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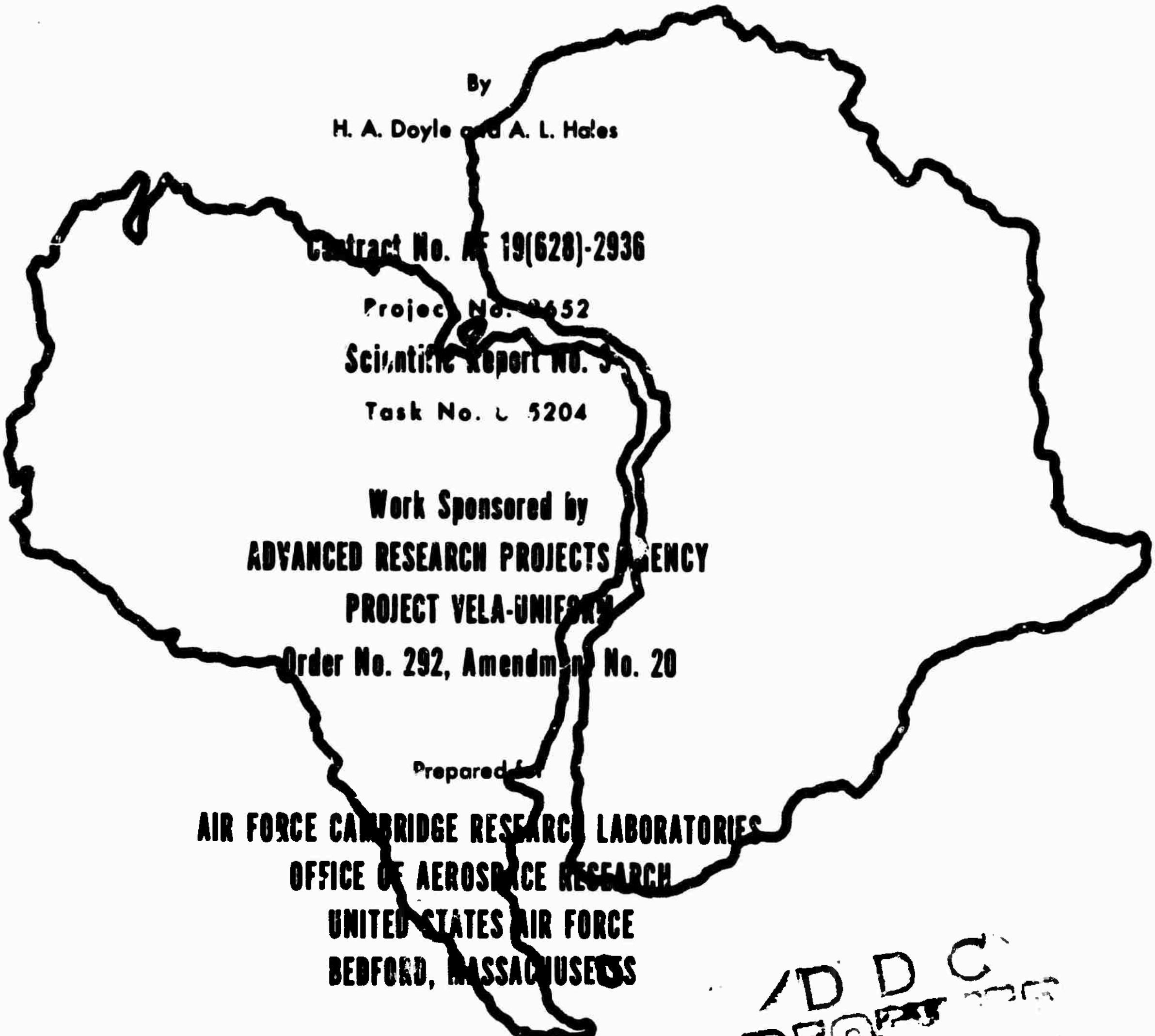
AN ANALYSIS OF THE TRAVEL TIMES OF S WAVES TO NORTH AMERICAN STATIONS, IN THE DISTANCE RANGE 28° TO 82°



By

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"An Analysis of the Travel Times of S Waves to North American Stations, in the Distance Range 28° to 82°"

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Abstract

The travel times of S waves from 20 earthquakes to stations in North America in the distance range 28° to 82° have been studied. The deviations from J-B times were analyzed into station, source and distance components using the least-squares time-term approach of Cleary and Hales. Station anomalies had a range of about eight seconds, as compared to three seconds for the P anomalies, and are believed to be caused largely by variations in the upper mantle velocity distribution. S residuals, like the P residuals, were generally positive in the western United States, and negative in the central and eastern United States. P and S residuals at the same station correlated with a coefficient of 0.75, the slope of the regression of S anomaly on P anomaly being 3.72. Corrections to J-B times for S were of the order of the standard errors of the determinations. Within the distance range of 28° to 82° large changes of the S travel times, such as were required by the lower mantle velocities proposed by MacDonald and Ness (1961), are not permitted by the present data. The analysis was checked by carrying out a univariate analysis of variance of the same data.

Introduction

The Jeffreys-Bullen travel time tables have been used extensively as a world-wide standard since they were first published in 1935 (Jeffreys and Bullen, 1935, 1940). Recently Carder et al. (1964, 1966), Cleary and Hales (1963, 1966a) (the 1966a paper will be referred to hereafter as Paper 1), Husebye (1965) and Herrin (1966) have studied departures of P times from the J-B tables at teleseismic distances using somewhat different methods of analysis. It was found that there were significant departures from J-B times. It was shown also that significant residuals were associated with stations, P being systematically early in the central United States, and late in much of the western United States.

A great deal less work has been done on S travel times. S times are more difficult to measure, for S is often not a sharp arrival and is immersed in the noise [illegible] the P tail. The microseismic noise background at the periods of 15 to 20 seconds, characteristic of S arrivals on long period records, is about an order of magnitude higher than that at the periods of one to two seconds characteristic of P on short period records (Brune and Oliver, 1959). However, in the present investigation all events were large, and microseismic noise did not affect the S readings.

Kogan (1960) has published observations of S from Pacific nuclear blasts, and Jeffreys (1966) has recently suggested revisions in S times from a study of Japanese shocks. Kogan's analysis suggested that S arrivals at teleseismic distances were later by several seconds than the J-B times, whereas Jeffreys' analysis suggested that the arrivals were early by one or two seconds. Some times of S from the Hindu-Kush to European stations by Lehmann (1964) give support to Kogan's late observations.

Methods

In this paper the methods of analysis used by Cleary and Hales in Paper 1 were applied to S arrivals at North American stations from 20 of the 25 earthquakes which they studied. The epicenters, origin times and depths determined in the P study were used for the S wave analysis.

S was, in general, poorly recorded on the short period seismograms used in the P study, and only long period records were used in this work. The North American stations were either LRSM or USCGS World-Wide Network stations, using long period vertical and horizontal components. S wave periods were usually 15 to 20 seconds. It might have been better for this study if a network of intermediate period seismographs (perhaps 5 to 15 sec band pass) had been available, for it was often difficult to determine S arrival times as precisely as we would have liked.

Most readings were obtained from the horizontal components, the arrivals on the vertical often being emergent. S times were measured from photographic copies of film or paper records using the usual criteria of change of amplitude, period or character to determine the onset. It is intended that particle motion studies from digitized records be made in an effort to improve reading accuracy and identification of S.

The Analysis

It is assumed that for station r and earthquake s

$$a_{rs} + b_r + d_s = \delta t_{rs} \qquad (1)$$

where δt_{rs} is the observed residual from the J-B tables, a_{rs} is the average difference from the tables for the distance of station r from earthquake s, the station residual b_r is a variation in the travel time caused by conditions in the vicinity of station r, and d_s is a variation associated with earthquake s or its vicinity.

As before, differences from the J-B tables a_i were assigned to each 2° distance interval, from 28° to 82°, and the observational equations (1) were used to form a set of normal equations in the unknowns a_i, b_r and d_s. One of the d_s and one of the a_i were set to zero to make the equations determinate, so that only relative values can be determined.

The results of the least-squares analysis are presented in Tables 1, 2 and 3. Table 1 gives the station residuals (or anomalies) and the standard errors of the determinations as found from the least-squares solution, Table 2 the travel time residuals, and Table 3 the source residuals. The standard deviation of the residuals in this analysis was 2.45 sec.

<u>The station residuals</u>

The S station residuals have a range which is about three times greater than that of the P station residuals for the same group of stations (see Table 5, Paper 1). The S residuals for each station are plotted against the corresponding P residuals in Figure 1. The two types of residual correlate rather well. A straight line was fitted to the observations using a method devised by York (1966) for determination of the regression line in cases in which both variables are subject to error. The observations were weighted inversely according to the s are of the standard errors found from the least squares solution.

This straight line was

$$S \text{ residual} = (3.72 \pm 0.43) (P \text{ residual}) - (1.50 \pm 0.20) \text{ sec.}$$

We then chose to adjust these relative S residuals so that the line of best fit goes through the origin, i.e., that the S residuals have the same zero as the P's. Accordingly we have increased all the S residuals of column 5 of Table 1 by 1.50 seconds. These residuals are plotted on a map of the United States (Figure 2). This figure shows a remarkable similarity to the corresponding figure for P station residuals (Paper 1, Figure 4).

P station anomalies have been shown to have an azimuthal component (Otsuka, 1966, Bolt and Nuttli, 1966, Cleary and Hales, 1966b, and Herrin and Taggart, personal communication). The azimuthal component should only be large in regions where the station anomaly is changing rapidly in space. The station corrections reported here represent means for three widely separated azimuths.

<u>The travel time residuals</u>

The travel time residuals are shown in Figure 3. They are of the same order as the standard errors. The absolute values are arbitrary, since the travel time residual at 81° was set to zero in order to make the solution determinate. In the P analysis the baseline was fixed using observations of the Bikini and Eniwetok explosions. In this case the only similar information is that of Kogan (1960). If a baseline value be determined from the Kogan data near 42^{o} (where she has three stations and six observations), then all residuals would be increased by 4.5 seconds (mean of the three stations' means) and would have the values shown in column 4 of Table 2.

It should be noted that the shift of baseline does not imply any large change of velocity distribution in the region below the depth corresponding to our minimum arc distance of 28^{o}, for the velocity distribution is determined from the relation between $\frac{dT}{d\Delta}$ and Δ. The correction of baseline requires only changes in the upper mantle velocity distribution. It is reasonable to expect that there will be regional changes in this distribution, and so it is in essence a matter of choice which upper mantle velocity distribution is to be regarded as standard. Tying the baseline to the Kogan data effectively chooses as standard an upper mantle structure related to the paths which Kogan used (i.e. from ocean sources to Siberian continental stations).

Within the limits of error of the analysis (i.e. $\pm$ 1 to 2 seconds) and for arc distances up to 80^{o}, there is no evidence of large systematic trends of the residuals. Thus there is no evidence for decreased S velocities in the lower mantle such as were suggested by MacDonald and Ness (1961) to account for the differences between the observed periods of the graver modes of free oscillation and those calculated from earth models having the Gutenberg S velocity distribution. This follows also from Jeffreys' (1966) analysis of S travel times, which are shown in Figure 3. This point was made by Landisman, Satô and Nafe (1965), who compared times calculated for the MacDonald and Ness model with the J-B times.

<u>The source corrections</u>

Since the station residuals have been increased by 1.50 seconds and the travel times increased by 4.5 seconds, it is necessary to reduce the source corrections by 6.0 seconds. The source effects so reduced are given in column 5 of Table 3. The range of the source residuals is 18 seconds, which is surprisingly high, and is greater than the range of station residuals. It is probable, however, that most of the differences between the source effects for different events can be ascribed to differences in upper mantle structure near the sources. The source corrections reported are, of course, source corrections in the direction of North America, and, as was pointed out in Cleary and Hales (1966a), include the effects of errors of location and depth of focus.

The restriction of the analysis to North American stations has the effect of reducing difficulties arising from azimuthal variations of the source effect, for in some degree the observations have been limited to rays leaving any particular source in a relatively narrow range of azimuths.

<u>The analysis of variance approach</u>

Other workers have used different methods for separating out the effects of source and station from the errors in the travel time curve. Herrin and Taggart (see Herrin, 1966) used a successive approximation method, Carder, Gordon and Jordan (1966) a bivariate analysis of variance for P travel time studies, and Freedman (1966) for Pn travel times. In view of the large range of the station and source residuals found for the S phases, we thought it worthwhile to carry out a univariate analysis of variance of the data used in the least-squares approach.

If, for example, the residuals are grouped by source, then source effects are as given in Table 4. It is clear that the range of the source effects is of the same order as that found using the C-H method of analysis, and application of an F distribution test shows that the source effects are in fact significant at the 0.1% level.

Similar groupings by station and distance interval were made. The results of the analysis of variance are presented in Table 5. The station effects are significant at the 1% level, while departures of travel times from the J-B tables are not.

Better estimates of the station residuals can be obtained by applying corrections for source effects before the residuals are grouped by stations. The procedure was to reduce all source residuals to a common (and arbitrary) value, for example, the mean residual for all sources. When this was done, a new set of station residuals was obtained. The data were then grouped by stations and a new set of station residuals obtained.

The analysis of variance information for this set is given in Table 6. The station residual effect is now significant at the 0.1% level. Figure 4 shows a plot of the residuals found by the C-H method against those found by grouping after the source effect was removed. The correlation coefficient is 0.974, and the slope of the regression line is 0.925.

The choice of a standard travel time curve

The evidence that regional differences in travel times occur raises difficulties with regard to the choice of standard travel times. This has been recognized by Jeffreys (1966), who remarked, "I have several times sought for differences of travel times of P according to azimuth, but have never found anything significant. Shimshoni however has pointed out to me that they must exist. .... It is very troublesome—it looks as if a satisfactory set of travel times will be a function of four variables."

It should be emphasized that the choices made above to adjust (1) the S residuals so that zero S residual corresponds to zero P residual and (2) the baseline to the Kogan nuclear explosion data, are arbitrary. One could make a case for adjusting both P and S station residuals to zero for the kind of upper mantle structure found in the stable shield regions on the grounds that the upper mantle velocity distribution in such regions is likely to be less complex than elsewhere. There would then be an advantage in calculating the travel times using the same structure at the source end of the path. There are, however, other choices of a standard path for which equally strong cases can be made. Fortunately the conclusions with regard to the relation between the S and P station residuals and the velocity distribution in the lower mantle are independent of the choices made.

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References

Bolt, B. A. and O. W. Nuttli (1966). P wave residuals as a function of azimuth, 1, Observations, J. Geophys. Res. 71, 5977-5986.

Brune, J. and J. Oliver (1959). The seismic noise of the Earth's surface, Bull. Seism. Soc. Am. 49, 349-353.

Carder, D. S. (1964). Travel times from central Pacific nuclear explosions and inferred mantle structure, Bull. Seism. Soc. Am. 54, 2271-2294.

Carder, D. S., D. W. Gordon, and J. N. Jordan (1966). Analysis of surface-foci travel times, Bull. Seism. Soc. Am. 56, 815-840.

Cleary, J. and A. L. Hales (1963). Travel times of P waves in the range 30° to 100° across the United States (Abstract), Trans. Am. Geophys. U. 44, 888.

Cleary, J. and A. L. Hales (1966a). An analysis of the travel times of P waves to North American stations, in the distance range 32° to 100°, Bull. Seism. Soc. Am. 56, 467-489.

Cleary, J. and A. L. Hales (1966b). Azimuthal variation of U. S. station residuals, Nature 210, 619-620.

Freedman, H. W. (1966). A statistical discussion of Pn residuals from explosions, Bull. Seism. Soc. Am. 56, 677-695.

Herrin, E. (1966). Revision of travel times for longitudinal body waves (Abstract), Trans. Am. Geophys. U. 47, 168-169.

Husebye, E. S. (1965). Correction analysis of Jeffreys-Bullen travel time tables, Bull. Seism. Soc. Am. 55, 1023-1038.

Jeffreys, H. (1966). Revision of travel times, Geophys. J. R. A. S. 11, 5-12.

Jeffreys, H. and K. E. Bullen (1935). Times of transmission of earthquake waves, Bur. Centr. Seism. Internat. A 11, 1-96.

Jeffreys, H. and K. E. Bullen (1940, 1958). Seismological Tables, Brit. Assoc. Advancement of Sci., Gray-Milne Trust, 50 pp.

Kogan, S. D. (1960). Travel times of longitudinal and transverse waves, calculated from data on nuclear explosions made in the region of the Marshall Islands, Bull. Acad. Sci. USSR (Izvestia), Geophys. Series 3, 246-253.

Landisman, M., Y. Satô and J. Nafe (1965). Free vibrations of the Earth and the properties of its deep interior regions, Part I: Density, Geophys. J. R. A. S. 9, 439-502.

Lehmann, I. (1964). The Hindu Kush earthquake of March 4, 1949 as recorded in Europe. Bull. Seism. Soc. Am. 54, 1915-1925.

MacDonald, G. J. F. and N. F. Ness (1961). A study of the free oscillations of the Earth, J. Geophys. Res. 66, 1865-1911.

Otsuka, M. (1966). Azimuth and slowness anomalies of seismic waves measured on the Central California Seismographic Array, Part I, Observations, Bull. Seism. Soc. Am. 56, 223-240.

York, D. (1966). Least squares fitting of a straight line, Can. Jour. Phys. 44, 1079-1086.

Captions

Figure 1. S Residuals/P residuals for U. S. stations.

Figure 2. Map of S Residuals for U. S. stations.

Figure 3. Travel Time Residuals from Jeffreys-Bullen.

Figure 4. S Residuals by C-H Method versus S residuals by Grouping.

Table 1. S Station Residuals.

Table 2. Differences from J-B Times.

Table 3. Source Residuals.

Table 4. Analysis of Variance, residuals grouped by source.

Table 5. Analysis of Variance, residuals grouped by station.

Table 6. Analysis of Variance by Station, after correcting for source.

TABLE 1

S Station Residuals

Station Code	Network Code*	State or Province	No. of Observations	Station Residual (sec)	Standard error (sec)
AAM	W	Michigan	6	-2.93	1.44
ALQ	W	New Mexico	14	-0.28	1.48
BKS	W	California	11	+0.19	1.53
BLA	W	Virginia	9	-4.29	1.58
BLWV	L	West Virginia	10	-5.48	1.58
CPCL	L	California	11	+2.11	1.45
CMC	W	N.W. Territory	2	(-4.05)	(2.33)
COR	W	Oregon	8	+1.51	1.54
DAL	W	Texas	4	-2.95	1.85
DHNY	L	New York	11	-0.99	1.57
DRCO	L	Colorado	13	+1.03	1.43
DUG	W	Utah	1	(-4.40)	(2.97)
FLO	W	Missouri	7	-4.72	1.67
FMUT	L	Utah	10	+0.41	1.57
FSAZ	L	Arizona	7	+0.81	1.66
GDH	W	Greenland	5	-3.29	1.78
GEO	W	Washington, D.C.	8	-3.93	1.64
GOL	W	Colorado	12	-1.47	1.47
GSC	P	California	3	(-3.42)	(1.87)
GVTX	L	Texas	8	-1.32	1.62
HBOK	L	Oklahoma	8	-0.34	1.65
HLID	L	Idaho	14	-1.20	1.40
HNME	L	Maine	9	-2.44	1.62
KNUT	L	Utah	12	+1.85	1.52
LCNM	L	New Mexico	10	+0.59	1.58
LON	W	Washington	4	-2.58	1.73
LUB	W	Texas	9	-2.35	1.60
MDS	W	Wisconsin	4	-5.[illegible]6	1.83
MMTN	L	Tennessee	11	-4.16	1.57

TABLE 1 (continued)

Station Code	Network Code*	State or Province	No. of Observations	Station Residual (sec)	Standard error (sec)
MNN	W	Minnesota	9	-5.53	1.51
MNNV	L	Nevada	10	-1.31	1.54
MPAR	L	Arkansas	10	-2.43	1.56
MVCL	L	California	11	-1.94	1.51
OGD	W	New Jersey	1	(-4.06)	(3.14)
PLM	P	California	1	(-3.12)	(2.98)
PMWY	L	Wyoming	10	-0.93	1.55
PTOR	L	Oregon	12	-1.05	1.51
SCP	W	Pennsylvania	7	-1.61	1.68
SHA	W	Alabama	5	-1.98	1.78
SUTX	L	Texas	5	+0.14	1.79
SEMN	L	Minnesota	7	-4.84	1.64
SSTX	L	Texas	12	-1.59	1.53
TFCL	L	California	10	+0.45	1.55
TUC	W	Arizona	3	(+1.50)	(1.99)
WES	W	Massachusetts	7	-2.46	1.68
WINV	L	Nevada	8	-0.70	1.53
WNSD	L	South Dakota	10	-3.43	1.56

* Networks:

W - WWSS
L - LRSM
P - Caltech (Pasadena)

( ) brackets emphasize values with three observations or less

TABLE 2

Differences from J-B Times

Distance range (degrees)	No. of observations	Difference (seconds)	Standard error (seconds)	Difference Adjusted to Kogan Data (seconds)
28-30	6	0.75	1.60	5.25
30-32	7	1.55	1.56	6.05
32-34	8	-1.24	1.52	3.26
34-36	4	1.36	1.77	5.86
36-38	8	-1.84	1.48	2.66
38-40	7	0.15	1.56	4.65
40-42	8	-0.48	1.56	4.02
42-44	9	-1.06	1.41	3.44
44-46	16	-1.18	1.33	3.32
46-48	10	0.40	1.47	4.90
48-50	22	-0.30	1.27	4.20
50-52	15	-0.84	1.31	3.66
52-54	19	0.27	1.30	4.77
54-56	17	-0.96	1.28	3.54
56-58	18	1.13	1.28	5.63
58-60	24	-0.31	1.24	4.19
60-62	25	-0.55	1.23	3.95
62-64	14	-0.25	1.30	4.25
64-66	22	-0.43	1.20	4.07
66-68	19	-1.57	1.25	2.93
68-70	21	-1.98	1.20	2.52
70-72	13	-0.63	1.30	3.87
72-74	16	-0.44	1.24	4.06
74-76	17	1.08	1.20	5.58
76-78	14	-0.13	1.27	4.37
78-80	12	1.02	1.26	5.52
80-82	8	0.00*	0.00*	4.50

*These values were assumed zero to make the solution determinate.

TABLE 3

Source Residuals

	Source Residuals			
Earthquake Code[1]	Residual (sec)	Standard error (sec)	Region	Adjusted Residuals
W1	5.65	1.04	Near Isles	-0.35
W2	3.32	1.22	Alaska	-2.68
E1	4.49	1.10	Atlantic Ridge	-1.51
E2	1.76	1.23	Atlantic Ridge	-4.24
S2	4.87	1.04	N. Chile	-1.13
E3	2.24	1.47	Greece	-3.76
W3	6.28	1.05	Rat Isles	+0.28
S4	9.75	1.17	S. of Panama	+3.75
S5	6.44	1.05	N. Peru	+0.44
S6	13.73	0.99	Easter Isle	+7.73
W4	1.76	1.07	Fox Isles	-4.24
W6	-0.58	1.00	Komandorskie Isles	-6.58
S7	4.15	0.96	N. Chile	-1.85
S8	4.55	1.22	Central Chile	-1.45
W8	3.80	1.17	Honshu, Japan	-2.20
W9	4.84	1.05	Kamchatka	-1.16
E5	-4.8[illegible][3]	2.11	Georgia, USSR	-10.83
E6	12.13	1.41	Turkey	+6.13
W10	5.10[4]	1.89	Kyushu, Japan	-0.90
W11	0.00[2]	0.00	Kurile Isles	-6.00

1 Networks:

W - WWSS
L - LRSM
P - Caltech (Pasadena)

2 These values assumed zero to make the solution determinate

3 Only two stations in the appropriate distance range for this earthquake.

4 Only three stations available.

TABLE 4

Analysis of Variance, residuals grouped by source

	Sum of Squares of Deviation	Mean Square Deviation	Degrees of Freedom
Variance Among Source Means	4674.9566	246.0503	19
Variance About Source Means	3381.3744	9.4189	359
Totals	8056.3310		378
From Observations, z=1.6314; From Tables, z(1%)=0.3334, z(0.1%)=0.4341			

TABLE 5

Analysis of Variance, residuals grouped by station or distance

	Sum of Squares of Deviation	Mean Square Deviation	Degrees of Freedom
Variance Among Station Means	1567.4818	34.0757	46
Variance About Station Means	6488.8493	19.5447	332
Totals	8056.3311		378
From Observations, z=0.2779; From Tables, z(1%)=0.2379 z(0.1%)=0.3123			
Variance Among Distance Means	541.0026	20 8078	26
Variance About Distance Means	7515.3284	21.3504	352
Totals	8056.3310		378
From Observations, z=0.0129; From Tables, z(1%)=0.3832, z(0.1%)=0.5226			

TABLE 6

Analysis of Variance by Station, after correcting for source

	Sum of Squares of Deviation	Mean Square Deviation	Degrees of Freedom
Variance Between Stations	1333.1782	28.9821	46
Variance About Means	2048.1962	6.1693	332
Totals	3381.3744		378
From Observations, $z=0.7735$; From Tables, $z(1\%)=0.2379$, $z(0.1\%)=0.3123$			

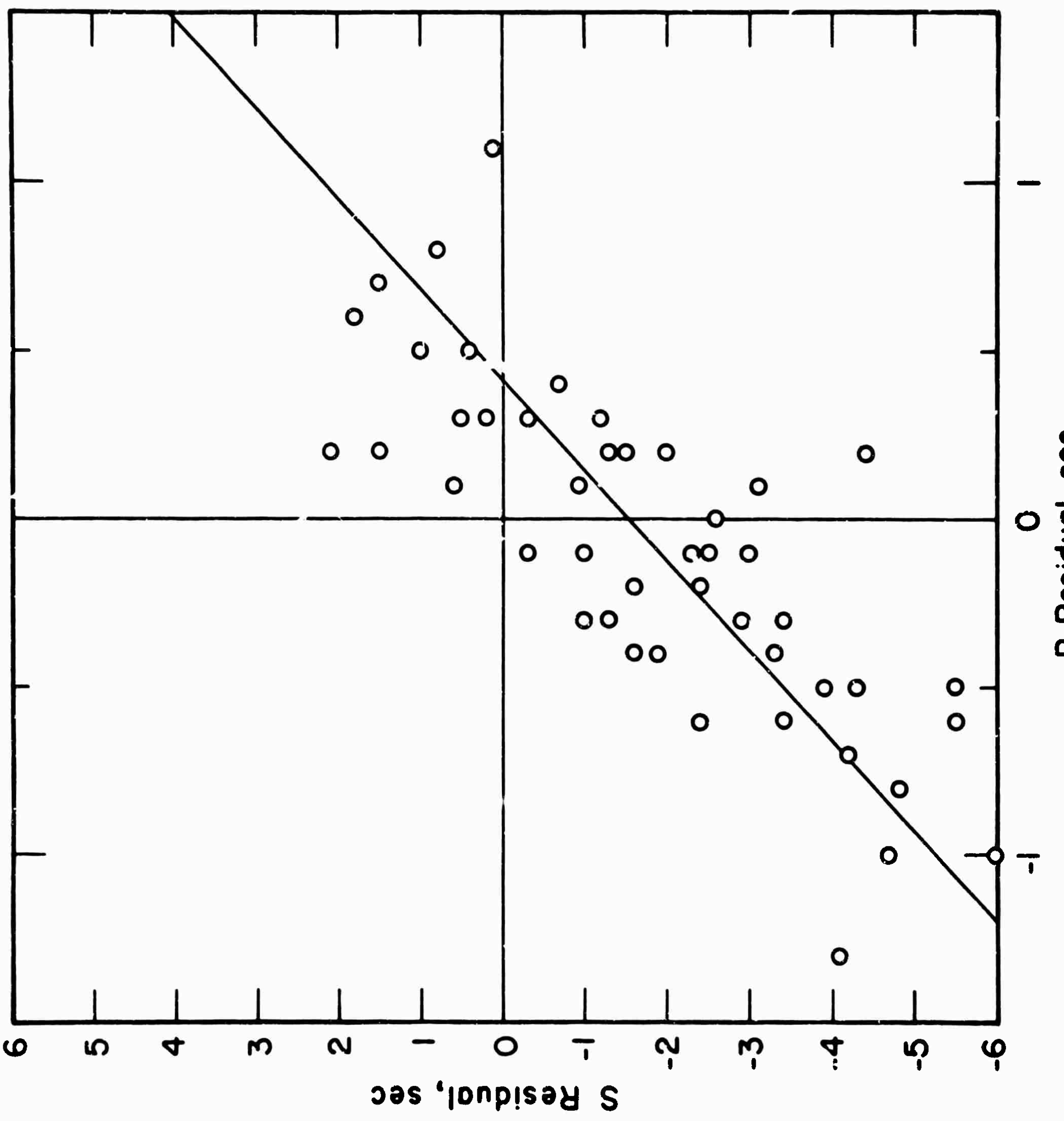

Figure 1

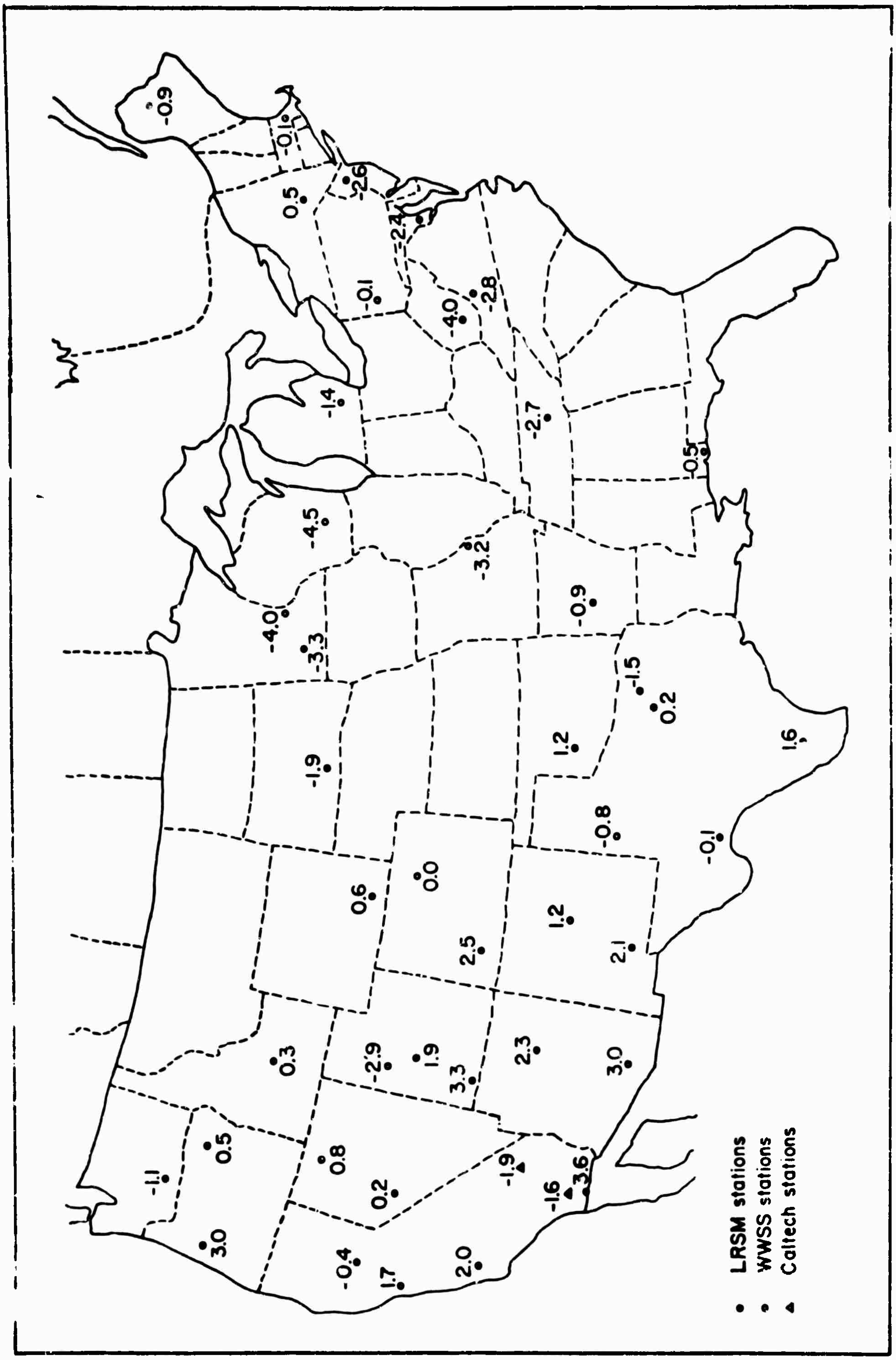

Figure 2

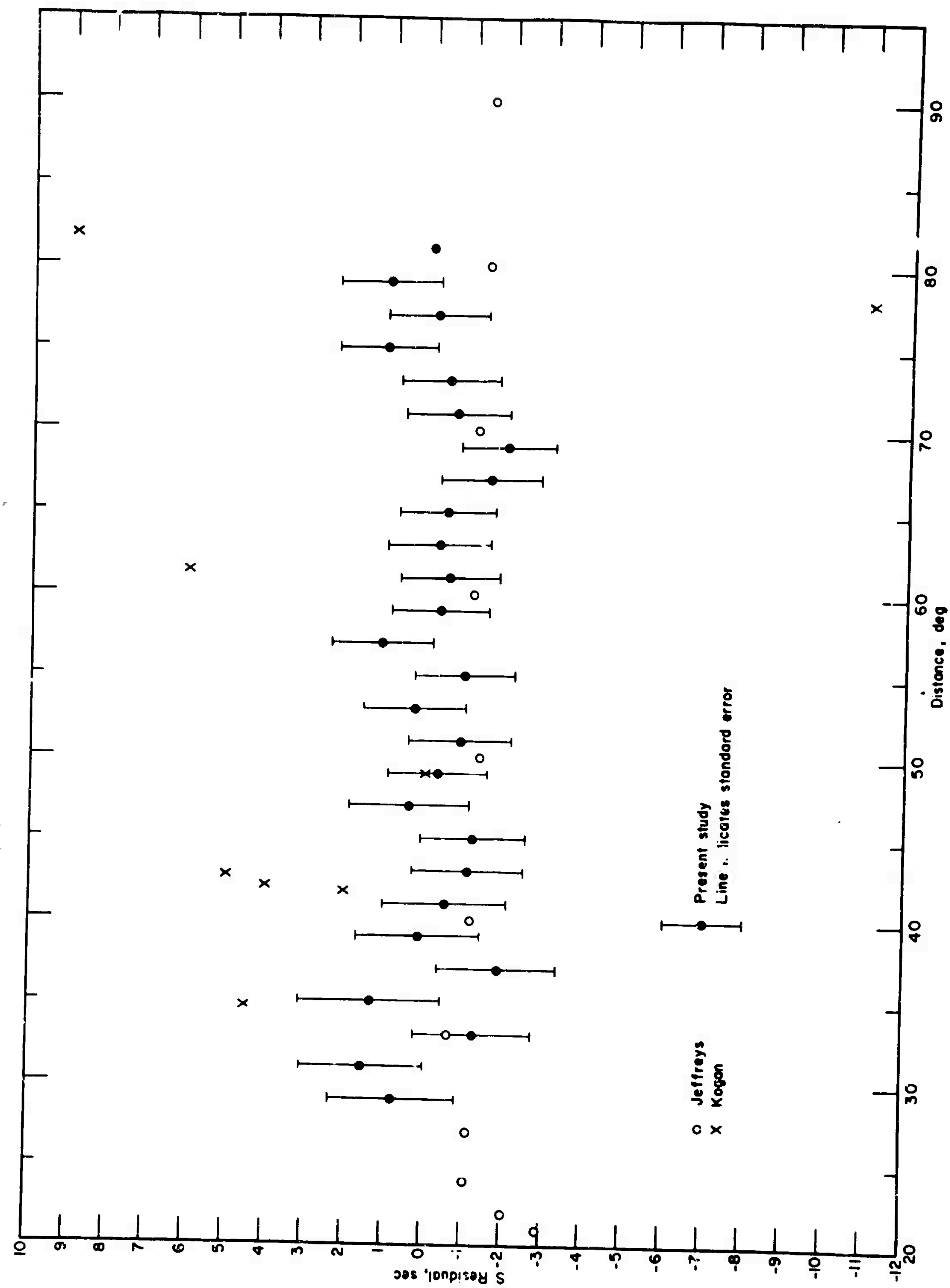
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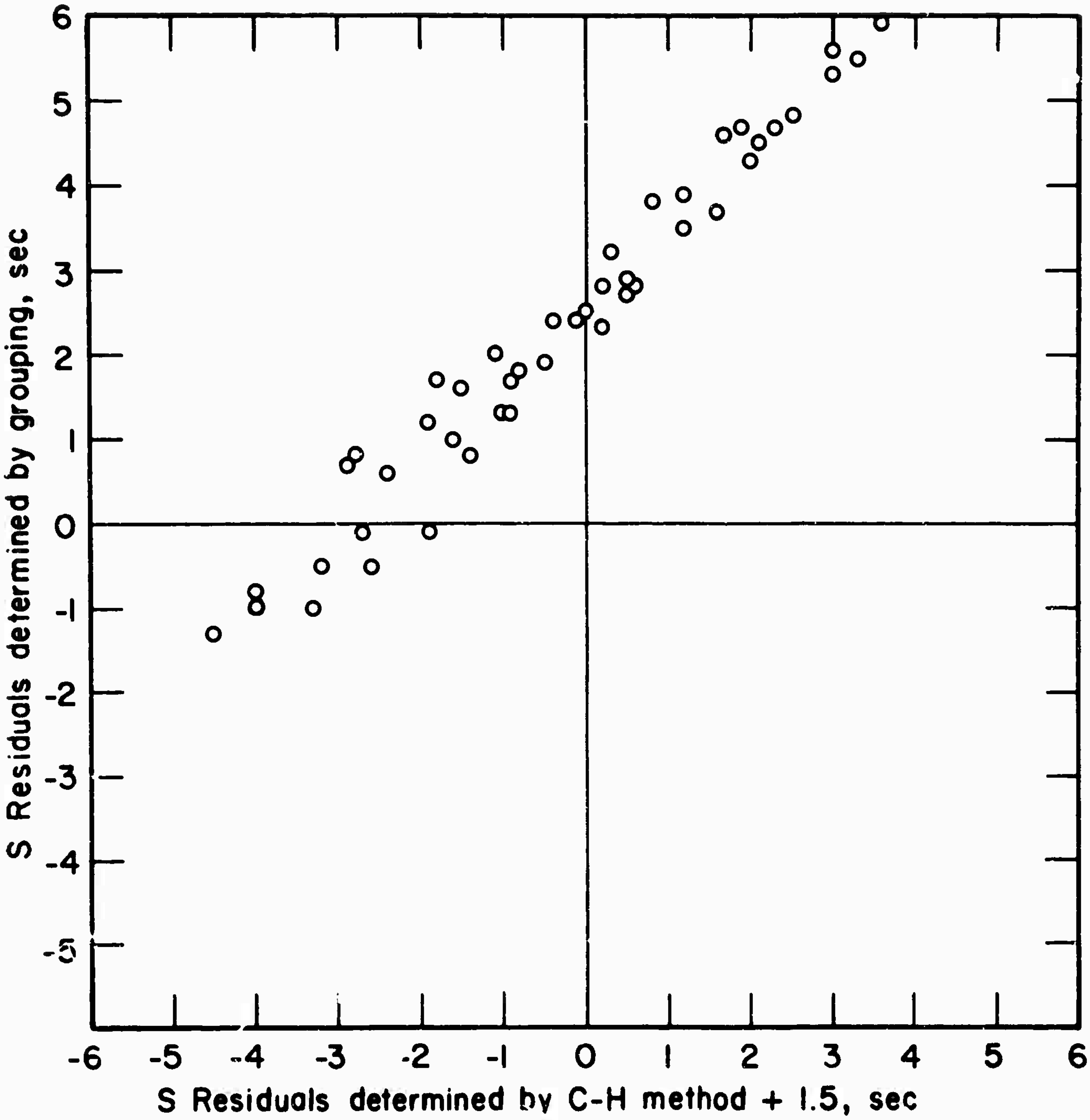
Figure 3



S Residuals determined by grouping, sec
S Residuals determined by C-H method + 1.5, sec

Figure 4

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13. ABSTRACT

The travel times of S waves from 20 earthquakes to stations in North America in the distance range 28° to 82° have been studied. The deviations from J-B times were analyzed into station, source and distance components using the least-squares time-term approach of Cleary and Hales. Station anomalies had a range of about eight seconds, as compared to three seconds for the P anomalies, and are believed to be caused largely by variations in the upper mantle velocity distribution. S residuals, like the P residuals, were generally positive in the western United States, and negative in the central and eastern United States. P and S residuals at the same station correlated with a coefficient of 0.75, the slope of the regression of S anomaly on P anomaly being 3.72. Corrections to J-B times for S were of the order of the standard errors of the determinations. Within the distance range of 28° to 82° large changes of the S velocities, such as were suggested by MacDonald and Ness (1961), are not permitted by the present data. The analysis was checked by carrying out a univariate analysis of variance of the same data.

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