UNIVERSITY OF PITTSBURGH

DEPARTMENT OF EARTH AND PLANETARY SCIENCES

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SEMI-ANNUAL TECHNICAL REPORT

TECTONIC FEATURES OF THE EARTH'S CRUST AND UPPER MANTLE

20 DEC 1966

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20 December 1966

W. L. Pilant

INTRODUCTION

This report describes a continuation of the research on the velocity of propagation of surface waves across the North American continent. Preliminary work was given in the first Semi-Annual Technical Report and since that time four additional seismic events have been analyzed at all available North American stations. A map has been constructed showing projected phase velocities across the United States (additional values are given for the Canadian Shield in the summary table). These values in general agree well with individual area phase velocity studies and with the U. S. study by Ewing and Press (1959).

DATA CHOSEN FOR ANALYSIS

Data from some twenty events has been digitized (a total of 365 individual seismograms) so that as complete as possible an azimuthal coverage of North America might be obtained. Records from events at Hegben Lake, Montana, and Oaxaca, Mexico, were chosen for a phase velocity analysis of higher modes as they cross the continent. The remainder of the records were chosen with regard to the cleanness of the amplitude modulation of the surface wave train, in order that the deduced phase velocities would be as free as possible from the contamination of "beats" or wave interferences. An analysis of the data obtained from one of the more well recorded events will be given later in the report. For some azimuths, however, it was not possible to pick waveforms that were of a superior nature and in these cases, the best possible waveforms were chosen for analysis. Table I lists those events that have been digitized to date.

ANALYSIS OF PHASE DATA

After digitization, the data were then subjected to a harmonic analysis using the new algorithm proposed by Cooley and Tukey (1965). This allowed the direct calculation of the phase integers (up to an additive constant which is the same for all frequencies) as a function of frequency inasmuch as one is now able to make frequency estimates so closely spaced as to remove the ambiguity of phase at points of rapid phase change with frequency. In the past, a closely spaced analysis was prohibitively expensive in computer time and extrapolation methods for rather widely spaced data were sometimes inaccurate.

The event of 24 October 1964 (off the Oregon coast) was chosen to illustrate the inherent noise in data as obtained from an event especially chosen so as to have the least noise and other contamination. To evaluate this noise, or phase scatter, the raw phase values given by the harmonic analysis program were fitted by a weighted least squares third order polynomial going through 11 points at approximately one millicycle intervals. The difference between the raw phase value and a smoothed value was then calculated at each frequency. For each recording of this particular event, the average phase deviation was computed for the range, 20 to 60 millicycles or for a period range of 50 to 17 seconds, and plotted in Fig. 1. The lowest average phase deviation was 0.004 circles and the highest value was 0.068 circles. (One circle equals 360° or 2 pi radians.) As a general rule the phase scatter increased with distance as one would expect for a signal that is degraded with distance. However, in a region to the southeast of the epicenter (see Fig. 1), the value of scatter recorded at ALQ was 0.051. The scatter in the recording at LUB was so large as to make the data unusable and the scatter at SHA was 0.033. Although it was not feasible to show wave front diagrams on this figure also, these high values of phase scatter were associated with a diffraction of the Rayleigh waves by the southern Rocky Mountain system. It turned out that in the other events analysed, this same mountainous region gave similar diffraction effects, retarding the wave fronts considerably and leading to a much poorer quality recording on the shadow side of this zone.

If one wants a phase velocity accuracy of one percent, then the maximum phase error allowable is

$$\text{Max. Phase Error} \quad \frac{0.01 * \text{Distance (km)}}{\text{Phase Velocity} * \text{Period (sec)}}$$

In the case of a path length of 1000 km, a period of 50 seconds and a nominal phase velocity of 4.0 km/sec, the maximum phase error allowable is 0.05. If the path length is shortened by a factor of ten, to 100 km, then the maximum allowable phase error is on the order of 0.005. It can be seen that this low value of phase error is obtainable only in the vicinity of the epicenter. At large distances, or where diffraction is present, one has to use longer propagation distances to get phase velocity data with an expected error of only one percent. In this case, however, one comes up with a phase velocity which represents an average velocity for the crustal path considered and loses resolution.

At the same time that the phase data is smoothed by the polynomial fitting, a local slope is determined that is related to a group delay time from the beginning of the record by the following:

Group Delay Time = d(Phase) / d(Frequency).

In the case of our data, an error of 0.01 circles change in phase over a frequency interval of 10 millicycles leads to an error of one second in the group delay time. It is apparent from an analysis of group delay times calculated in this manner that there are systematic variations in the group delay time (and hence inferred variations in the slope of the phase curve) that are greater than this value. This means also that there may be systematic errors in phase not apparent in the phase scatter data give by Fig. 1. Up to now the calculation of a meaningful group velocity has been only possible on certain selected records and we are in the process of developing techniques for obtaining better group velocity determinations over selected regions of the North American continent.

PHASE TIME RESIDUALS

After the smoothed phase data are calculated, these are then converted into phase time residuals relative to an arbitrary phase time assigned at a given station and to a propagation velocity of 4.0 km/sec. (See Technical Report dated 20 May 1966, page 3 and figs 1-5.) In this report, we have chosen the event of 14 September 1964 (Chiapas, Mexico) as an illustration. Preliminary phase time residuals are plotted by contour lines of 10 seconds difference in Figs. 2-6. The delaying effect of the Rocky Mountain system can clearly be seen here just as in Figs. 1-5 of the Semi-Annual Technical Report dated 20 May 1966. We note in Figs. 2-6 that there is an apparent rotation of the lines of constant phase time residual, with the long period residuals being generally parallel to the great circle epicentral paths. This means that if two stations are at slightly different azimuths, there can be much larger time differences between stations at the same epicentral distance than if the contours were more or less perpendicular to the great circle paths. It also indicates that diffraction effects are present, inasmuch as some portions of the wave front are advanced by as much as 20 seconds relative to nearby (within 10°) portions of the wave front. This would correspond to some 80 km, but at a distance of 2500 km this does not show enough on a plot. The phase time residuals magnify this effect. These diffraction effects do not seem to degrade the wave form to a large degree except in the shadow zone of the Southern Rocky Mountain area. However, the advances and retardations do significantly effect the apparent phase velocities computed from the individual station time differences.

In addition to the difficulties presented in phase velocity determination, this particular illustration shows the relatively increased phase velocity as Rayleigh waves traverse the region from the western Gulf of Mexico to the eastern Gulf. This increase is present at all periods, although it is more pronounced as the shorter periods. This is in agreement with results obtained earlier by Papazachos (1964) wherein he investigated a number of earthquakes from the Central American region and recorded in the vicinity of the station FLO with varying propagation vectors.

PHASE VELOCITY ANALYSIS

From the earthquakes listed in Table I, five were selected for analysis to give a rough azimuthal coverage of the North American continent. These were:

14 Sep 1964, off Chiapas, Mex.
28 Sep 1964, Central Mid-Atlantic Ridge
11 Oct 1964, off Hawaii
21 Oct 1964, Hegben Lake
24 Oct 1964, off Oregon Coast

From each of these events, projected phase velocities were calculated where the phase time residual contours indicated that meaningful phase velocities might be obtained. The projected phase velocity is calculated by computing the difference in epicentral distances between two stations and dividing by the time difference between two stations for a particular phase. This would give the true phase velocity if both stations are on an epicentral great circle path, or if the phase time residual contours were rigorously perpendicular to the great circle paths. Projected phase velocities were calculated along paths that differed as little as possible from the great circle path, and where the contours were sufficiently near to the ideal. This necessitated throwing out a considerable number of velocities at the start. Even after this rather arbitrary selection of phase velocities to be included in the end analysis, several rather strange values remained. These are indicated in Figs. 7-11 by question marks following the calculated value.

Figs. 7-11 show the projected phase velocities between a large number of station pairs together with a small arrow indicating the direction of propagation along the indicated path. It will be noted that paths, particularly in the north-south direction, in the Rocky Mountain region are sparce. This was because the contours indicated that the data was considerably in error.

The North American continent was divided up into several regions and average projected phase velocities as a function of period are given in Table II. Values of phase velocity followed by question marks were not used in the analysis. Paths for the region including the Canadian Shield and Greenland are not shown inasmuch as there were only a few paths and to include them on the map would have reduced its scale prohibitively. Critical paths were unavailable from the five selected earthquakes to give a determination of phase velocities along the core of the Appalachian mountains, the core of the Sierra Nevada, and along the Canadian Rockies from Bozeman, Montana, to College, Alaska. It may be that suitable earthquakes to delineate these rather long, narrow regions will not be found among those earthquakes chosen for their smooth envelopes, inasmuch as diffraction is expected to be rather large in a wave travelling along the axis of such structures. A discussion of each of the regions follows.

Northwest U.S. This includes the area between stations COR, LON, and BOZ. This is a rather heterogeneous region including the Cascade Range, the Columbia Plateau, the Idaho batholith, and some of the Northern Rockies. Phase velocities are somewhat higher here than in the Basin and Range region to the south, and somewhat lower than in the Northern Rocky Mountain region to the east. Phase velocities as given for the period range 33 1/3 to 20 seconds are approximately 0.07 km/sec lower than those given by Ewing and Press (1959) for this region. This confirms the result given in the previous report for the Mid-Atlantic earthquake alone.

Basin and Range Phase velocities for this region are the lowest for the continent at all periods, but are hardly distinguishable from velocities calculated for the Southwest Plateaus. This region included paths between COR, DUG, and BKS. No data was available for the path from GSC to DUG. Phase velocities are approximately 0.04 km/sec higher than Ewing and Press.

Southwest Plateaus Includes paths between GSC, TUC, and ALQ. Values for the path between ALQ and LUB were similar, but not included in any average. Values for this region are 0.05 km/sec higher than those given by Ewing and Press for roughly the same area but extending to LUB. However, they agree with Ewing and Press' values for the Southern California-Arizona deserts. On a rather gross average the Basin and Range region is not distinguishable from the Southwest Plateaus.

Northern Rocky Mountains Includes the region between BOZ, RCD, GOL, and DUG. The average values for this region may be a bit high, inasmuch as the path between BOZ and RCD yielded very high results. Values here are approximately 0.09 km/sec higher than those for the Southern Rocky Mountains and 0.12 km/sec higher than in the Basin and Range region to the West. These values are considerably above those of Ewing and Press, with the greatest difference at 20 sec period where the present data is 0.15 km/sec above theirs. Agreement is better at 33 1/3 sec.

Southern Rocky Mountains Includes area between DUG, GOL, and ALQ. Here results were few, much data had to be discarded, and yet many high values remained to be included in the average. No comparable region was covered by Ewing and Press, although these results are much closer to an extrapolation of their data (for the Northern Rockies) to longer periods. It is to be noted that data at 20 and 25 seconds was not reliable in this region due to diffraction and distortion mentioned previously.

Canadian Shield and Greenland This area is not shown on the map, but is comparable to the area investigated by Brune and Dorman (1963). Values for 50 sec and 40 sec are within 0.01 km/sec of their values, and diverge to 0.06 km/sec low at 20 seconds period.

Northern Great Plains Paths between RCD, MNN, GOL, and FLO. At long periods phase velocities are similar to those for the Canadian Shield, and drop 0.10 km/sec below these values for 20 seconds period. Fair agreement with the data of Ewing and Press.

Southern Great Plains Paths between GOL, FLO, ALQ, LUB, and DAL. Phase velocities are lower at long periods, but merge with those of the Northern Great Plains at short periods. Good agreement with Ewing and Press.

Northeast U.S. Paths between MNN, AAM, WES, OGD, SCP, GEO, and FLO. Values over the period range 33 1/3 to 20 seconds 0.05 km/sec higher than Ewing and Press.

Southeast U.S. Paths between FLO, DAL, GEO, BLA, OXF, and ATL. Values at long periods are 0.05 km/sec above those in the Northeast U.S., again merging at short periods. Data at short periods are 0.03 km/sec above thore given by Ewing and Press.

Continental Margin Values given for comparison with Eastern U.S.

SUMMARY

The greatest differences between the values obtained for this report and those given by Ewing and Press are in the regions of the west, where it is obvious from the phase time residual charts that there is a greater expectation of erroneous values. The data gathered here is insufficient, especially at the short period range to present a definite phase velocity contour map of the North American continent. However it is hoped that by the inclusion of many more events, one can give such a picture. This analysis will be undertaken in the next period of investigation.

One trend definitely does appear from the analysis. This is that there is a definite merging of the phase velocity values as one goes from 50 seconds period to 20 seconds period. It is particularly apparent and also believable due to the higher quality of the raw data in that part of the United States east of the Rocky Mountains. It is also true if one includes the rather more unreliable data from the Western U.S. For all continental area (excluding the continental margin values) we find the spread to be at 50 sec, 0.35 km/sec; 40 sec, 0.31; 33 1/3 sec, 0.29; 25 sec, 0.23; and at 20 sec, 0.18. If one deletes the Canadian Shield values from the data (and hence eliminating the high velocities at short periods due to a lack of sedimentary cover), the convergence is even greater. This convergence is even apparent on the phase time residual charts where the contour spacing becomes much more smooth as one looks at shorter periods. (See Figs. 2-7 this report, and Figs. 1-5, Report dated 20 May 1966.)

The 40 sec and 50 sec data are largely dependent upon the parameters of the top layer of the upper mantle and to a lesser extent upon the low velocity channel beneath this layer when one considers the partial derivitives of phase velocity with respect to layer parameters as given by Brune and Dorman (1963). Hence, if the data is reliable there seems to be a lateral inhomogeneity of greater magnitude beneath the Moho than above it. The percentage variation however, is comparable to the percentage change in P_n velocity, which ranges from an average low of 7.6 to an average high of 8.3 in the U.S.

The shorter period data of 25 and 20 seconds are on the other hand, strongly influenced by a combination of crustal and upper mantle properties. Despite large local variations in crustal velocities, the regions considered here have paths which are relatively long and consequently give average values. The interrelationship between crustal and upper mantle velocities that give this small variation in the short period range is unknown at present, but it is certain that it must be a complex one. For example, the simple model originally considered by Ewing and Press attributing the total change in phase velocity to a change in crustal thickness, gives exactly the opposite results as a function of period.

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Brune, J., and J. Dorman, Seismic waves and earth structure in the Canadian Shield, Bull. Seis. Soc. Amer., 53, 167-210, 1963.

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Ewing, M., and F. Press, Determination of crustal structure from phase velocity of Rayleigh waves, Part III: The United States, Bull. Geol. Soc. Amer., 70, 229-244, 1959.

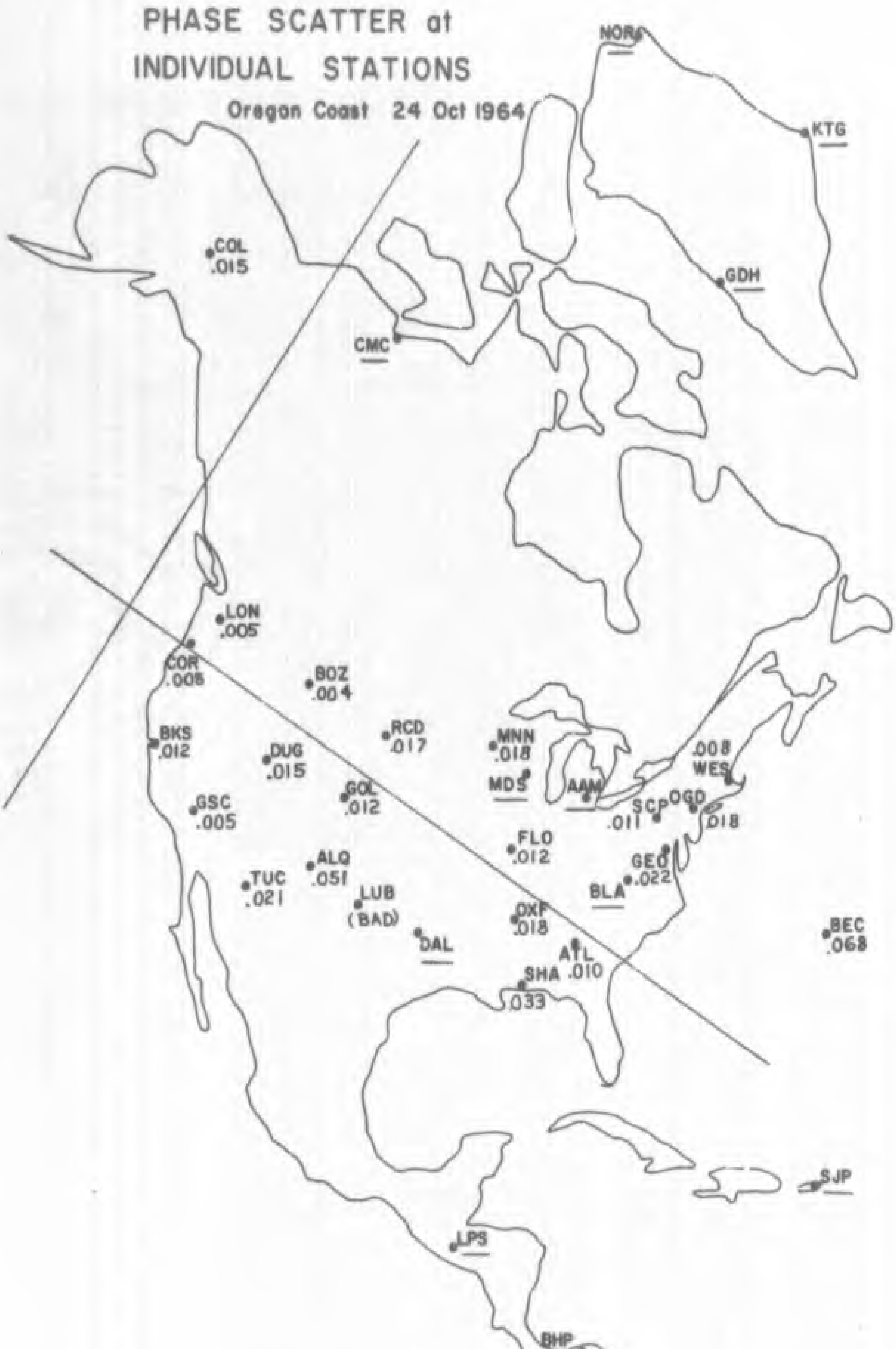
Papazachos, Basil, Dispersion of Rayleigh waves in the Gulf of Mexico and Caribbean Sea, Bull. Seis. Soc. Amer., 54, 909-925, 1964.

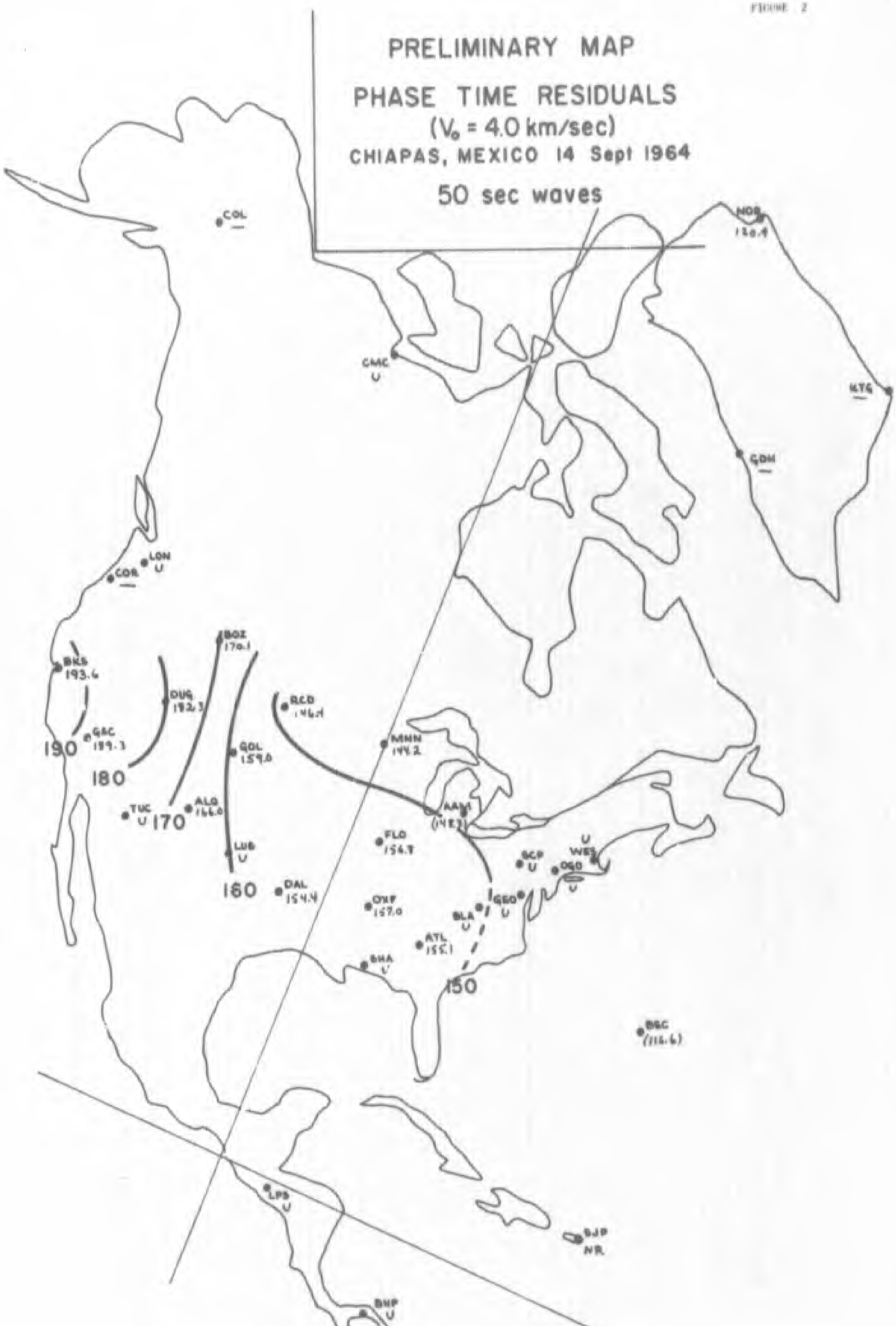
TABLE I

Date 1964	Origin Time G.C.T.	Lat.	Long.	Focal Depth	Mag GGS	Region
23 July	22:46:34.0	14.1N	96.1E	14 Km	5.6	Andaman Is. Region
4 Aug	17:24:29.2	46.5N	141.1E	101	5.9	Kurile Is.
7 Aug	15:31:13.0	14.0N	91.9W	89	5.0	Guatemala
22 Aug	03:03:20.7	31.5N	114.3W	15	5.3	Gulf of California
4 Sept	03:28:33.1	7.6N	36.9W	22	5.4	Central Mid-Atlantic Ridge
5 Sept	12:27:22.2	0.6N	25.9W	33	4.7	Central Mid-Atlantic Ridge
6 Sept	18:55:47.4	38.3N	26.6W	33	4.9	NW of Azores Is.
17 Sept	15:02:00.9	44.5N	31.3W	24	5.6	N. Atlantic Ridge
14 Sept	13:33:33.7	15.0N	93.2W	64	4.9	Near coast of Chiapas, Mex.
16 Sept	22:23:36.3	22.9N	45.1W	33	5.4	North Mid-Atlantic Ridge
18 Sept	13:12:42.3	39.8N	29.7W	20	5.5	Azores Is.
19 Sept	05:08:15.1	15.3N	94.0W	42	5.3	Near coast of Oaxaca, Mex.
28 Sept	05:04:55.5	1.2S	24.1W	37	5.5	Central Mid-Atlantic Ridge
1 Oct	18:30:01.9	49.3N	128.8W	9	5.3	Vancouver Is.
3 Oct	13:39:39.9	61.4N	147.1W	48	5.2	South Alaska
11 Oct	10:06:44.9	19.1N	156.6W	33	5.3	Off Hawaii
17 Oct	14:48:10.9	26.7N	44.6W	33	4.9	North Mid-Atlantic Ridge
18 Oct	10:45:15.5	12.2N	89.3W	33	4.7	Off coast of Central America
21 Oct	07:38:31.0	44.8N	111.6W	33	5.3	Hegben Lake
24 Oct	06:37:46.0	44.5N	129.5W	33	4.7	Off Oregon coast

TABLE II

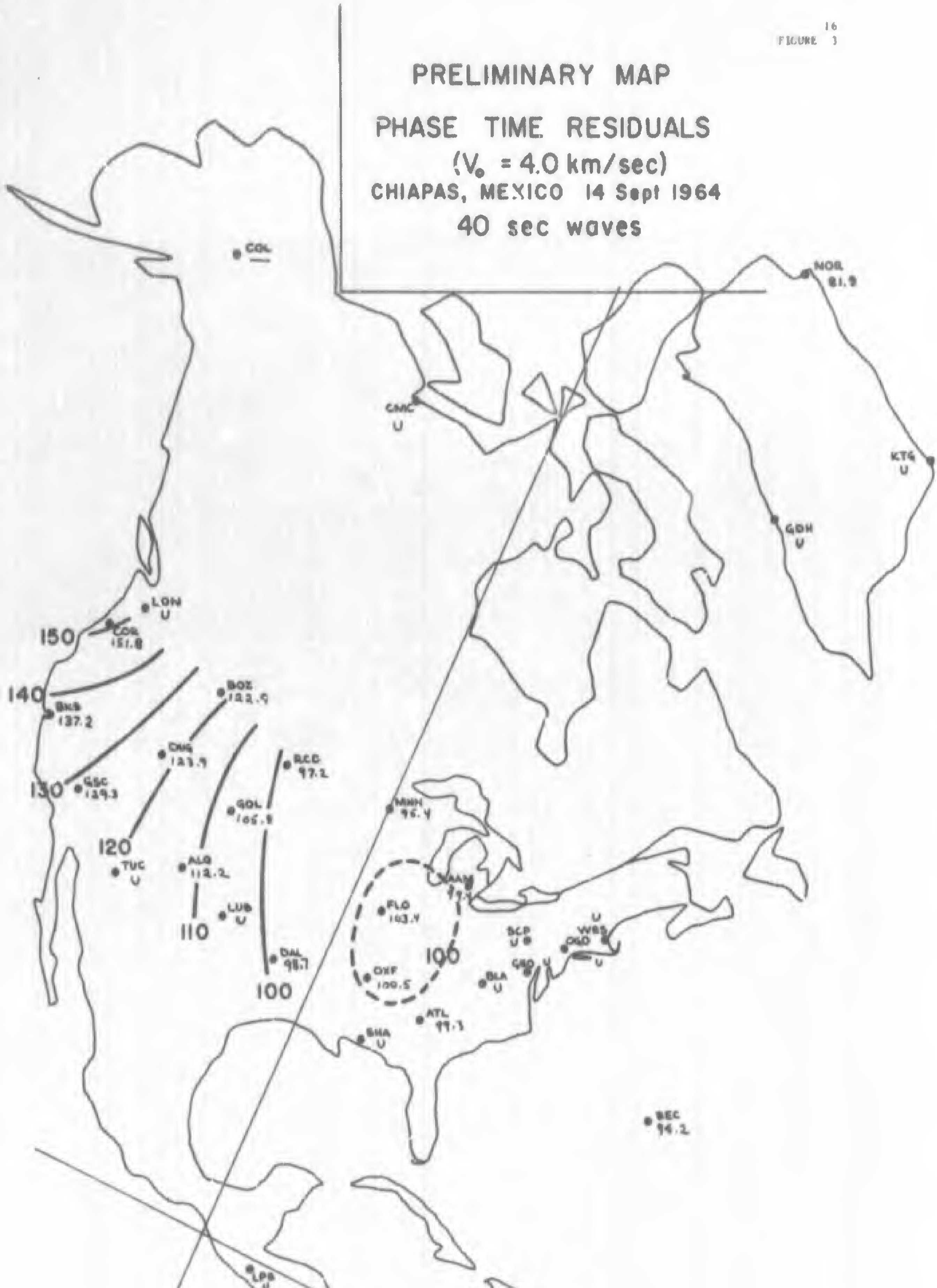
Location	Period......50 sec	40 sec	33 1/3 sec	25 sec	20 sec
	Projected Phase Velocity (km/sec)				
Northwest United States	3.83	3.79	3.72	3.59	3.46
Basin and Range Province	3.77	3.74	3.68	3.57	3.45
Southwest Plateaus	3.76	3.76	3.70	3.57	3.43
Northern Rocky Mountains	3.98	3.87	3.79	3.67	3.52
Southern Rocky Mountains	3.85	3.84	3.69	--	--
Canadian Shield and Greenland	4.11	4.05	3.97	3.80	3.61
Northern Great Plains	4.10	4.01	3.93	3.69	3.51
Southern Great Plains	4.02	3.93	3.86	3.67	3.50
Northeast United States	4.05	3.97	3.89	3.72	3.53
Southeast United States	4.10	4.01	3.89	3.71	3.55
Continental Margin	4.13	4.06	4.04	3.97	3.86


PHASE SCATTER at
INDIVIDUAL STATIONS
Oregon Coast 24 Oct 1964
NOR
KTG
COL .015
GDH
CMC
LON .005
COR .008
BOZ .004
RCD .017
MNN .018
BKS .012
DUG .015
MDS
AAM
.008 WES
GOL .012
GSC .005
SCP
OGD
.011
.018
FLO .012
ALQ .051
GEO .022
TUC .021
LUB (BAD)
BLA
OXF .018
BEC .068
DAL
ATL .010
SHA
.033
SJP
LPS
BHP



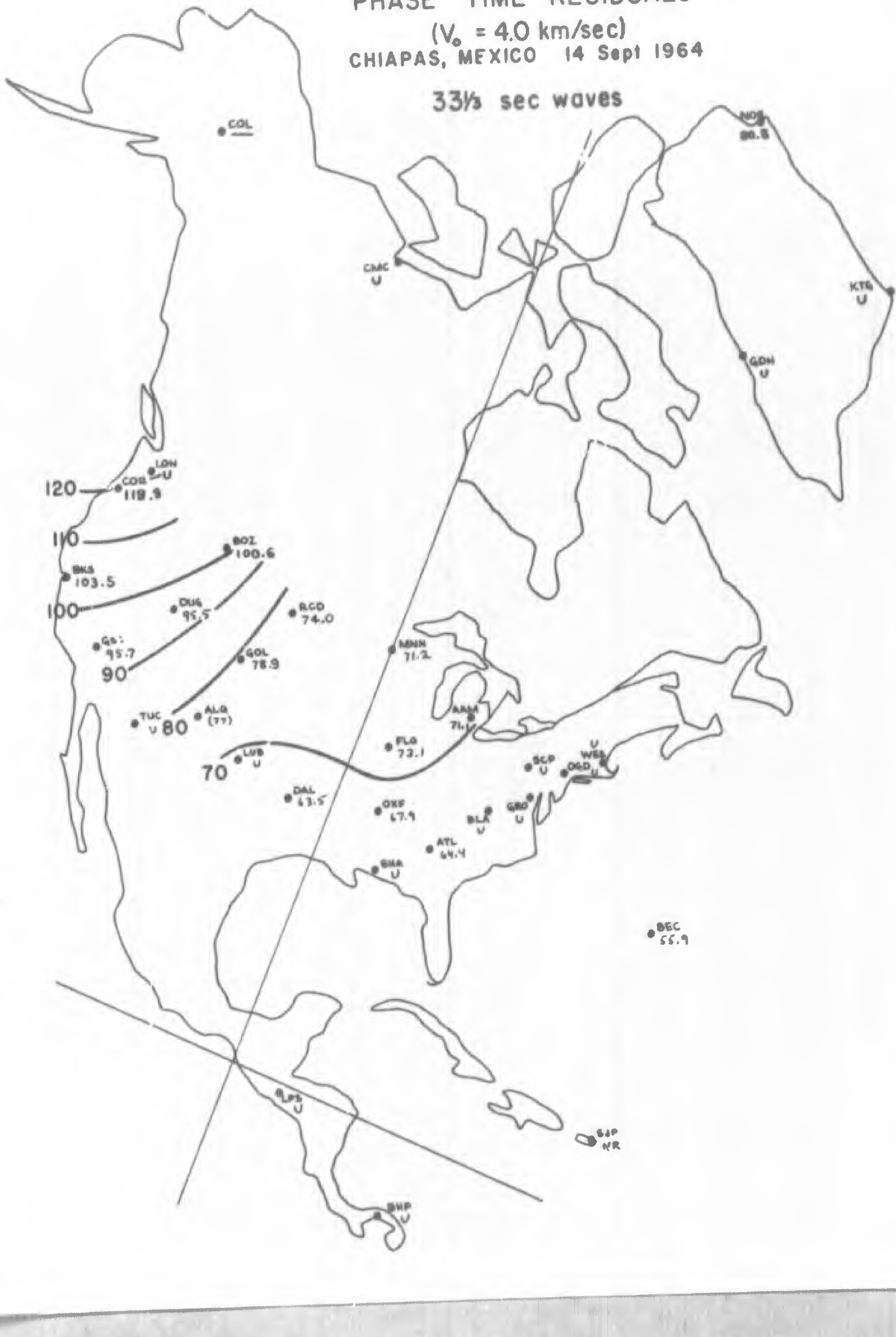
PRELIMINARY MAP
PHASE TIME RESIDUALS
(V_o = 4.0 km/sec)
CHIAPAS, MEXICO 14 Sept 1964
50 sec waves

FIGURE 3


PRELIMINARY MAP
PHASE TIME RESIDUALS
(V_0 = 4.0 km/sec)
CHIAPAS, MEXICO 14 Sept 1964
40 sec waves
COL
NOR 81.9
CMC U
KTG U
GDH U
LON U
COR 151.8
150
140
BKS 137.2
BOZ 122.9
130
GSC 129.3
CNG 123.9
RCD 97.2
MNH 96.4
GOL 105.9
120
TUC U
ALQ 112.2
FLO 103.4
LUB U
110
SCP U
WES
OXF 100.5
100
DAL 95.7
BLA U
ATL 99.3
SHA U
BEC 94.2
LPS U
SJP NR
CHP U

PRELIMINARY MAP
PHASE TIME RESIDUALS
(V_0 = 4.0 km/sec)
CHIAPAS, MEXICO 14 Sept 1964

33⅓ sec waves



PRELIMINARY MAP

PHASE TIME RESIDUALS

(V_0 = 4.0 km/sec)

CHIAPAS, MEXICO 14 Sept 1964

25 sec waves

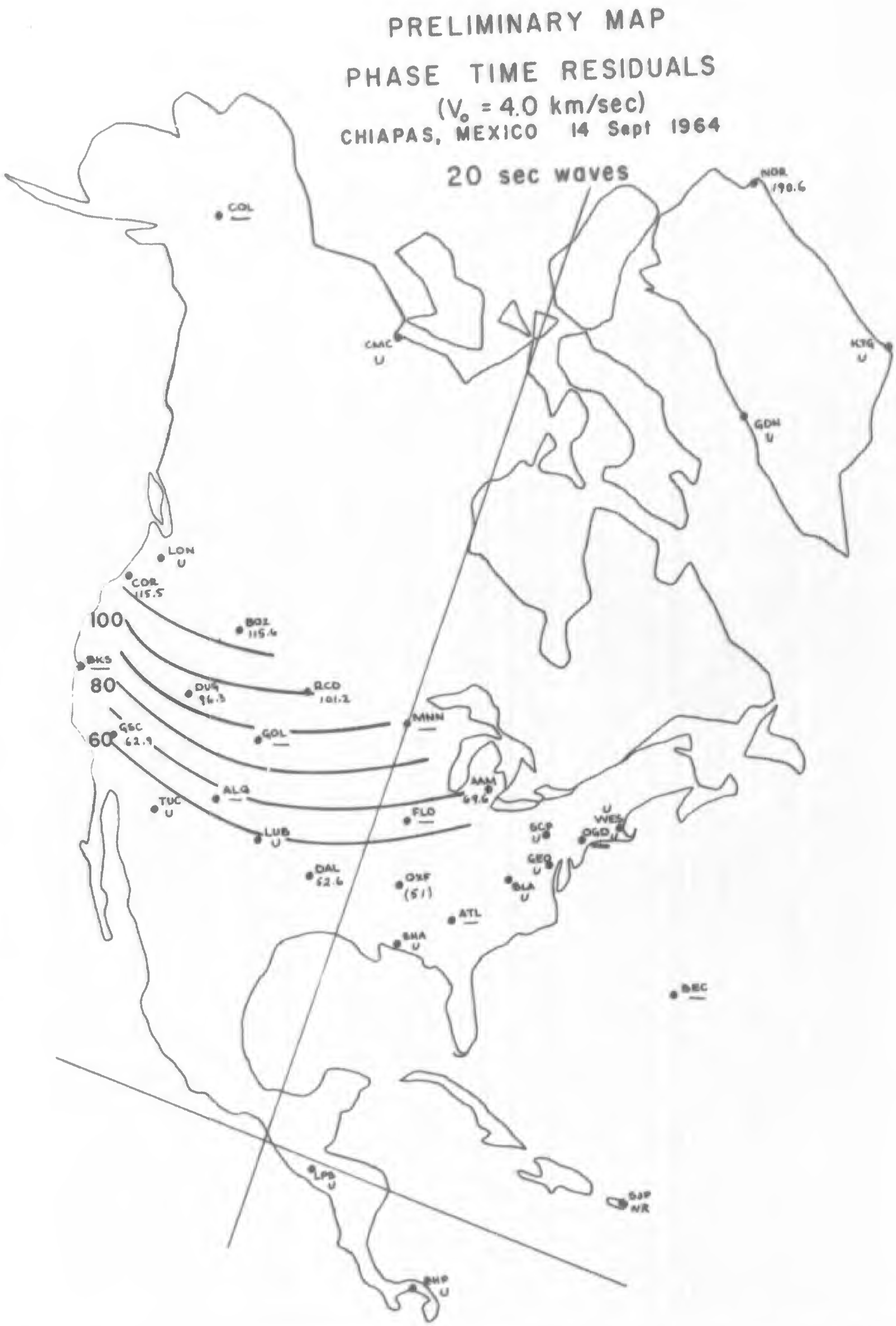

PRELIMINARY MAP
PHASE TIME RESIDUALS
(V_o = 4.0 km/sec)
CHIAPAS, MEXICO 14 Sept 1964
20 sec waves
COL
NOR 190.6
CMC U
KTG U
GDH U
LON U
COR 115.5
BOZ 115.4
100
BKS
80
DUG 96.3
RCD 101.2
MNN
GOL
60
GSC 62.9
ALQ
AAM 69.6
TUC U
FLO
LUB U
SCP U
WES U
OGD
GEO U
DAL 62.6
OXF (51)
BLA U
ATL
SHA U
BEC
LPB U
SJP NR
BHP U

Figure 7

PROJECTED PHASE VELOCITIES
50 sec waves

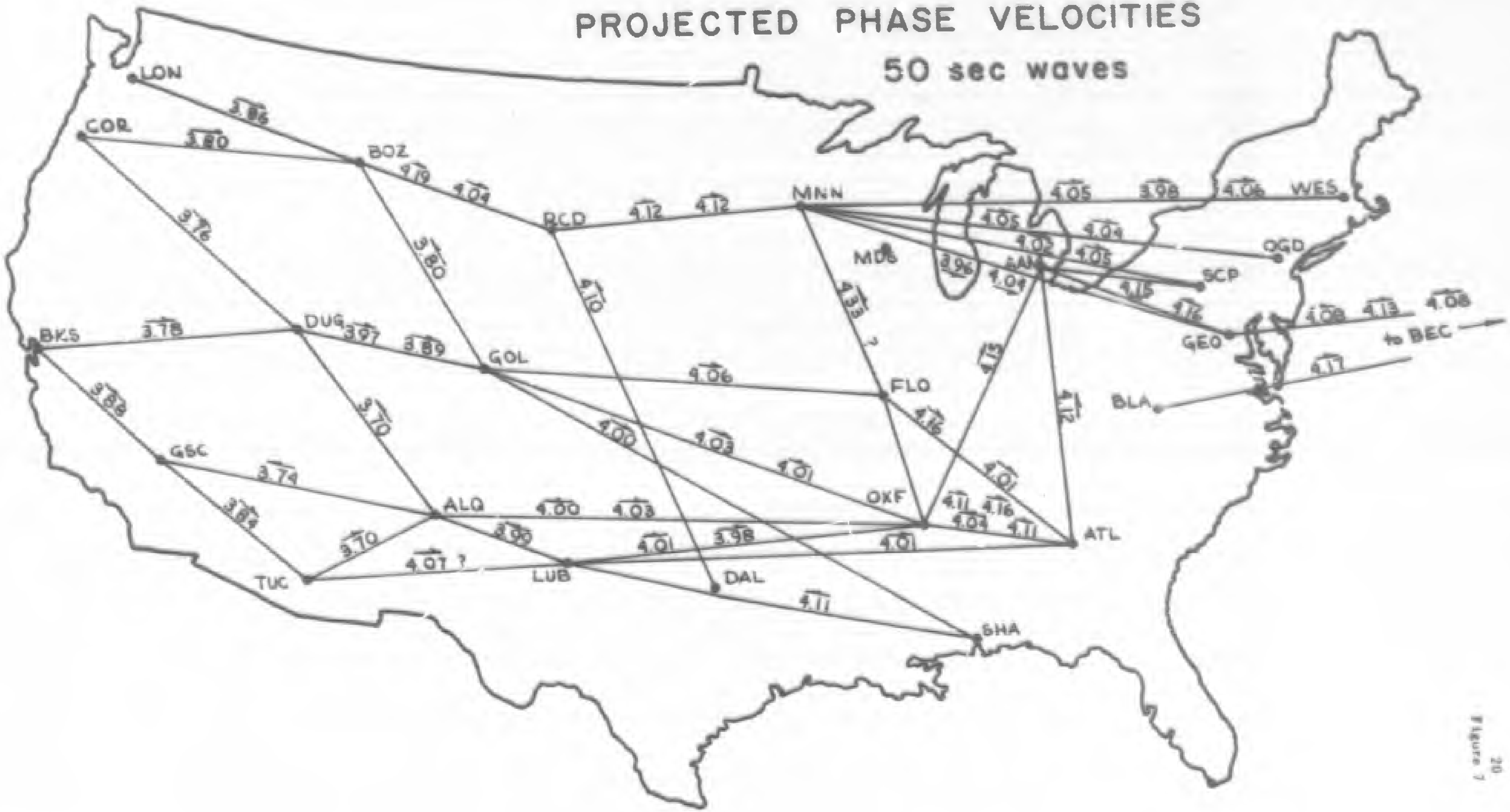
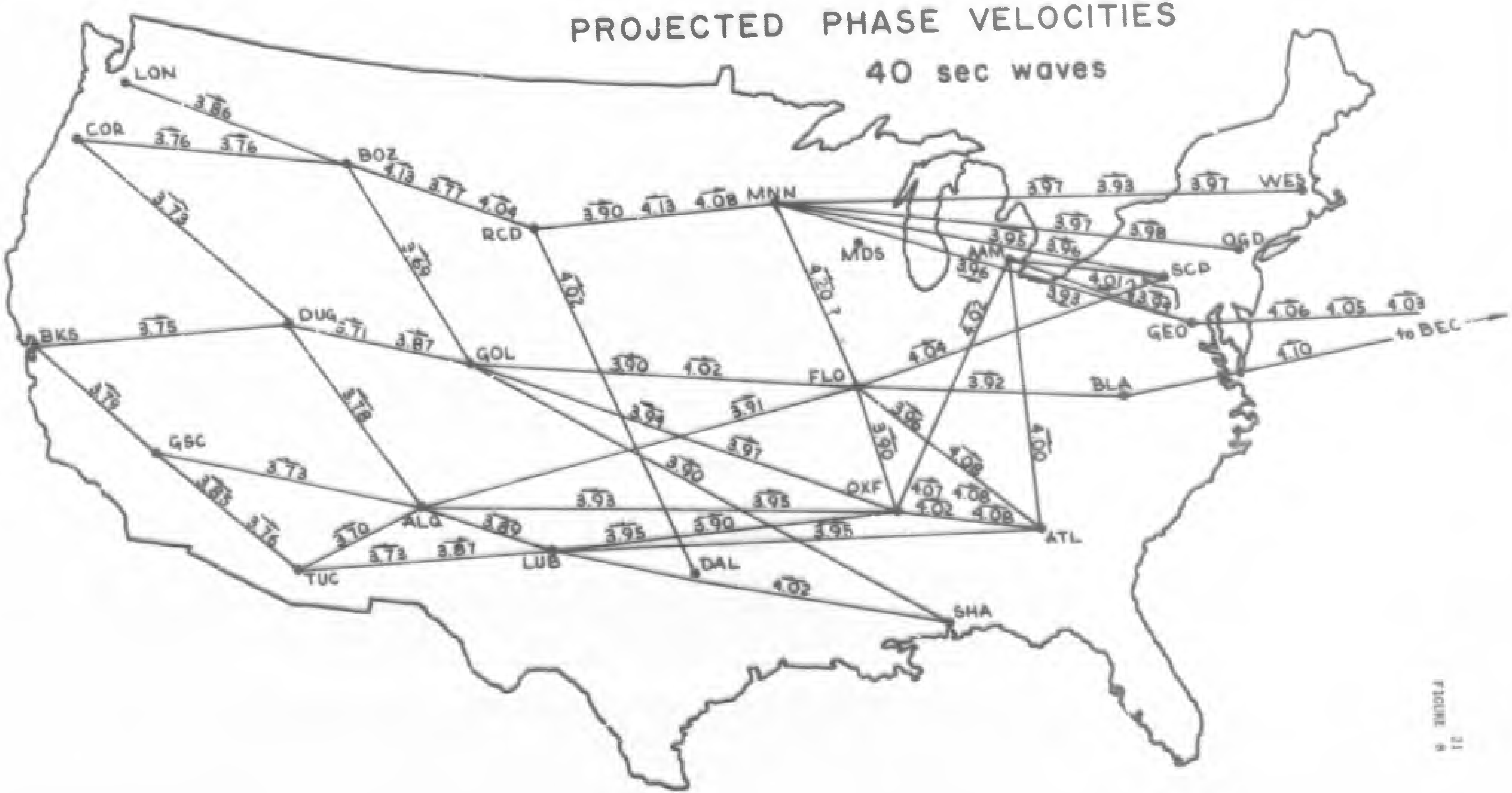


FIGURE 8



PROJECTED PHASE VELOCITIES

40 sec waves

FIGURE 9

PROJECTED PHASE VELOCITIES

33⅓ sec waves

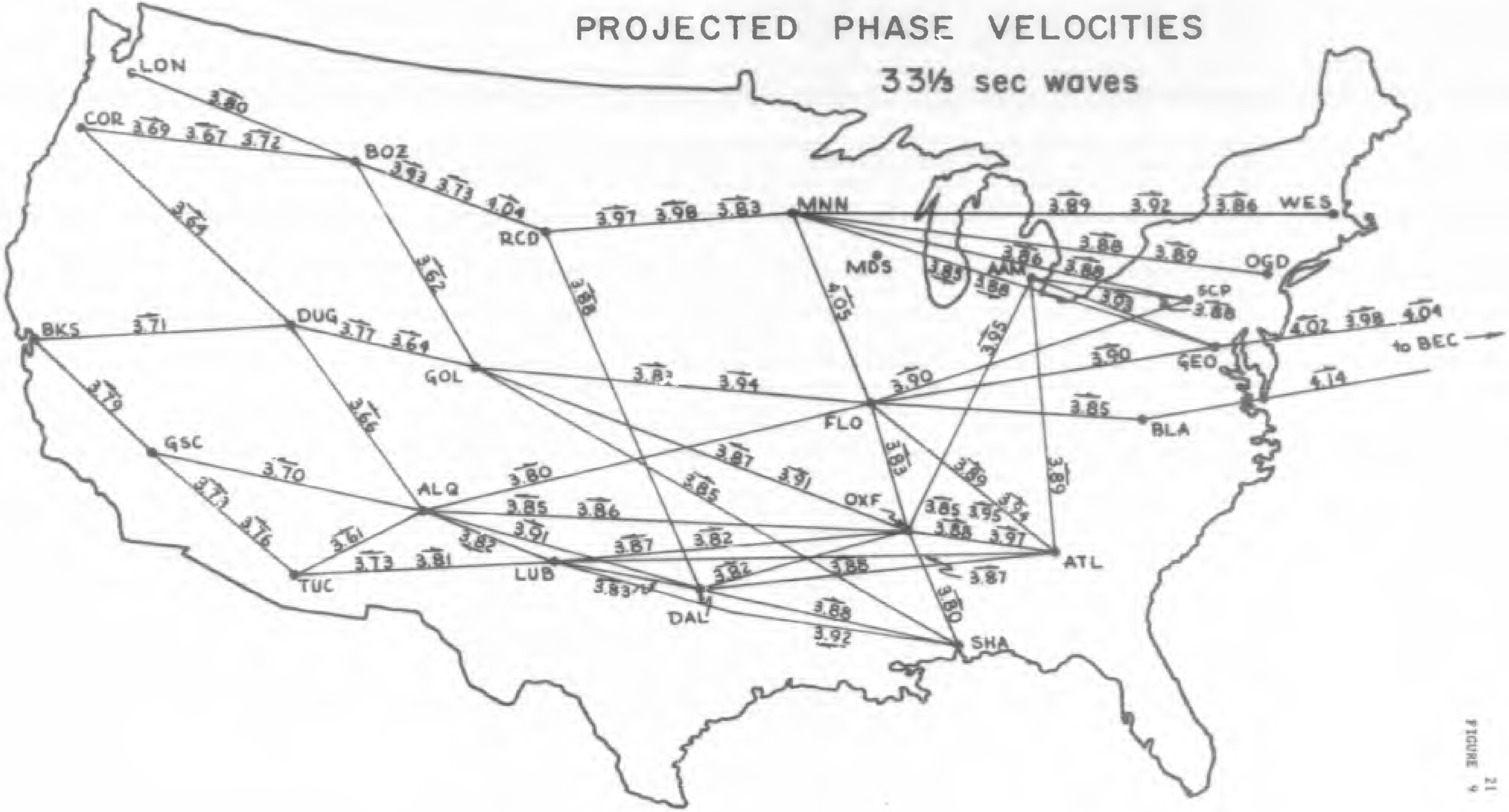


FIGURE 10

PROJECTED PHASE VELOCITIES
25 sec waves

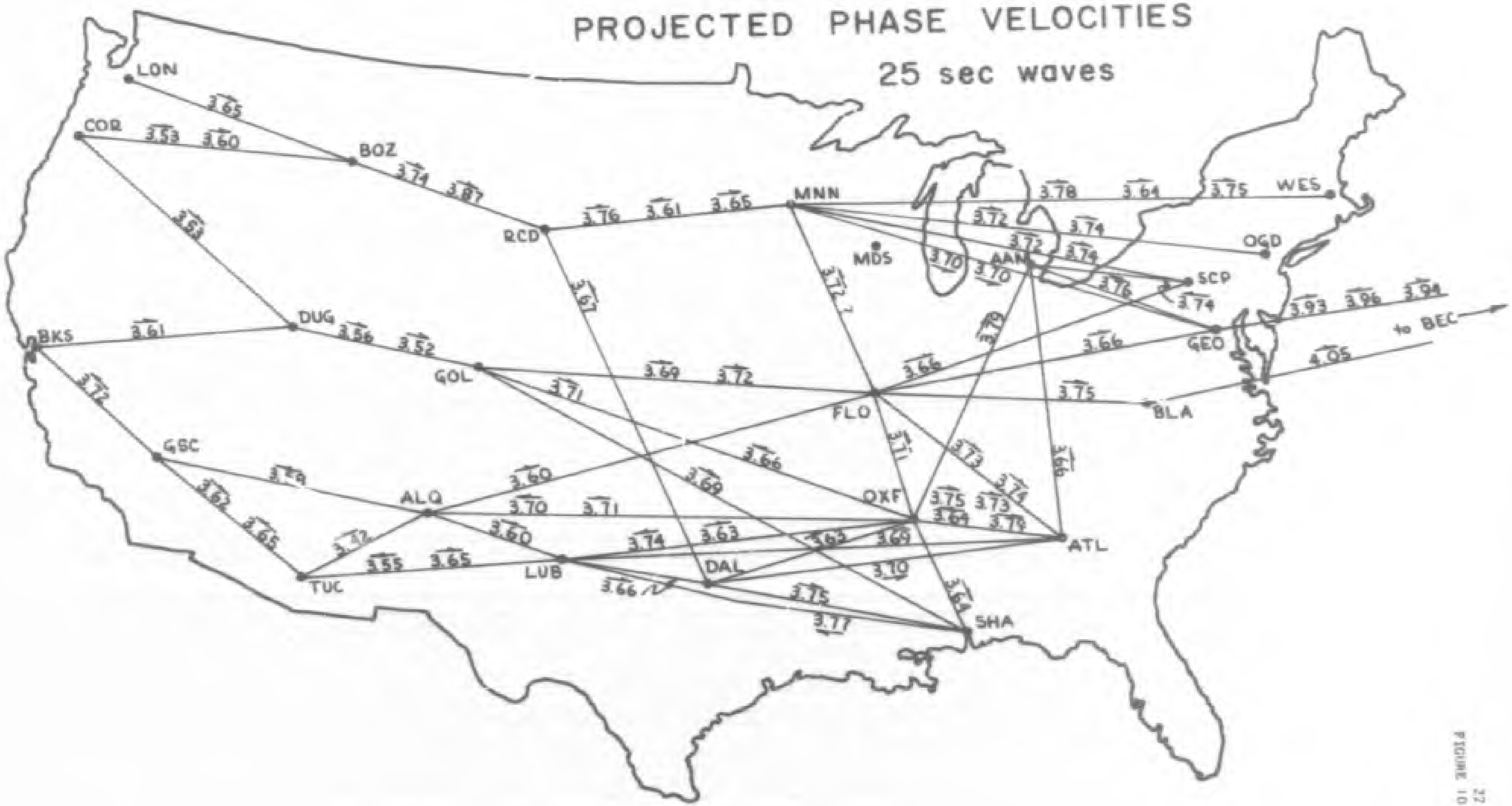
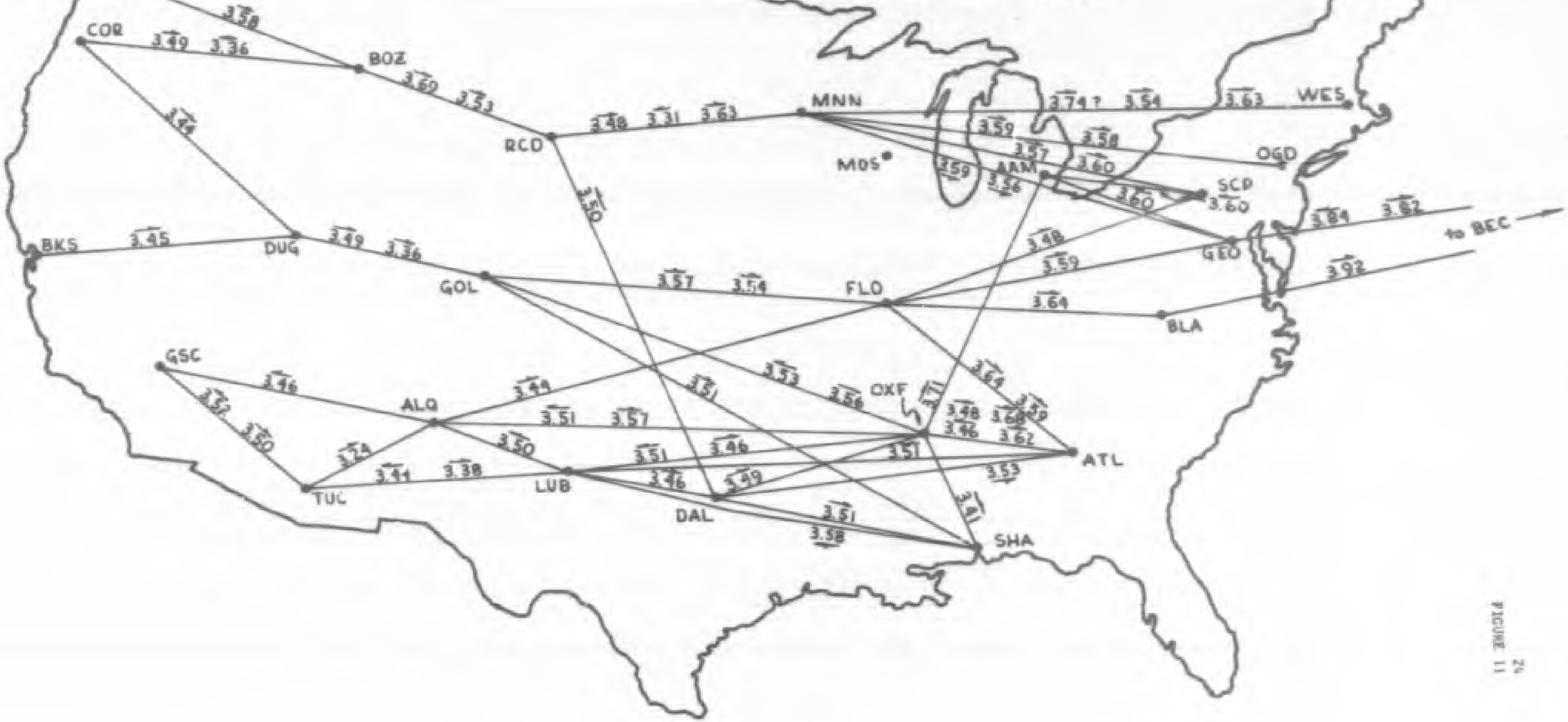


FIGURE 11

PROJECTED PHASE VELOCITIES

20 sec waves



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13. ABSTRACT

A discussion is given of the quality of the data obtainable from carefully selected Rayleigh Surface Waves traversing the North American continent. Using data from five events, a phase velocity map is constructed for the United States, the Canadian Shield, and Greenland. Average values are computed for various regions of this area and a given in a table and compared from region to region as well as with previous results.

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Group delay time residuals						
North America (phase velocity map)						
Regional phase velocities						

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