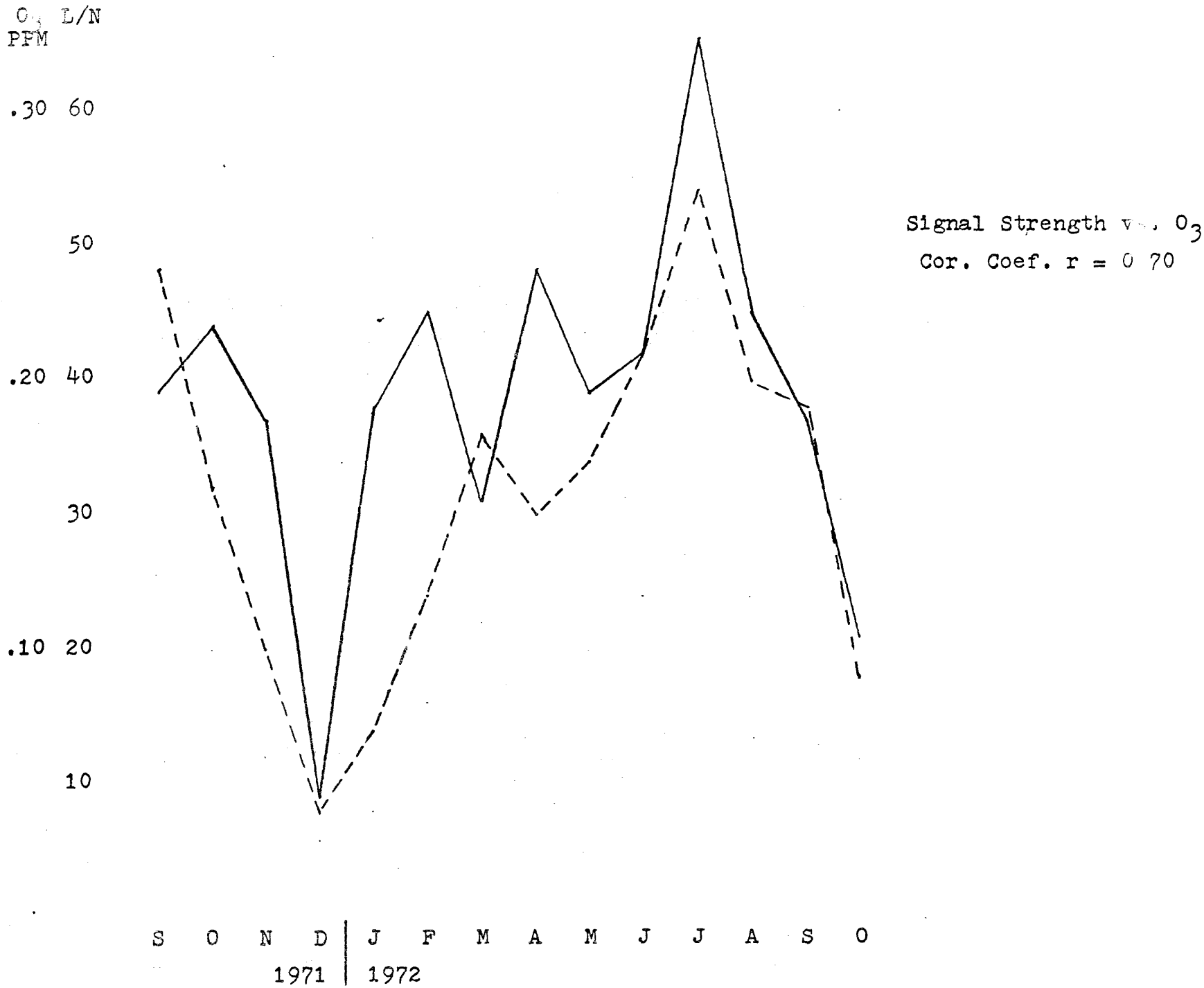


Figure 20

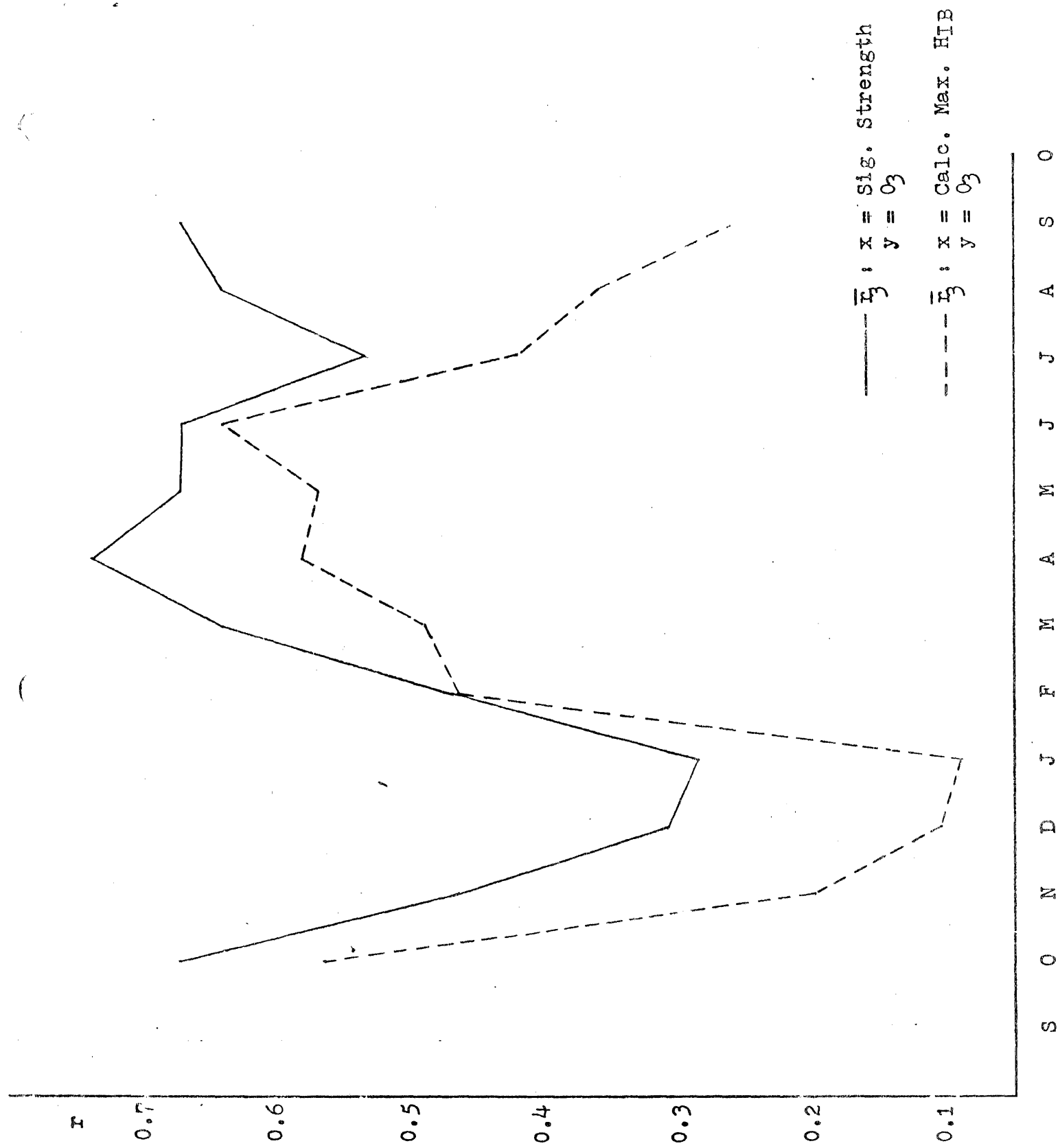
Monthly % of Total Possible Monthly Hours of Anomalous Propagation
Monthly Average of Daily Maximum Hour of O_3 at 13th & J, Sacramento



Monthly Average of Daily Maximum Signal Strength ____

Monthly Average of South Coast Basin Daily Maximum Oxidant ----

Figure 21



Monthly Correlation Coefficients - L. A. Basin

3-Month Rolling Mean

1 Sep. 71 - 31 Oct. 72

O_3 Daily Max. vs. Signal Strength
O_3 Daily Max. vs. Calc. Max. H_{IB}

Figure 22