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PHASE-MATCHED FILTERS FOR SELECTED SOURCE-RECEIVER PATHS

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ABSTRACT

Phase-matched filters have been developed for several paths of interest for both Rayleigh and Love waves. The filters are presented in the form of tabled values of apparent group velocity as a function of frequency. Detailed instructions are given as to how the tabled values can be used to construct phase-matched filters and how the filters can be applied to low-level signals which have travelled the same path. Application of the filters provides a time series in which the effects of multipaths have been minimized and on which the signal-to-noise ratio is improved by a factor proportional to the time compression of the signal achieved by the filtering. For a signal bandwidth of 0.1 - 0.015 Hz and an epicentral distance of 30 degrees, the signal-to-noise ratio is about 10 dB better than on the original seismogram. The filtered seismogram can be used for the determination of surface wave magnitude.

INTRODUCTION

Phase-matched filters have been defined (Herrin and Goforth, 1977) as a class of linear filters in which the Fourier phase of the filter is made equal to that of a given signal.

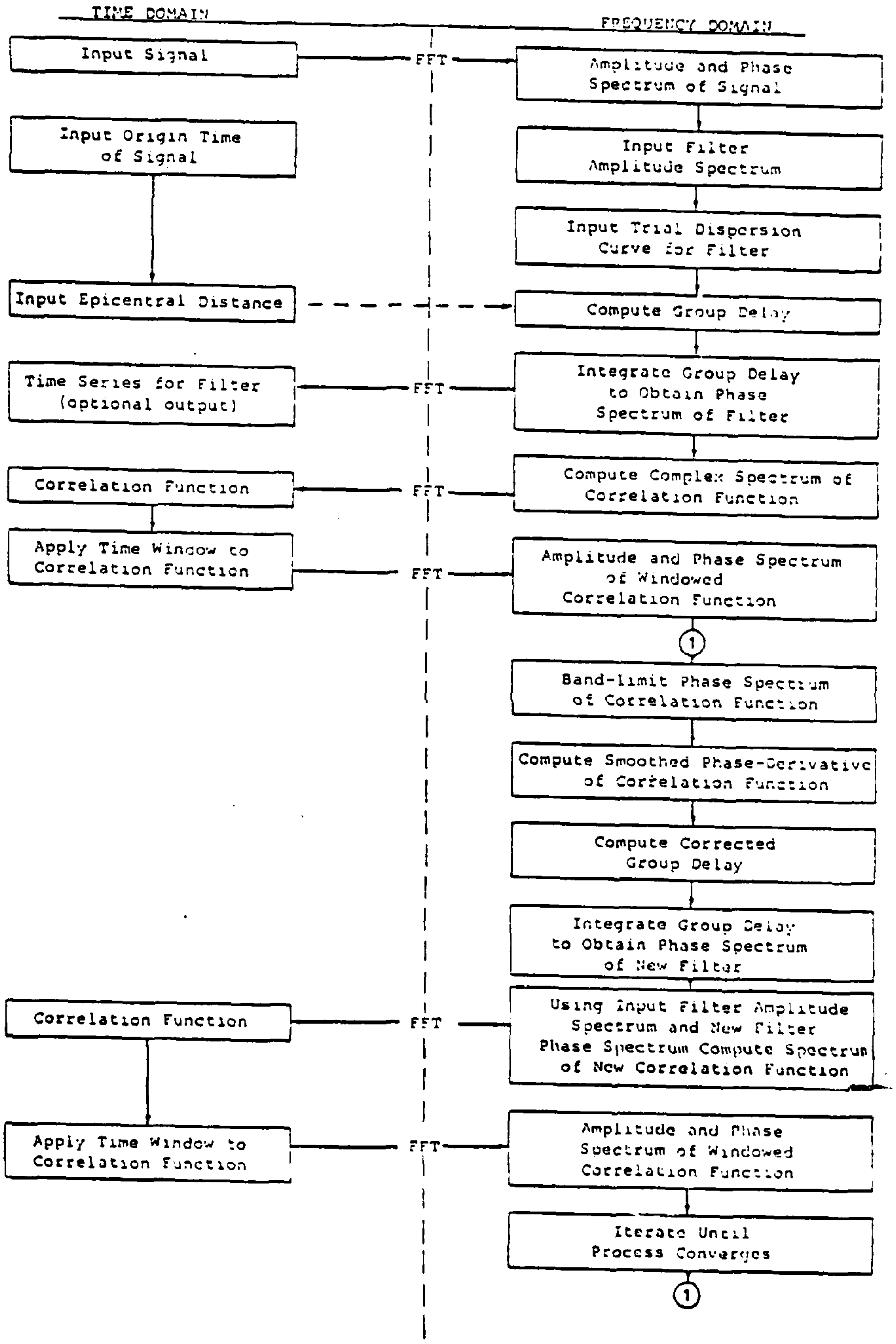
Consider the Fourier transform of the cross-correlation of a signal, s(t), with a time function, f(t), to be

$$s(t) \otimes f(t) \Longrightarrow |S(\omega)|\,|F(\omega)| \exp i[\sigma(\omega) - \phi(\omega)]$$

Now suppose that we choose fp(t) such that the Fourier phase is the same as that of s(t). We define the class of linear operators, fp(t), such that $\sigma(\omega) = \phi(\omega)$, as phase-matched filters with respect to the signal, s(t). The output of the above operation will then have the Fourier transform, $|S(\omega)|\,|Fp(\omega)|$, and will be an even function in the time domain as is the autocorrelation function. We call this output a pseudo-autocorrelation function (PAF). If means can be found for matching the Fourier phase of the signal and the filter, then the PAF will depend, for a given signal, only upon the amplitude spectrum of the particular phase-matched filter used in the operation. If $|Fp(w)|$ is chosen to be equal to $|S(w)|$, the phase-matched filter becomes the matched filter and maximizes the signal to noise power ratio assuming "white noise". The PAF becomes the autocorrelation function. At the other extreme, if $|Fp(w)|$ is chosen to be $1/|S(w)|$, the PAF becomes the impulse function. In practice, this choice would maximize the time resolution of the output but would greatly reduce the signal to noise ratio. Experience has shown that in the case where the amplitude spectrum is unknown a useful choice for the filter is $|Fp(w)| = 1$, the "white" filter.

In many cases, seismic signals are composed of two or more components overlapping in time. For example, Rayleigh and Love waves are almost always composed of overlapping wave trains representing multi-path propagation. A first task in the analysis of seismic surface waves is to identify and separate the various component wave trains so that each can be analyzed separately. Herrin and Goforth (1977) described an iterative technique which can be used to find a phase-matched filter for a particular component of a seismic signal. A flow diagram of the technique is shown in Table 1. They applied this process to digital records of Rayleigh waves from an earthquake and an explosion. Application of the filters allowed multiple arrivals to be identified and removed, and allowed recovery of the complex spectrum of the primary wave train and the estimation of the group velocity dispersion curve.

TABLE 1
FLOW DIAGRAM



The amplitude spectrum of the primary signal obtained by this linear process was not contaminated by interference from the multipath arrivals.

The application of phase-matched filtering to Love waves was demonstrated by Goforth and Herrin (1979), and the use of the technique to improve the signal-to-noise ratio of Rayleigh waves was documented by McDonald et al (1974).

This report contains the initial entries of a catalog of phase-matched filters obtained for various paths of interest for both Rayleigh and Love waves. The catalog, which will be augmented in future reports, is in the form of tabled values of apparent group velocity as a function of frequency. The group velocity curves are termed apparent because it is not known if the surface wave has travelled a great circle path. Also, the initial phase spectrum of the source has been incorporated into the dispersion curves; the phase response of the seismograph has not been removed; and the group delays from which the dispersion curves are calculated are relative to an arbitrarily assigned signal delay. However, these factors do not affect the use of the phase-matched filters as described in this report. Detailed instructions are given as to how the tabled values can be used to construct phase-matched filters, which in turn can be applied to low-level signals which have travelled the same path.

DESIGN AND APPLICATION OF THE FILTERS

The tabulated dispersion curves provided in the catalog in the Appendix can be used to design phase-matched filters for the indicated paths. The first step is to calculate the group delay; i. e.,

$$G(f) = \frac{d}{U(f)} - \frac{d}{V_o}$$

where G(f) is the group delay at each frequency in seconds,

- d is the great circle distance in km between the epicenter and the recording station,
- U(f) is the tabulated value of apparent group velocity at each frequency, and
- V_o is taken to be 4.0 for Rayleigh waves and 4.5 for Love waves.

The term $\frac{d}{V_o}$ is an arbitrary signal delay which was assumed in determining the apparent group velocity. The integral of the group delay is the Fourier phase of the dispersed wave train; i.e.,

$$\emptyset(f_o) = \int_o^{f_o} G(f)df + C$$

where C is a constant given for each path and $\emptyset(f_o)$ is the Fourier phase at f_o in cycles. The quantity $\emptyset(f)$ is the phase of the phase-matched filter; the amplitude spectrum of the filter should be specified to be unity to frequencies as high as 0.1 Hz and to roll off sharply at higher frequencies. A recommended amplitude spectrum is shown in figure 1. The phase-matched filter, whose Fourier transform is $A(f)e^{i\emptyset(f)}$, can then be correlated with

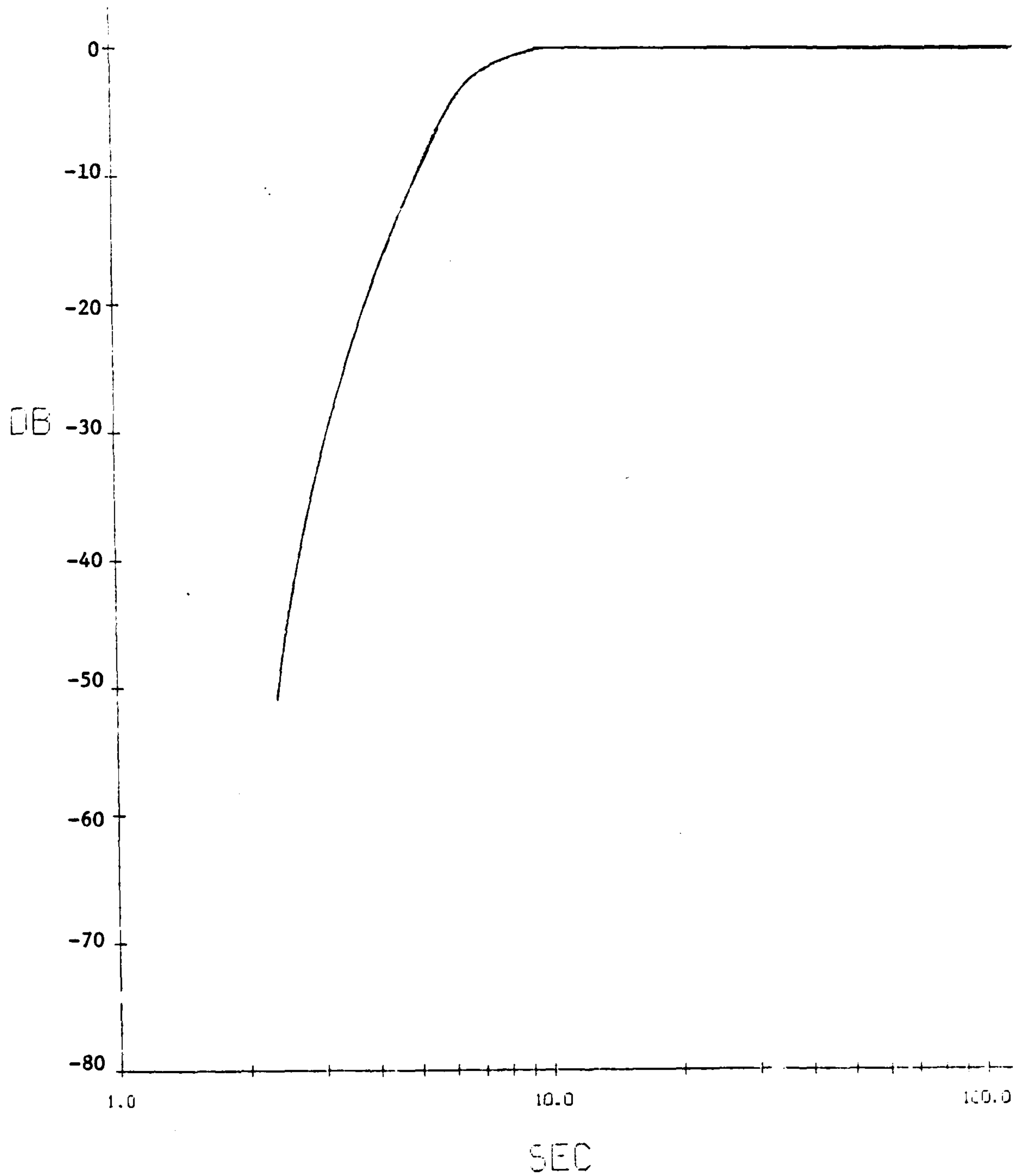


Figure 1. Amplitude spectrum recommended for the phase-matched filters.

a surface wave of interest which has travelled approximately the same path. The correlation can be accomplished in the frequency domain by first taking the Fourier transform of the signal. It is convenient to select the arrival time of energy travelling at 4.0 km/sec as the left side of the transform window for Rayleigh waves. A value of 4.5 km/sec is satisfactory for Love waves. A window length of 2048 seconds has been found to be adequate for nearly all signals in the period range 10 to 100 seconds which are sampled once per second. If the Fourier transform of the signal is

$$S(f)e^{i\theta(f)},$$

the correlation function in the frequency domain is

$$C(f)e^{i\psi(f)} = A(f)S(f)e^{i[\theta(f) - \phi(f)]}.$$

where $\psi(f)$ is close to zero in the band of interest. The inverse Fourier transform of $C(f)e^{i\psi(f)}$ will yield a time domain representation of the correlation function which will have a S/N improvement, relative to the original signal, that is proportional to the time compression of the signal achieved by phase-matched filtering. For a bandwidth of 0.10 to .015 Hz and an epicentral distance of 30°, the S/N improvement for seismic surface waves is about 10 dB.

Phase-matched filters offer an advantage over master event matched filtering in that the same filter can be used over significant deviations in travel path. The phase characteristics of most surface waves are quite strongly influenced by multipathing, and the effects of multipathing are extremely sensitive to small changes in travel path. Thus, master events, which include multipathing effects, are usually found to be inefficient when applied to slightly different paths. Phase-matched filters are designed to ... h the phase of the primary (first arriving) wave train and exclude the effects on the phase of later arriving compo .... The characteristics of the phase-matched filter are therefore controlled by the average of the earth properties along the path and are not so sensitive to small changes in path.

APPLICATION OF PHASE-MATCHED FILTERING TO MAGNITUDE DETERMINATION

The Rayleigh waves shown in figure 2 were recorded on the vertical seismograph at the Albuquerque Seismic Research Observatory (SRO). Epicentral information concerning the two earthquakes is given in Table 2. The two events were located near Iceland within 20 kilometers of each other. The Rayleigh wave of event 76-004 (figure 2b) contains interfering body waves from an earthquake in Argentina. The interference is especially noticeable in the portion of the wave in which 20-sec energy is arriving. A magnitude (Ms) determination made by measuring the amplitude at a period of 20 seconds would be in error.

Following the iterative technique diagrammed in Table 1, a phase-matched filter was determined for event 76-033 (figure 2a). The filter was applied to both events; the resulting pseudo-autocorrelation functions (PAFs) are shown in figure 3. A comparison of the PAFs indicates the following; (1) The same filter produces almost identical results on the two signals as should be the case since the epicenters are so close together. Even the multipath structure which trails the peak for about 170 seconds is nearly identical. (2) The Iceland earthquake has been completely resolved from interfering Argentina event by the correlation, and an amplitude measurement, undisturbed by either the low-level multipathing or by the relatively strong Argentina body waves, could be made on the main peak of the PAF. Such a measurement, if accompanied by an empirically-derived relationship between the PAF amplitude and the conventional amplitude at a period of 20 seconds, could be used to calculate a surface wave magnitude from which the effects of multipathing and interfering events have been eliminated. In addition, the measurement would be made on a time series in which the signal-to-noise ratio is approximately 10 dB higher than on the seismogram.

The amplitude of the *pseudo-autocorrelation* peak is a function of the integral of the signal spectrum. Thus, the PAF peak amplitude is determined not only by the peak spectral amplitude of the signal but also by the frequency bandwidth of the signal. For a given signal peak spectral amplitude, the PAF amplitude will increase with the signal bandwidth. If a relation is established empirically between conventional Ms (at 20 sec) and PAF peak amplitude for explosions, then a magnitude (Mp) determined from the PAF may prove a useful Mp:m_b discriminant because of the greater bandwidth of earthquake surface waves.

We are developing phase-matched filters for as many paths as possible and, beginning with the Appendix to this report, we plan to present the data in a format so that anyone interested can construct and use the filters. The epicentral information concerning the seismic events included in the Appendix is given in Table 3.

The phase response of the seismograph has not been removed from the data from which the phase-matched filters can be constructed. Thus, the filters can be applied directly to signals recorded at the Albuquerque and Meshed Seismic Research Observatories. However, the instrument phase response incorporated in the ALPA phase-matched filters is that of the Geotech Triaxial Long-period seismometer. These instruments have recently been replaced by Geotech KS-36,000 seismometers; phase-matched filters applied to ALPA data recorded after the instrument change should be adjusted by the difference in phase response of the seismographs.

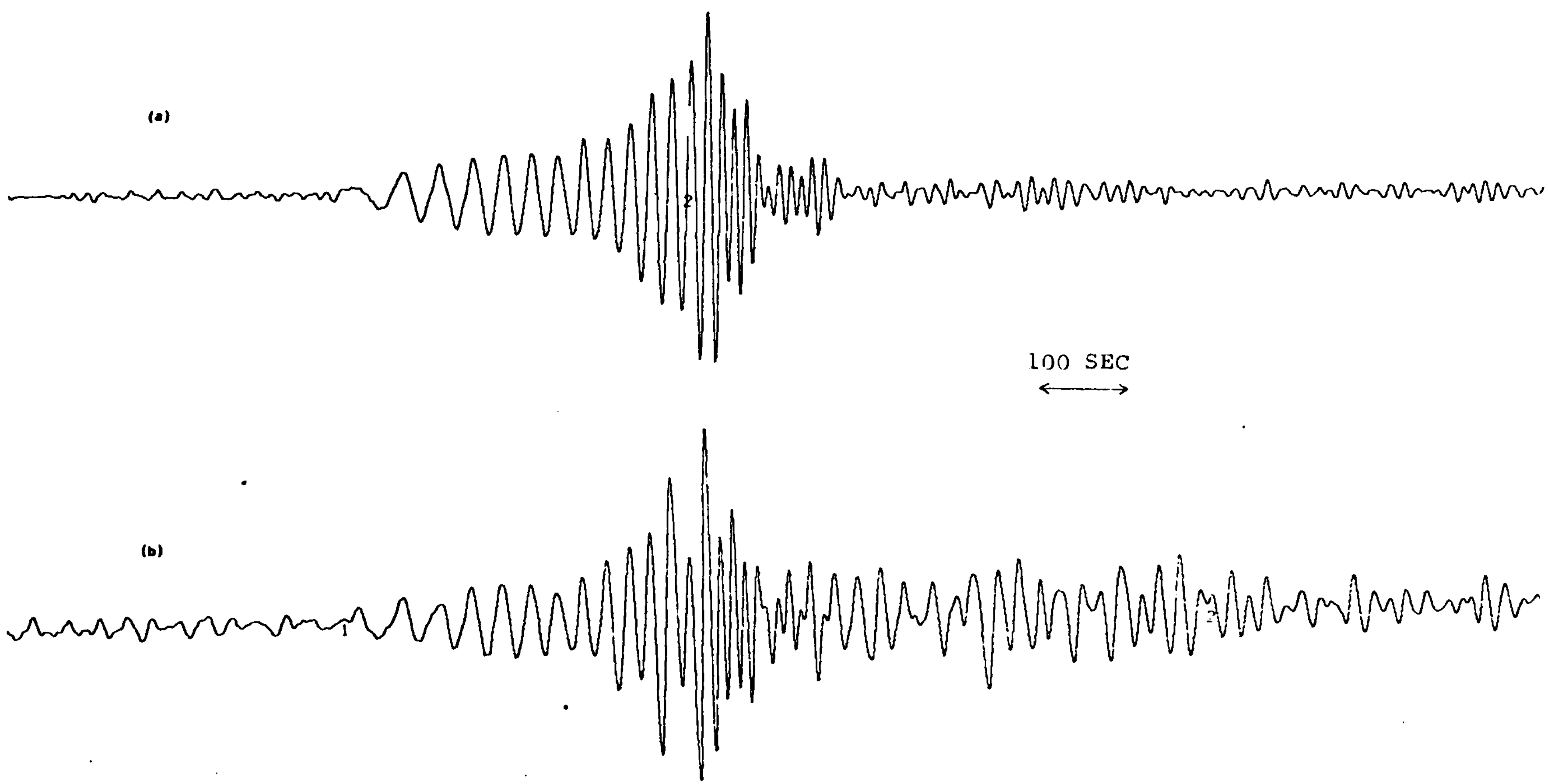


Figure 2. Rayleigh waves from Iceland earthquakes recorded at Albuquerque, N. M.
(a) event 1976-033,
(b) event 1976-004.

TABLE 2

EVENT	ORIGIN TIME	LAT	LONG	DISTANCE	m_b	DEPTH	RECORDING SITE
Iceland	1976-004-04-29-29.3	66.047N	16.688W	58.558	5.0	33	Albuquerque
Iceland	1976-033-13-16-45.7	66.122N	16.773W	58.504	4.8	5	Albuquerque

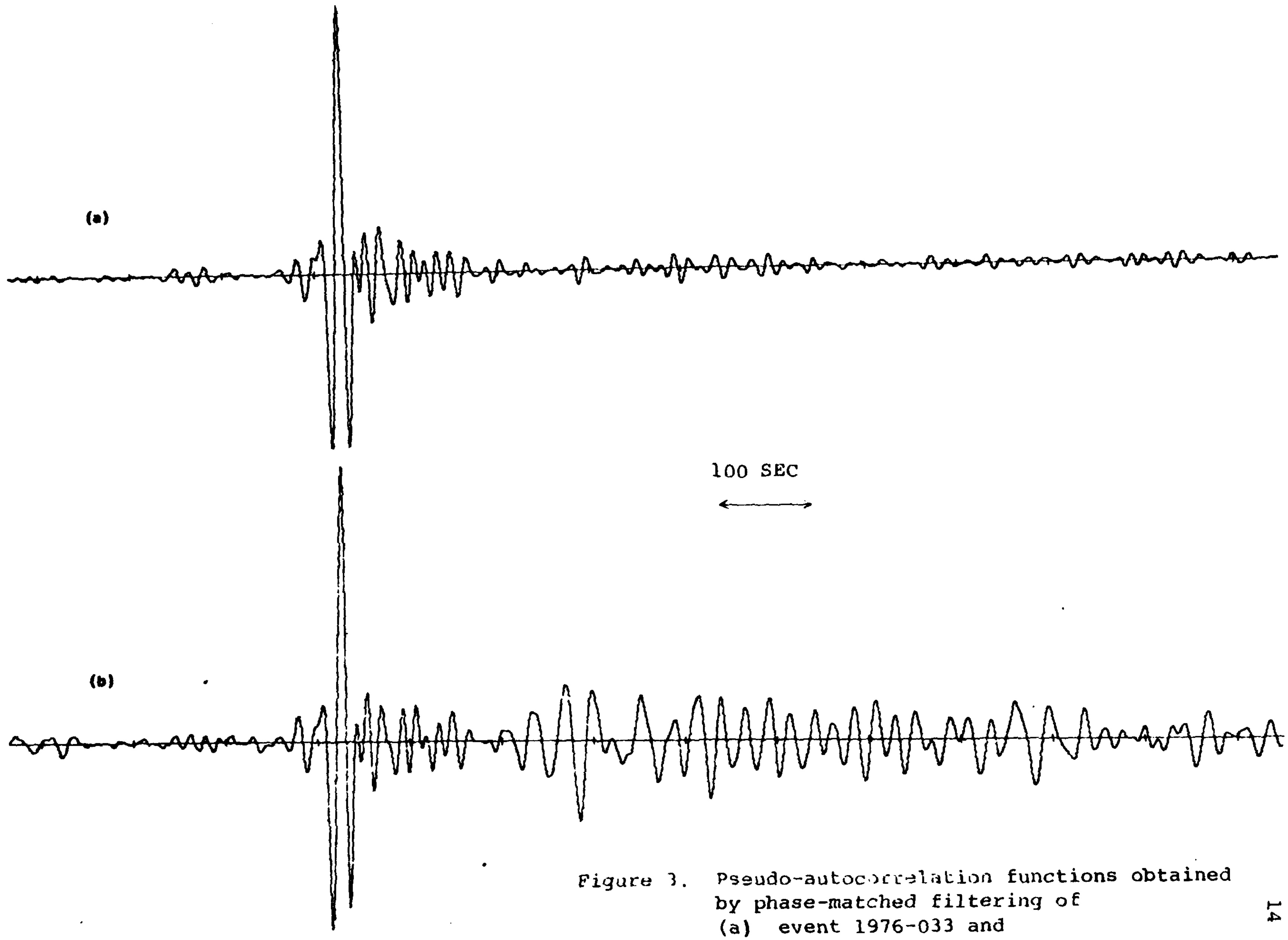


Figure 3. Pseudo-autocorrelation functions obtained by phase-matched filtering of
(a) event 1976-033 and
(b) event 1976-004.

TABLE 3

EVENT	ORIGIN TIME	LAT	LONG	DISTANCE	m_b	DEPTH	RECORDING SITE
Iceland	1976-004-04-29-29.3	66.047N	16.688W	58.558	5.0	33	Albuquerque
Novaya Zemlya	1975-294-11-59-57.3	73.35N	55.08W	71.28	6.5	0	Albuquerque
Kuril Is.	1976-022-08-07-10.4	44.39N	149.617E	65.83	5.4	44	Meshed, Iran
Andreanof Is.	1974-201-00-48-3.9	51.60N	173.50W	19.03	4.9	45	ALPA
Komandorsky Is.	1975-308-12-05-56.9	54.40N	167.50W	24.65	5.5	24	ALPA

REFERENCES

Goforth, Tom and Eugene Herrin, 1979. Phase-matched filters: Application to the study of Love waves, Bull. Seis. Soc. Amer., vol. 67, no. 1, February.

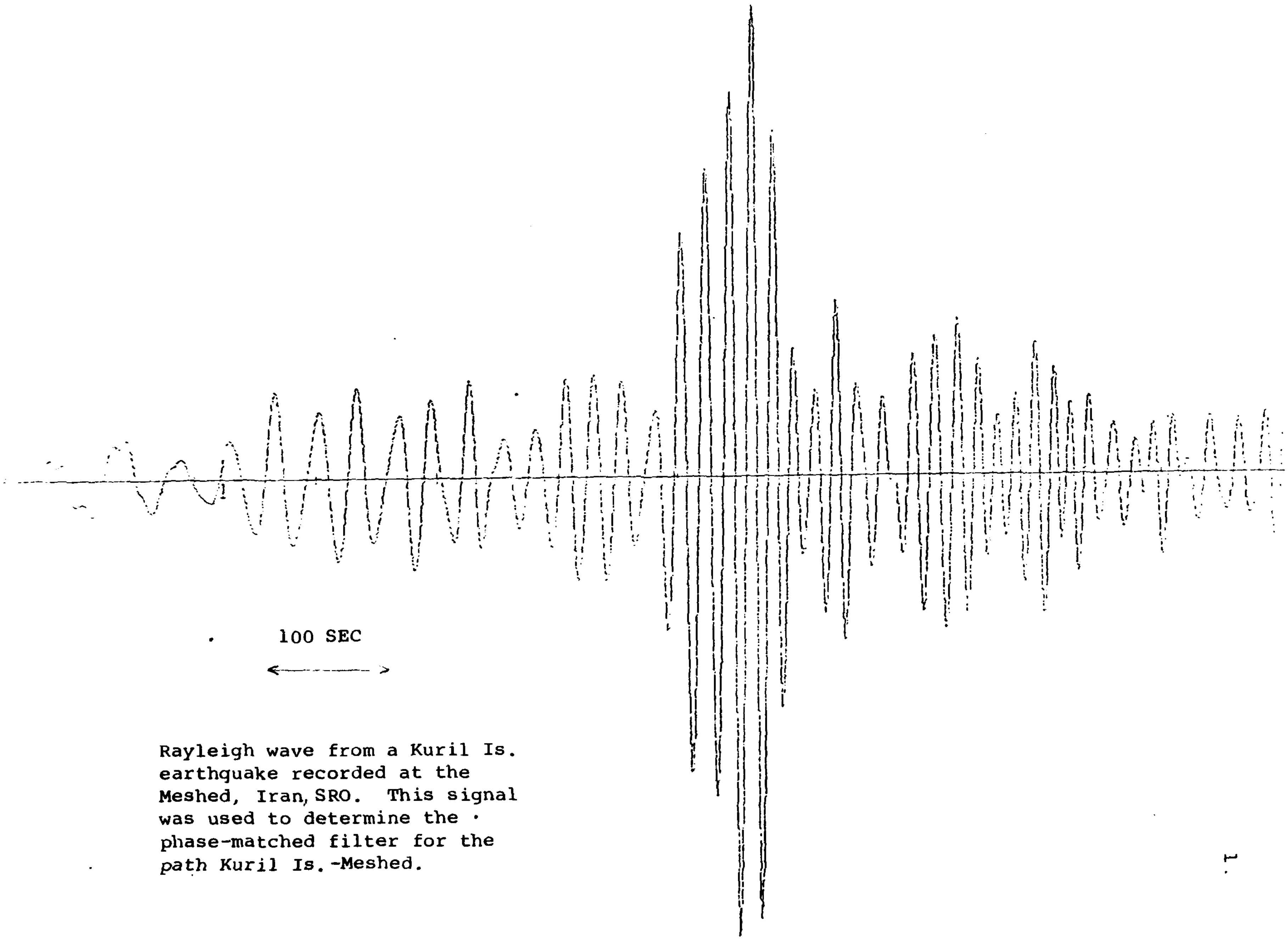
Herrin, Eugene and Tom Goforth, 1977. Phase-matched filters: Application to the study of Rayleigh waves, Bull. Seis. Soc. Amer., vol. 67, no. 5, 1259-1275.

McDonald, J. A., William Tucker, and Eugene Herrin, 1974. Matched filter detection of surface waves of periods up to 75 seconds generated by small earthquakes, Bull. Seis. Soc. Amer., vol. 64, 1843-1854.

APPENDIX

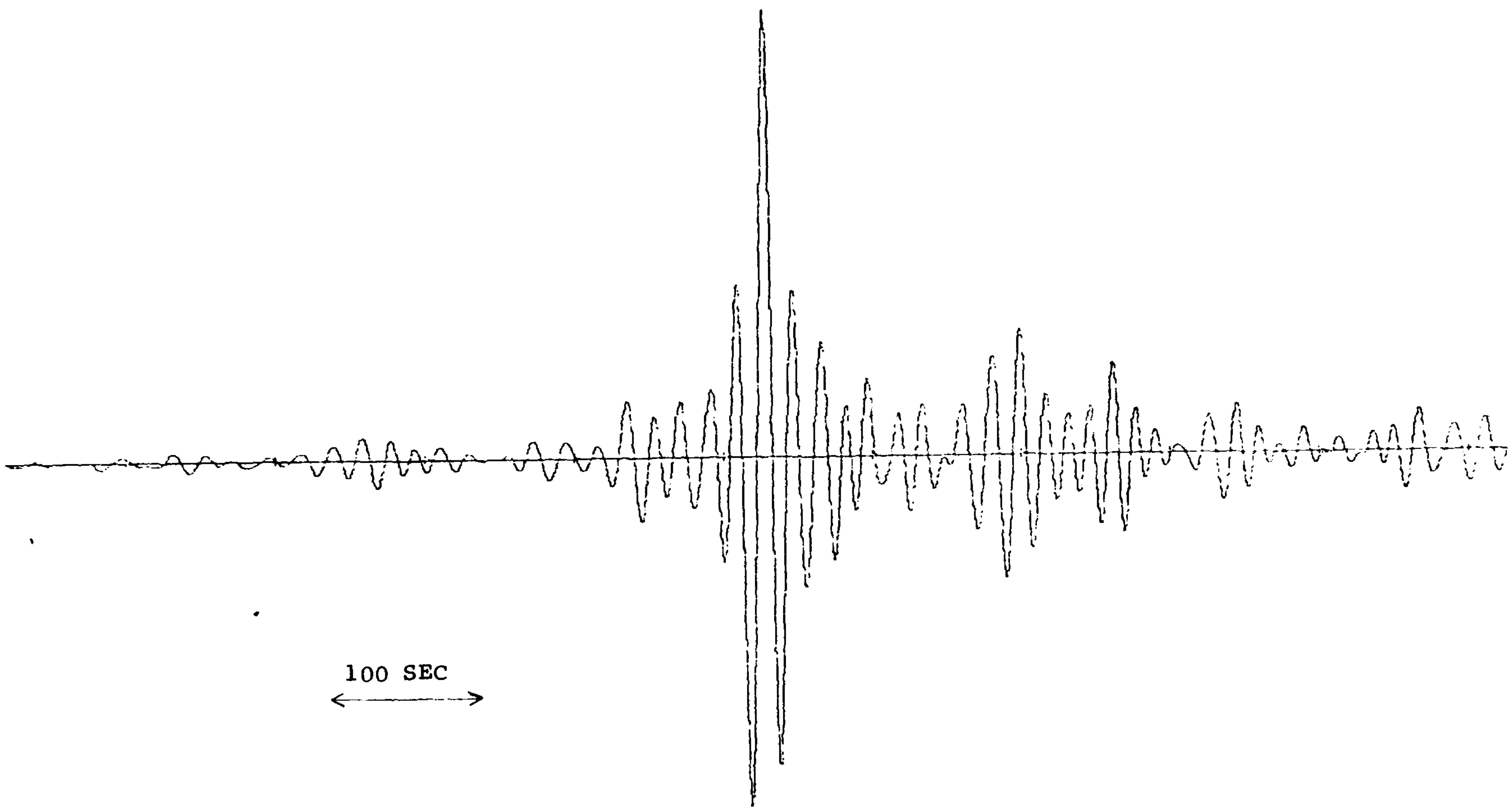
CATALOG OF GROUP VELOCITY DISPERSION CURVES AND TABLES

1. Kuril Islands - Meshed, Iran (Rayleigh)
2. Novaya Zemlya - Albuquerque, N. M. (Rayleigh)
3. Novaya Zemlya - Albuquerque, N. M. (Love)
4. Andreanof Island - ALPA (Rayleigh)
5. Komandorsky Island - ALPA (Rayleigh)
6. Iceland - Albuquerque, N. M. (Rayleigh)



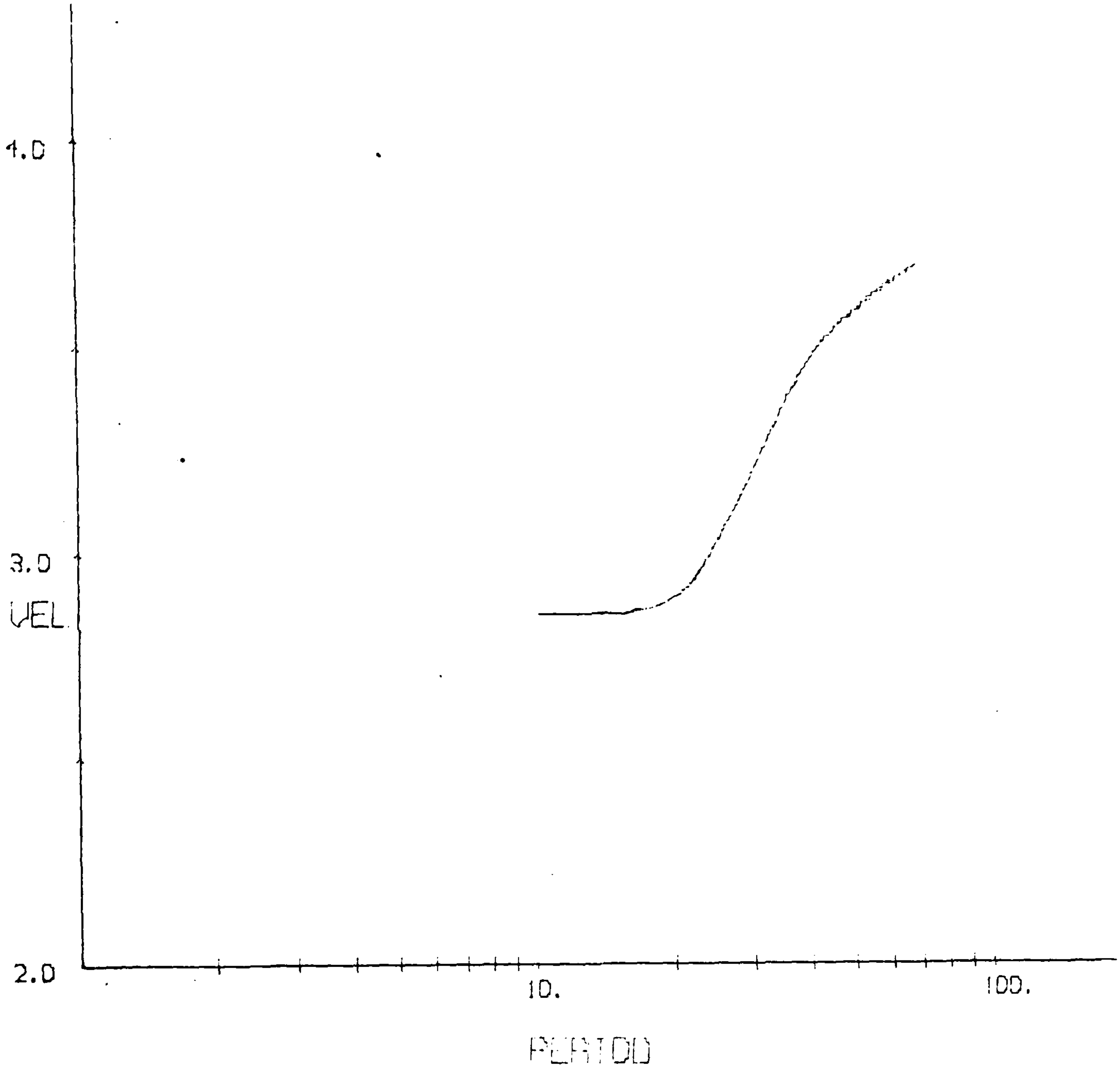
Rayleigh wave from a Kuril Is. earthquake recorded at the Meshed, Iran, SRO. This signal was used to determine the phase-matched filter for the path Kuril Is.-Meshed.

1.



The pseudo-autocorrelation function obtained by the application of the Kuril-Meshed phase-matched filter to the Kuril event.

2



Plot of the apparent Rayleigh group velocity dispersion curve obtained for the Kuril-Meshed path.

TABLED VALUES OF THE APPARENT RAYLEIGH GROUP VELOCITY DISPERSION CURVE FOR THE PATH KURIL ISLANDS (44.39N, 149.62E) - MESHED, IRAN (36.30N, 59.49E).

KURIL IS. (44.39N, 149.62E) - MESHAD, IRAN (36.30N, 59.49E)

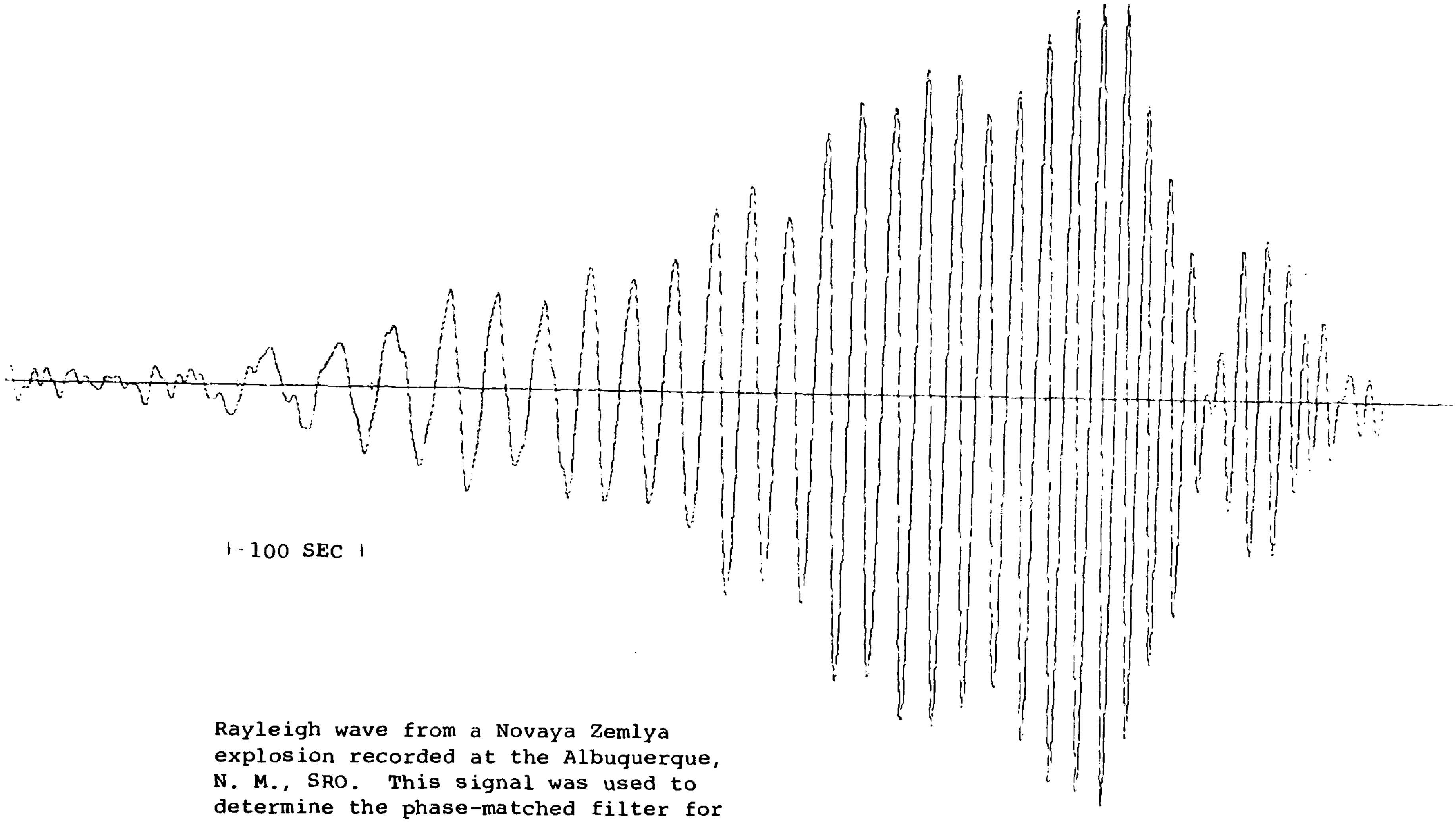
C = +0.010 cycles

FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)	FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)
.00049	3.9837	.02100	3.5714
.00098	3.9558	.02148	3.5619
.00146	3.9187	.02197	3.5521
.00195	3.8755	.02246	3.5421
.00244	3.8267	.02295	3.5316
.00293	3.7773	.02344	3.5208
.00342	3.7303	.02393	3.5095
.00391	3.6897	.02441	3.4978
.00439	3.6565	.02490	3.4842
.00488	3.6506	.02539	3.4698
.00537	3.6589	.02588	3.4549
.00586	3.6735	.02637	3.4398
.00635	3.6924	.02686	3.4243
.00684	3.7127	.02734	3.4086
.00732	3.7249	.02783	3.3926
.00781	3.7310	.02832	3.3766
.00830	3.7354	.02881	3.3604
.00879	3.7383	.02930	3.3442
.00928	3.7397	.02979	3.3282
.00977	3.7406	.03027	3.3124
.01025	3.7412	.03076	3.2966
.01074	3.7409	.03125	3.2809
.01123	3.7397	.03174	3.2653
.01172	3.7375	.03223	3.2499
.01221	3.7339	.03271	3.2346
.01270	3.7291	.03320	3.2195
.01318	3.7232	.03369	3.2047
.01367	3.7165	.03418	3.1900
.01416	3.7092	.03467	3.1758
.01465	3.7012	.03516	3.1621
.01514	3.6923	.03564	3.1486
.01563	3.6829	.03613	3.1354
.01611	3.6731	.03662	3.1224
.01660	3.6631	.03711	3.1097
.01709	3.6528	.03760	3.0973
.01758	3.6423	.03809	3.0851
.01807	3.6316	.03857	3.0732
.01855	3.6203	.03906	3.0616
.01904	3.6099	.03955	3.0502
.01953	3.5991	.04004	3.0387
.02002	3.5900	.04053	3.0274
.02051	3.5805	.04102	3.0165

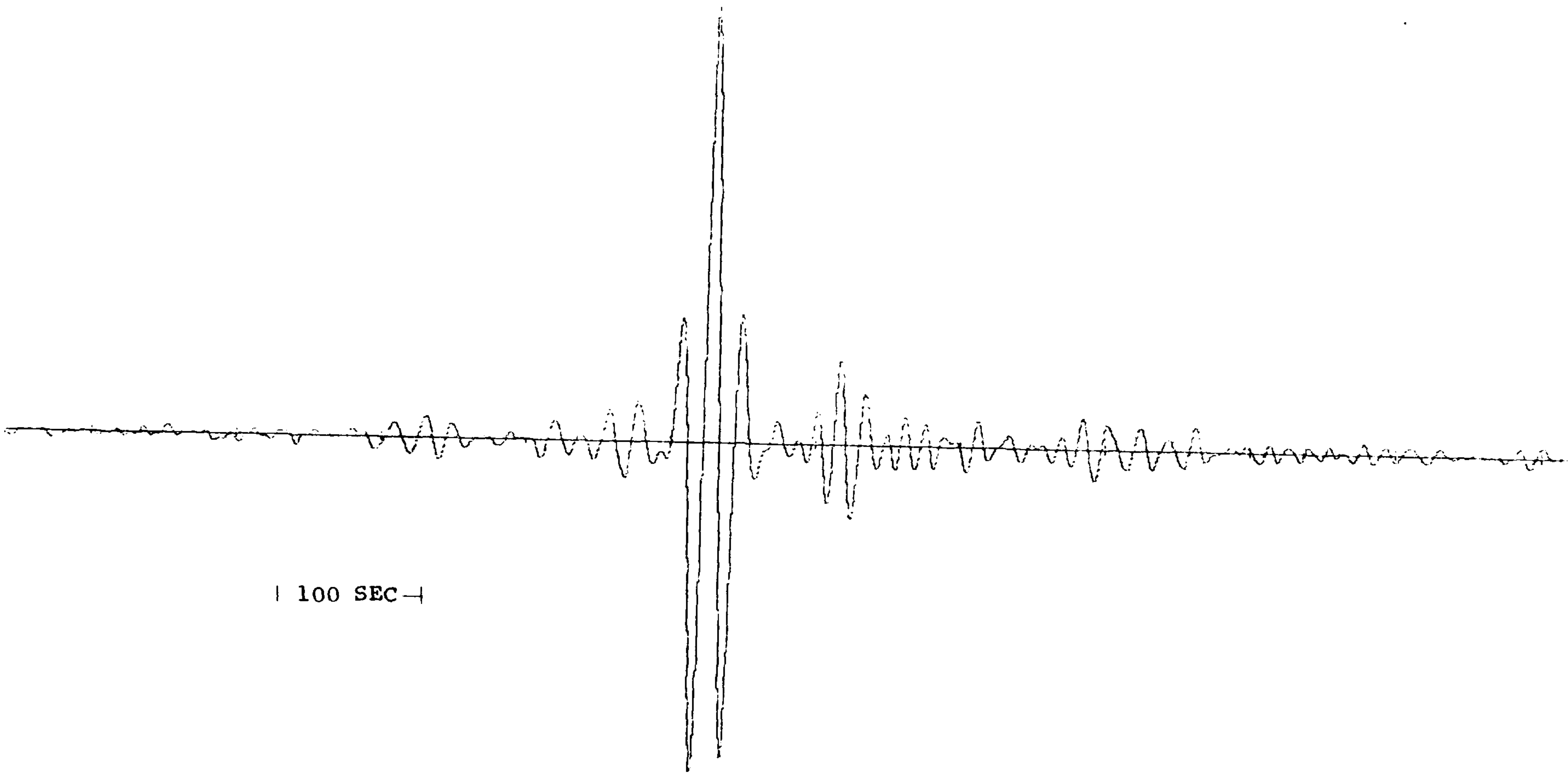
FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)
.04150	3.0060
.04199	2.9958
.04248	2.9860
.04297	2.9767
.04346	2.9678
.04395	2.9593
.04443	2.9514
.04492	2.9448
.04541	2.9389
.04590	2.9333
.04639	2.9283
.04688	2.9236
.04736	2.9193
.04785	2.9152
.04834	2.9115
.04883	2.9081
.04932	2.9049
.04980	2.9017
.05029	2.8986
.05078	2.8956
.05127	2.8928
.05176	2.8902
.05225	2.8878
.05273	2.8856
.05322	2.8835
.05371	2.8816
.05420	2.8798
.05469	2.8783
.05518	2.8769
.05566	[illegible]
.05615	2.8745
.05664	2.8734
.05713	2.8725
.05762	2.8716
.05811	2.8707
.05859	2.8699
.05908	2.8692
.05957	2.8684
.06006	2.8672
.06055	2.8661
.06104	2.8649
.06152	2.8638
.06201	2.8628
.06250	2.8618
.06299	2.8609

FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)
.06348	2.8601
.06396	2.8593
.06445	2.8587
.06494	2.8586
.06543	2.8586
.06592	2.8588
.06641	2.8590
.06689	2.8593
.06738	2.8595
.06787	2.8600
.06836	2.8604
.06885	2.8609
.06934	2.8613
.06982	2.8617
.07031	2.8620
.07080	2.8623
.07129	2.8626
.07178	2.8630
.07227	2.8634
.07275	2.8634
.07324	2.8600
.07373	2.8600
.07422	2.8600
.07471	2.8600
.07520	2.8600
.07568	2.8600
.07617	2.8600
.07666	2.8600
.07715	2.8600
.07764	2.8600
.07813	2.8600
.07861	2.8600
.07910	2.8600
.07959	2.8600
.08008	2.8600
.08057	2.8600
.08105	2.8600
.08154	2.8600
.08203	2.8600
.08252	2.8600
.08301	2.8600
.08350	2.8600
.08398	2.8600
.08447	2.8600
.08496	2.8600

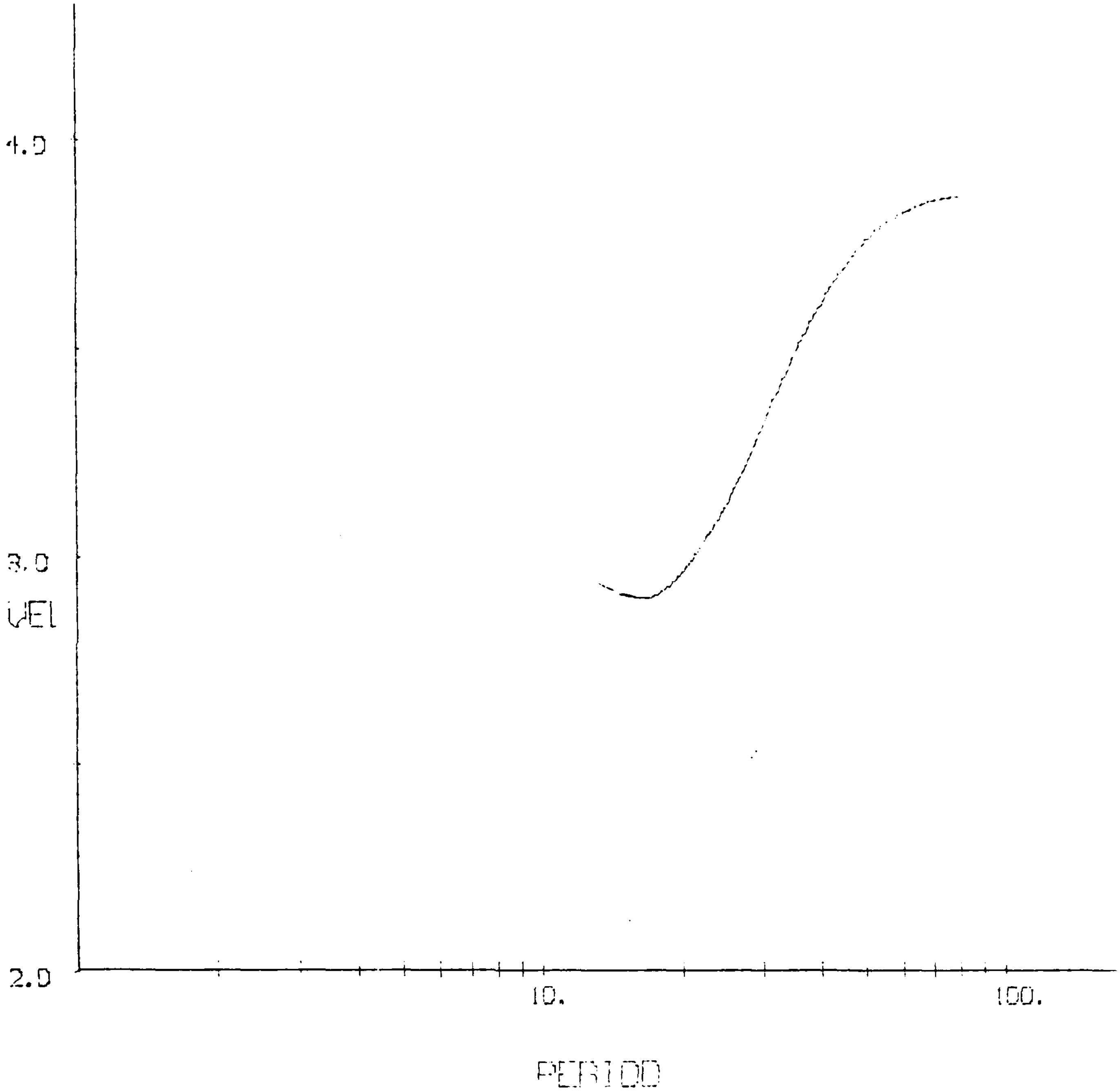
FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)
.08545	2.8600
.08594	2.8600
.08643	2.8600
.08691	2.8600
.08740	2.8600
.08789	2.8600
.08838	2.8600
.08887	2.8600
.08936	2.8500
.08984	2.8600
.09033	2.8600
.09082	2.8600
.09131	2.8600
.09180	2.8600
.09229	2.8600
.09277	2.8600
.09326	2.8600
.09375	2.8500
.09424	2.8600
.09473	2.8600
.09521	2.8600
.09570	2.8600
.09619	2.8600
.09668	2.8600
.09717	2.8600
.09766	2.8600
.09814	2.8500
.09863	2.8600
.09912	2.8500



Rayleigh wave from a Novaya Zemlya explosion recorded at the Albuquerque, N. M., SRO. This signal was used to determine the phase-matched filter for the path Novaya Zemlya-Albuquerque.



Pseudo-autocorrelation function obtained by the application of the Novaya Zemlya-Albuquerque phase-matched filter to the Novaya Zemlya Rayleigh wave.



Plot of the apparent Rayleigh group velocity dispersion curve obtained for the Novaya Zemlya-Albuquerque path.

TABLED VALUES OF THE APPARENT RAYLEIGH GROUP VELOCITY DISPERSION CURVE FOR THE PATH NOVAYA ZEMLYA (73.35N, 55.08E) - ALBUQUERQUE, N. M., (34.93N, 106.45W)

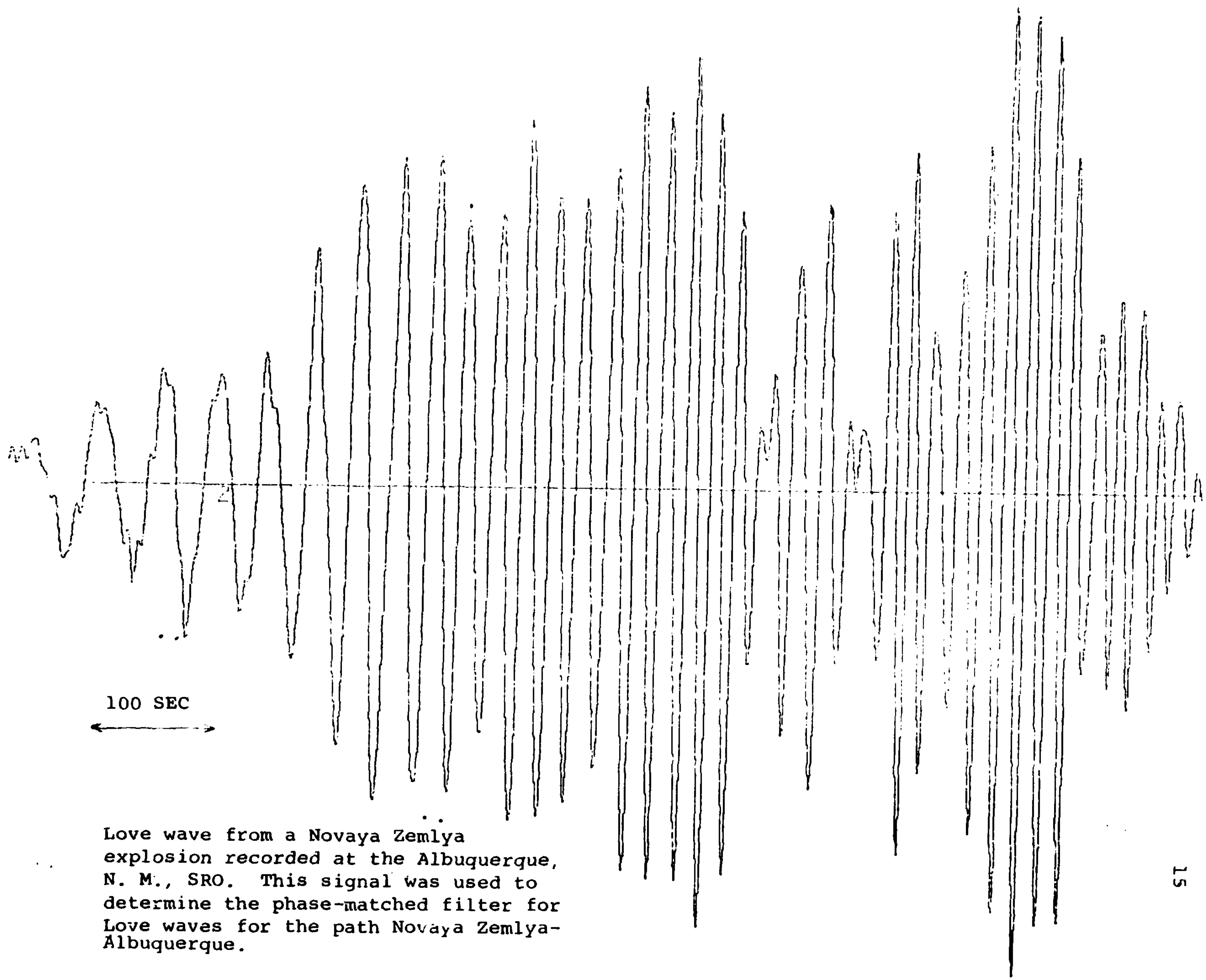
NOVAYA ZEMLYA (73.35N, 55.08E) - ALBUQUERQUE (34.93N, 106.45W)

C = 0.500 cycles

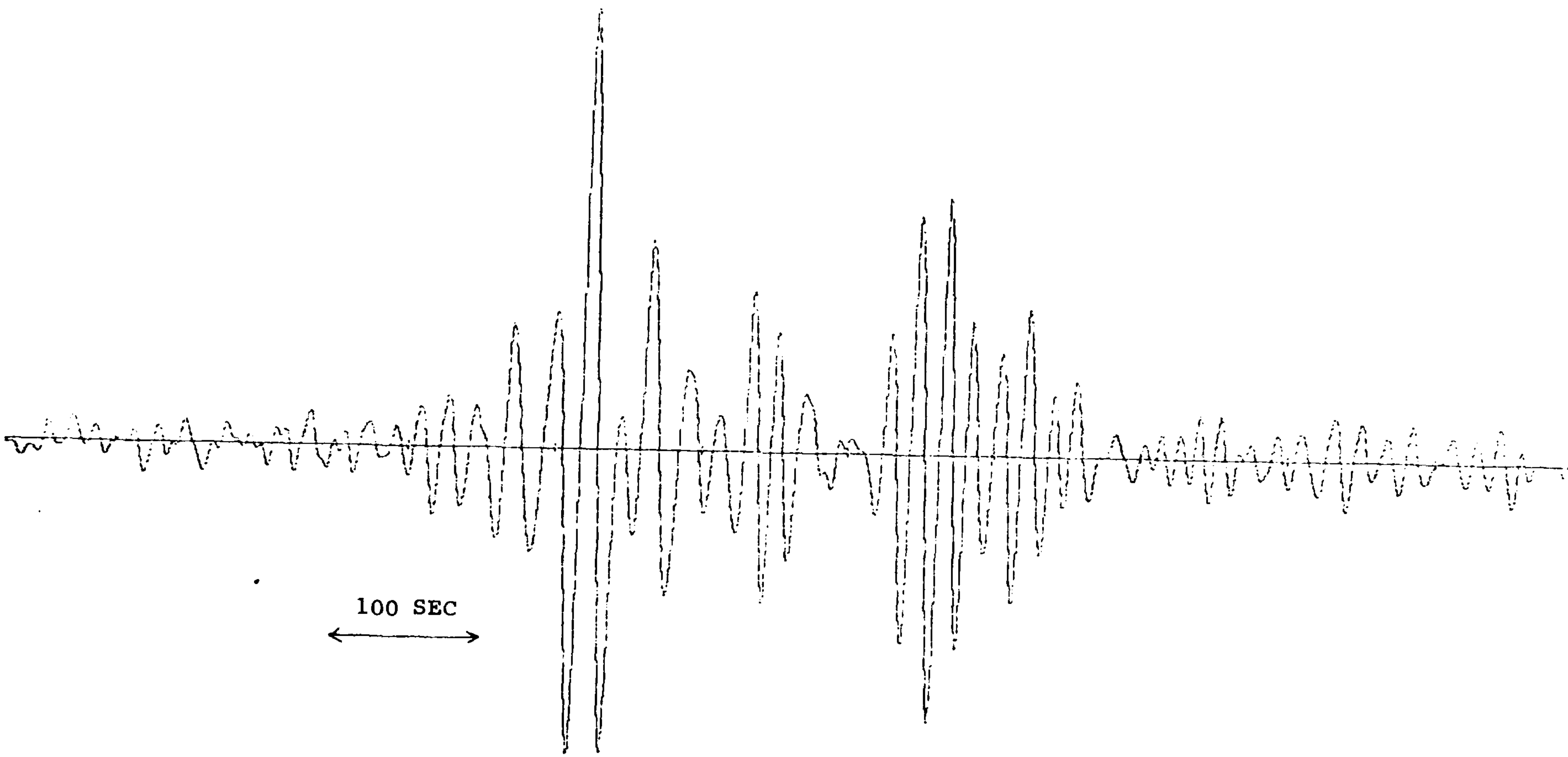
FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)
.00049	3.9898
.00098	3.9736
.00146	3.9536
.00195	3.9325
.00244	3.9217
.00293	3.9142
.00342	3.9084
.00391	3.9040
.00439	3.9007
.00488	3.8973
.00537	3.8942
.00586	3.8915
.00635	3.8893
.00684	3.8873
.00732	3.8853
.00781	3.8833
.00830	3.8815
.00879	3.8797
.00928	3.8781
.00977	3.8768
.01025	3.8759
.01074	3.8750
.01123	3.8741
.01172	3.8730
.01221	3.8718
.01270	3.8703
.01318	3.8684
.01367	3.8661
.01416	3.8633
.01465	3.8595
.01514	3.8542
.01563	3.8482
.01611	3.8415
.01660	3.8343
.01709	3.8264
.01758	3.8179
.01807	3.8087
.01855	3.7990
.01904	3.7886
.01953	3.7776
.02002	3.7656
.02051	3.7531
.02100	3.74[illegible]
.02148	3.7264
.02197	3.7124
.02246	3.6980
.02295	3.6831
.02344	3.6679
.02393	3.6524
.02441	3.6365
.02490	3.6203
.02539	3.6038
.02588	3.5871
.02637	3.5702
.02686	3.5532
.02734	3.5362
.02783	3.5190
.02832	3.5018
.02881	3.4846
.02930	3.4674
.02979	3.4503
.03027	3.4333
.03076	3.4164
.03125	3.3996
.03174	3.3830
.03223	3.3664
.03271	3.3500
.03320	3.3338
.03369	3.3177
.03418	3.3019
.03467	3.2861
.03516	3.2702
.03564	3.2547
.03613	3.2394
.03662	3.2244
.03711	3.2098
.03760	3.1956
.03809	3.1818
.03857	3.1684
.03906	3.1555
.03955	3.1432
.04004	3.1324
.04053	3.1221
.04102	3.1122
.04150	3.1027
.04199	3.0936

FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)
.04248	3.0846
.04297	3.0761
.04346	3.0678
.04395	3.0597
.04443	3.0519
.04492	3.0436
.04541	3.0354
.04590	3.0274
.04639	3.0196
.04688	3.0120
.04736	3.0046
.04785	2.9974
.04834	2.9905
.04883	2.9838
.04932	2.9774
.04980	2.9713
.05029	2.9655
.05078	2.9601
.05127	2.9548
.05176	2.9498
.05225	2.9451
.05273	2.9406
.05322	2.9364
.05371	2.9325
.05420	2.9288
.05469	2.9254
.05518	2.9224
.05566	2.9196
.05615	2.9170
.05664	2.9147
.05713	2.9127
.05762	2.9109
.05811	2.9093
.05859	2.9079
.05908	2.9069
.05957	2.9061
.06006	2.9058
.06055	2.9057
.06104	2.9059
.06152	2.9061
.06201	2.9065
.06250	2.9071
.06299	2.9078
.06348	2.9085
.06396	2.9093
.06445	2.9101
.06494	2.9106
.06543	2.9111
.06592	2.9116
.06641	2.9121
.06689	2.9126
.06738	2.9131
.06787	2.9136
.06836	2.9140
.06885	2.9145
.06934	2.9149
.06982	2.9148
.07031	2.9145
.07080	2.9142
.07129	2.9140
.07178	2.9139
.07227	2.9139
.07275	2.9141
.07324	2.9145
.07373	2.9152
.07422	2.9162
.07471	2.9181
.07520	2.9214
.07568	2.9250
.07617	2.9288
.07666	2.9328
.07715	2.9369
.07764	2.9410
.07813	2.9450
.07861	2.9491
.07910	2.9529
.07959	2.9563
.08008	2.9583
.08057	2.9599
.08105	2.9614
.08154	2.9627
.08203	2.9636
.08252	2.9648
.08301	2.9657
.08350	2.9665
.08398	2.9672
.08447	2.9679
.08496	2.9690
.08545	2.9702
.08594	2.9713
.08643	2.9723
.08691	2.9734
.08740	2.9745
.08789	2.9755
.08838	2.9766
.08887	2.9776
.08936	2.9787
.08984	2.9797

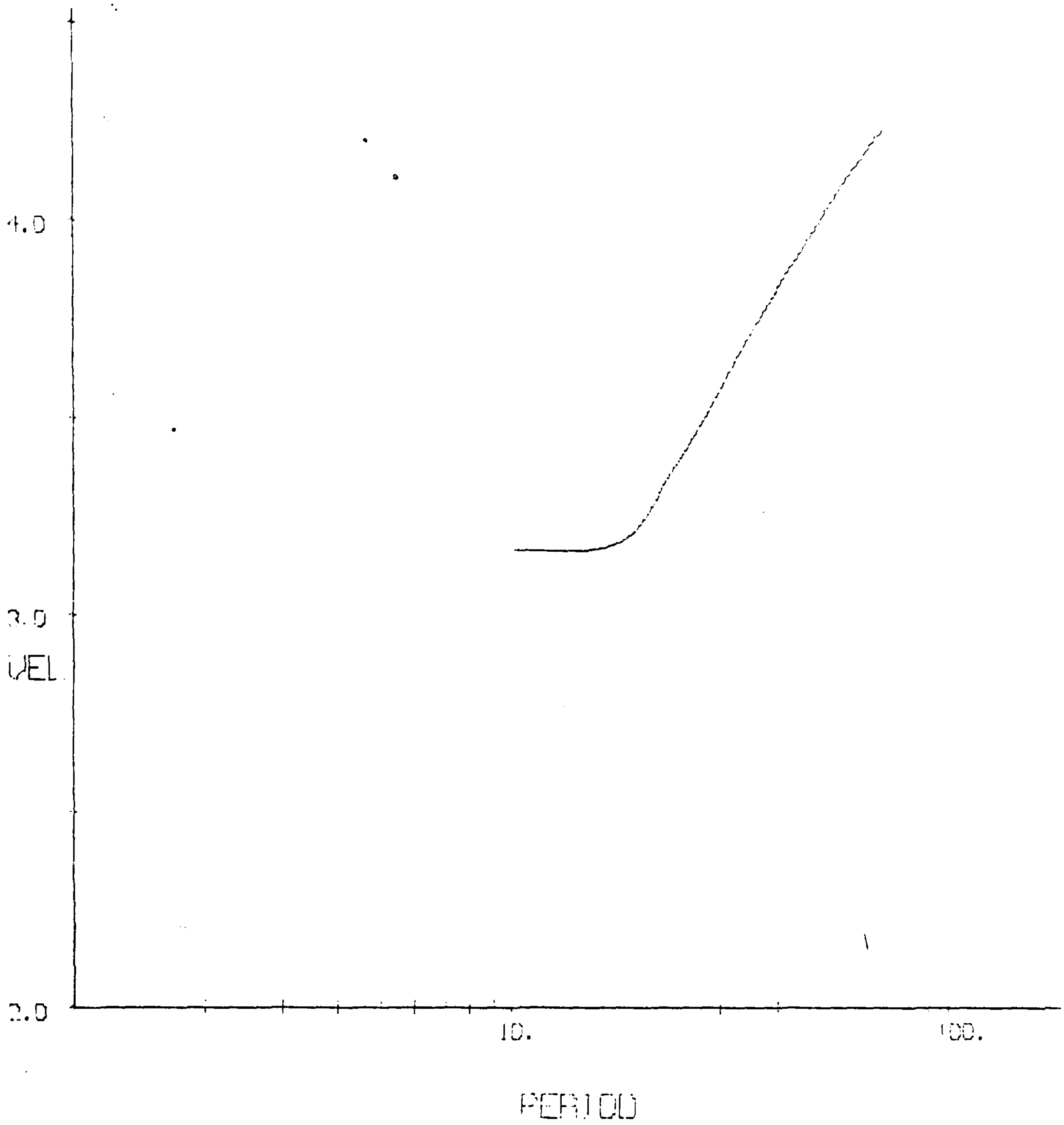
FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)
.09033	2.9807
.09082	2.9817
.09131	2.9827
.09180	2.9837
.09229	2.9847
.09277	2.9856
.09326	2.9866
.09375	2.9875
.09424	2.9885
.09473	2.9894
.09521	2.9903
.09570	2.9912
.09619	2.9921
.09668	2.9930
.09717	2.9939
.09766	2.9948
.09814	2.9956
.09863	2.9965
.09912	2.9973



Love wave from a Novaya Zemlya explosion *recorded* at the Albuquerque, N. M., SRO. This signal was used to determine the phase-matched filter for Love waves for the path Novaya Zemlya-Albuquerque.



Pseudo-autocorrelation function obtained by the application of the Novaya Zemlya-Albuquerque phase-matched filter to the Novaya Zemlya Love wave.



Plot of the apparent Love group velocity dispersion curve obtained for the Novaya Zemlya-Albuquerque path.

TABLED VALUES OF THE APPARENT LOVE GROUP VELOCITY DISPERSION CURVE FOR THE PATH NOVAYA ZEMLYA (73.35N, 55.08E) - ALBUQUERQUE, N. M. (34.93N, 106.45W)

NOVAYA ZEMLYA (73.35N, 55.08E) - ALBUQUERQUE (34.93N, 106.45W)

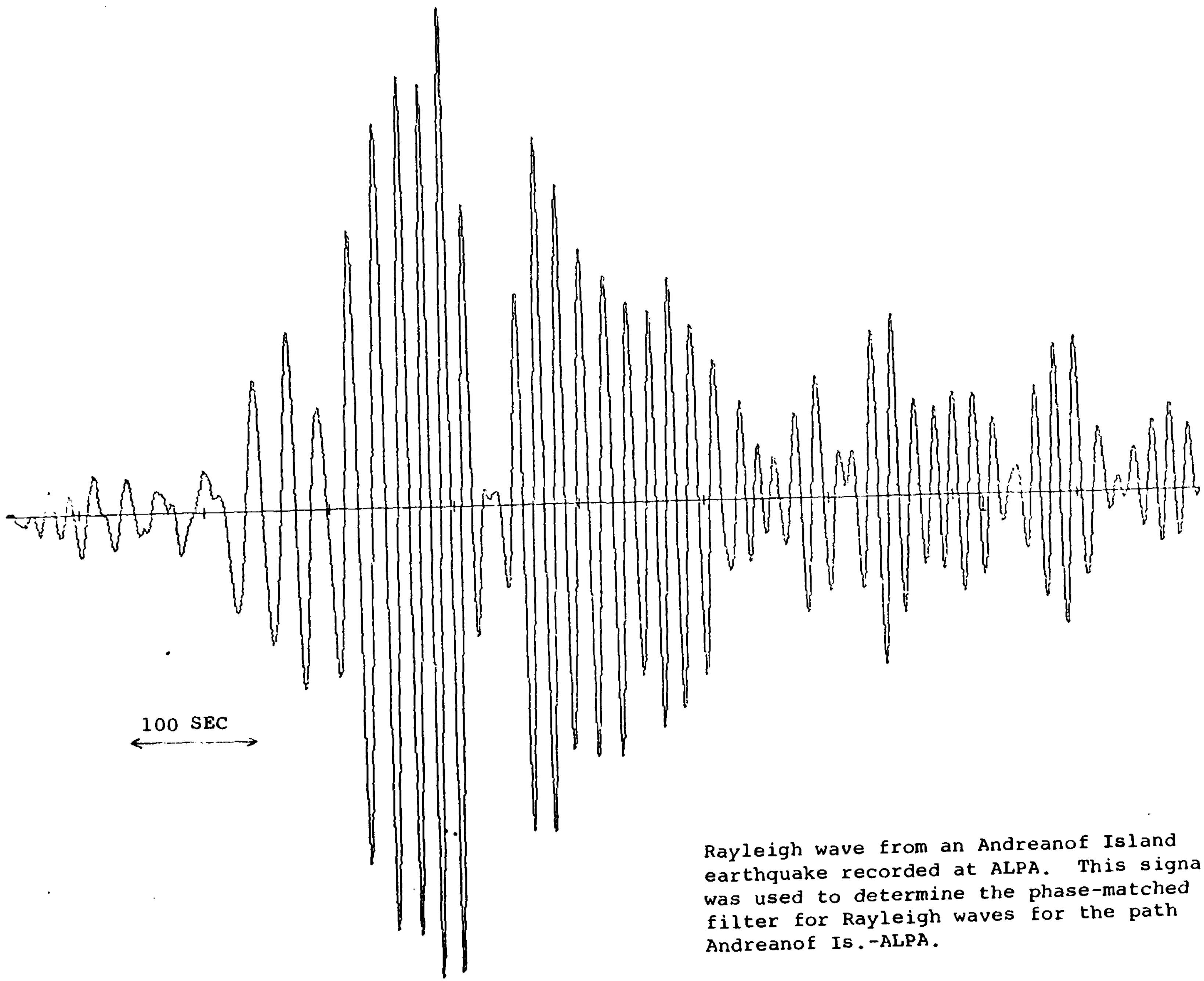
C = +0.450 cycles

FREQUENCY (Hz)	LOVE GROUP VELOCITY (KM/SEC)	FREQUENCY (Hz)	LOVE GROUP VELOCITY (KM/SEC)
.00049	4.5004	.02197	3.9235
.00098	4.5007	.02246	3.9064
.00146	4.5003	.02295	3.8895
.00195	4.5002	.02344	3.8729
.00244	4.4966	.02393	3.8565
.00293	4.4917	.02441	3.8404
.00342	4.4864	.02490	3.8245
.00391	4.4805	.02539	3.8088
.00439	4.4745	.02588	3.7933
.00488	4.4703	.02637	3.7780
.00537	4.4666	.02686	3.7630
.00586	4.4626	.02734	3.7481
.00635	4.4579	.02783	3.7334
.00684	4.4523	.02832	3.7190
.00732	4.4445	.02881	3.7047
.00781	4.4348	.02930	3.6906
.00830	4.4240	.02979	3.6766
.00879	4.4121	.03027	3.6628
.00928	4.3993	.03076	3.6492
.00977	4.3858	.03125	3.6357
.01025	4.3719	.03174	3.6224
.01074	4.3572	.03223	3.6093
.01123	4.3419	.03271	3.5963
.01172	4.3260	.03320	3.5835
.01221	4.3095	.03369	3.5709
.01270	4.2924	.03418	3.5584
.01318	4.2748	.03467	3.5460
.01367	4.2568	.03516	3.5335
.01416	4.2382	.03564	3.5213
.01465	4.2190	.03613	3.5092
.01514	4.1988	.03662	3.4973
.01563	4.1783	.03711	3.4856
.01611	4.1576	.03760	3.4742
.01660	4.1368	.03809	3.4631
.01709	4.1159	.03857	3.4522
.01758	4.0951	.03906	3.4415
.01807	4.0743	.03955	3.4313
.01855	4.0537	.04004	3.4221
.01904	4.0334	.04053	3.4132
.01953	4.0134	.04102	3.4045
.02002	3.9948	.04150	3.3960
.02051	3.9765	.04199	3.3876
.02100	3.9586	.04248	3.3793
.02148	3.9409	.04297	3.3711

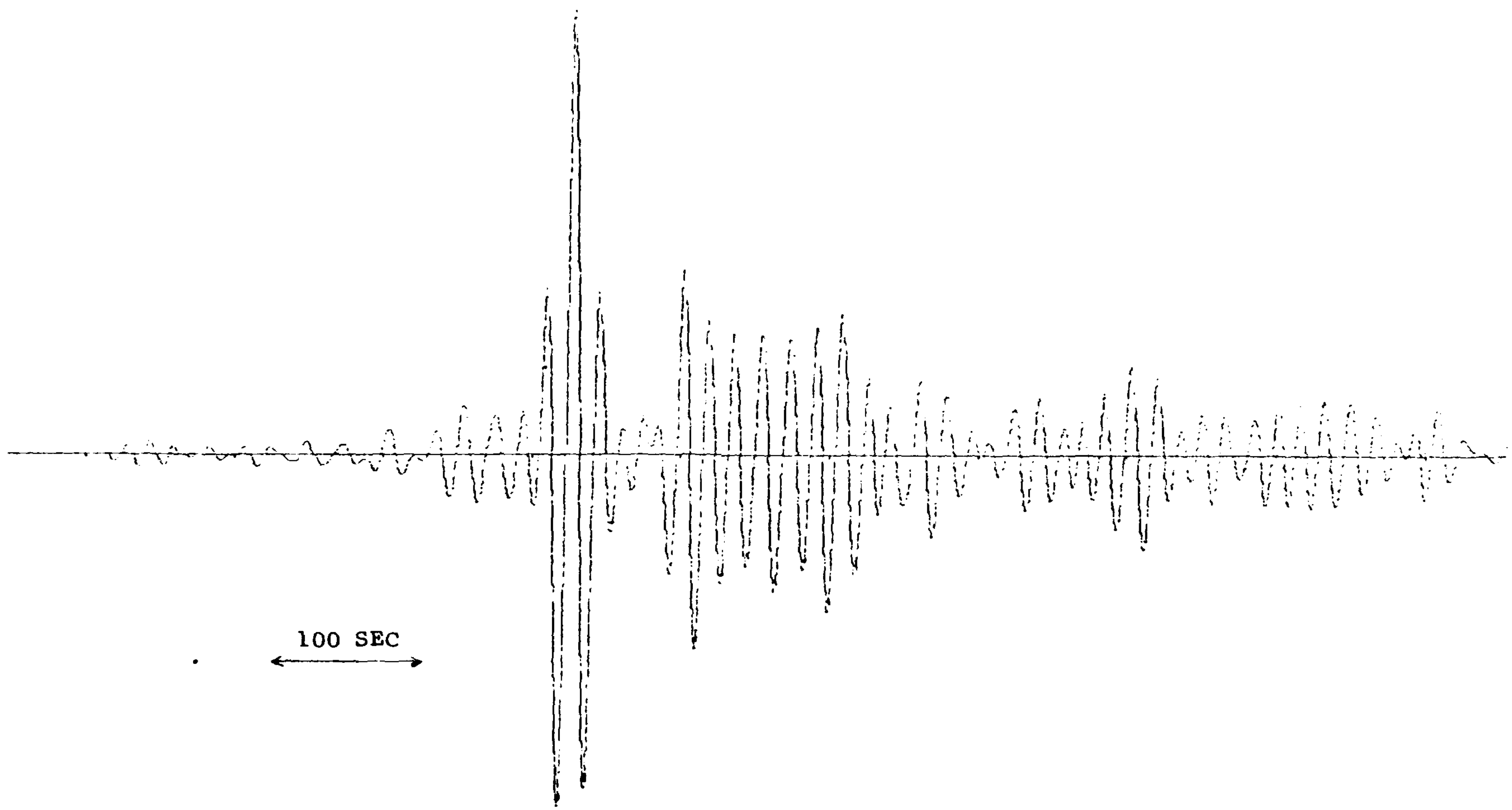
FREQUENCY (Hz)	LOVE GROUP VELOCITY (KM/SEC)
.04346	3.3528
.04395	3.3546
.04443	3.3463
.04492	3.3367
.04541	3.3268
.04590	3.3170
.04639	3.3072
.04688	3.2776
.04736	3.2382
.04785	3.2790
.04834	3.2700
.04883	3.2614
.04932	3.2532
.04980	3.2460
.05029	3.2397
.05078	3.2337
.05127	3.2282
.05176	3.2230
.05225	3.2181
.05273	3.2136
.05322	3.2095
.05371	3.2057
.05420	3.2021
.05469	3.1989
.05518	3.1961
.05566	3.1935
.05615	3.1911
.05664	3.1890
.05713	3.1871
.05762	3.1854
.05811	3.1838
.05859	3.1824
.05908	3.1811
.05957	3.1798
.06006	3.1785
.06055	3.1772
.06104	3.1760
.06152	3.1749
.06201	3.1739
.06250	3.1730
.06299	3.1721
.06348	3.1714
.06396	3.1707
.06445	3.1701
.06494	3.1695
.06543	3.1692
.06592	3.1689
.06641	3.1685
.06689	3.1684

FREQUENCY (Hz)	LOVE GROUP VELOCITY (KM/SEC)
.06738	3.1683
.06787	3.1682
.06836	3.1681
.06885	3.1680
.06934	3.1680
.06982	3.1680
.07031	3.1679
.07080	3.1679
.07129	3.1679
.07178	3.1679
.07227	3.1679
.07275	3.1679
.07324	3.1679
.07373	3.1680
.07422	3.1680
.07471	3.1680
.07520	3.1680
.07568	3.1680
.07617	3.1680
.07666	3.1680
.07715	3.1680
.07764	3.1680
.07813	3.1680
.07861	3.1680
.07910	3.1680
.07959	3.1680
.08008	3.1680
.08057	3.1680
.08105	3.1680
.08154	3.1680
.08203	3.1680
.08252	3.1680
.08301	3.1680
.08350	3.1680
.08398	3.1680
.08447	3.1680
.08496	3.1680
.08545	3.1680
.08594	3.1680
.08643	3.1680
.08691	3.1680
.08740	3.1680
.08789	3.1680
.08838	3.1680
.08887	3.1680
.08936	3.1680
.08984	3.1680
.09033	3.1680
.09082	3.1680

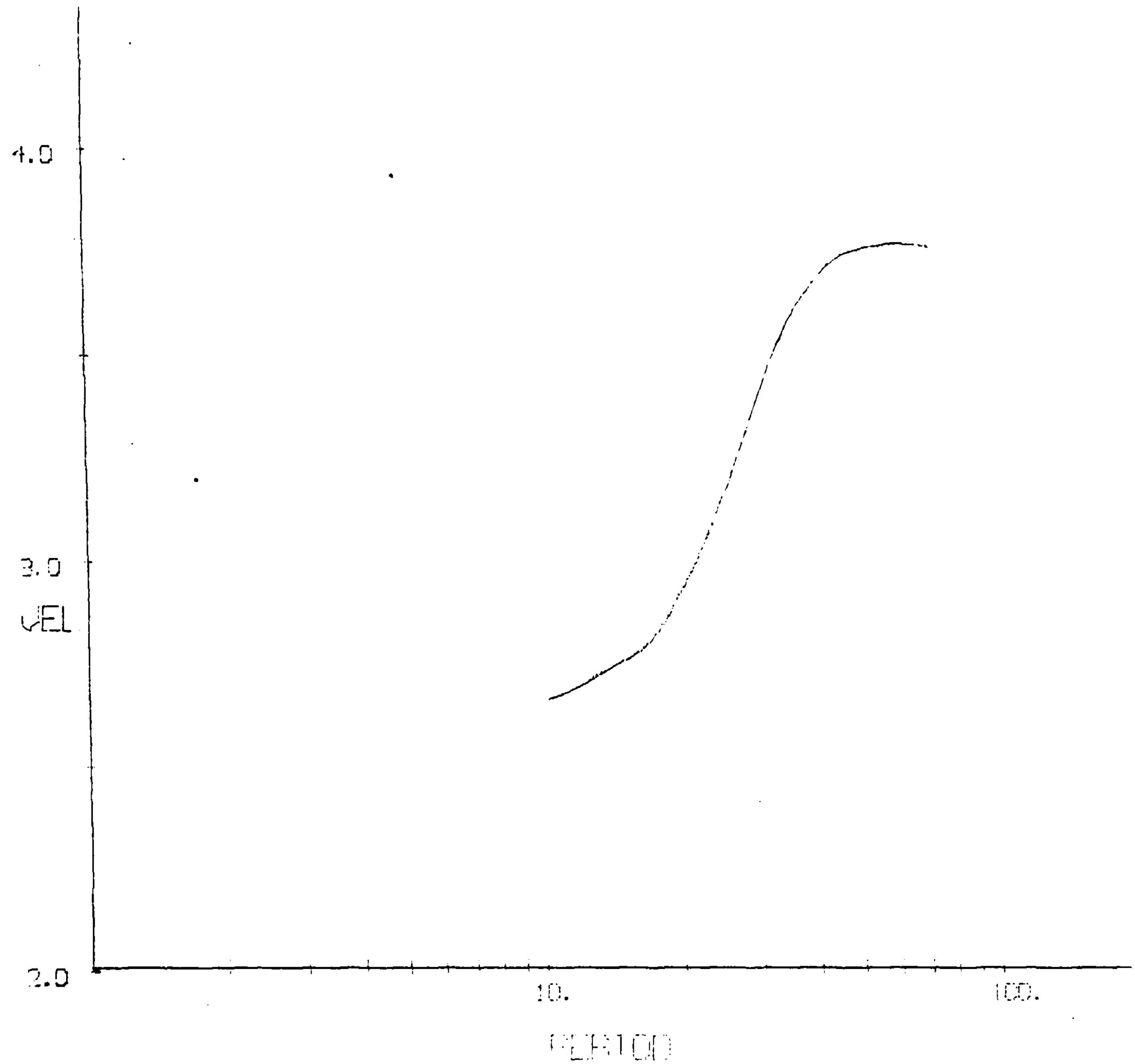
FREQUENCY (Hz)	LOVE GROUP VELOCITY (KM/SEC)
.09131	3.1680
.09180	3.1680
.09229	3.1680
.09277	3.1680
.09326	3.1680
.09375	3.1680
.09424	3.1680
.09473	3.1680
.09521	3.1680
.09570	3.1680
.09619	3.1680
.09668	3.1680
.09717	3.1680
.09766	3.1680
.09814	3.1680
.09863	3.1680
.09912	3.1680



Rayleigh wave from an Andreanof Island earthquake recorded at ALPA. This signal was used to determine the phase-matched filter for Rayleigh waves for the path Andreanof Is.-ALPA.



Pseudo-autocorrelation function obtained by the application of the Andreanof Is.-ALPA phase-matched filter to the Andreanof Island Rayleigh wave.



Plot of the apparent Rayleigh group velocity dispersion curve obtained for the Andreanof Is.-ALPA path.

TABLED VALUES FOR THE APPARENT RAYLEIGH GROUP VELOCITY DISPERSION CURVE FOR THE PATH ANDREANOF ISLAND (51.60N, 173.50W) - ALPA (65.40N, 147.90W)

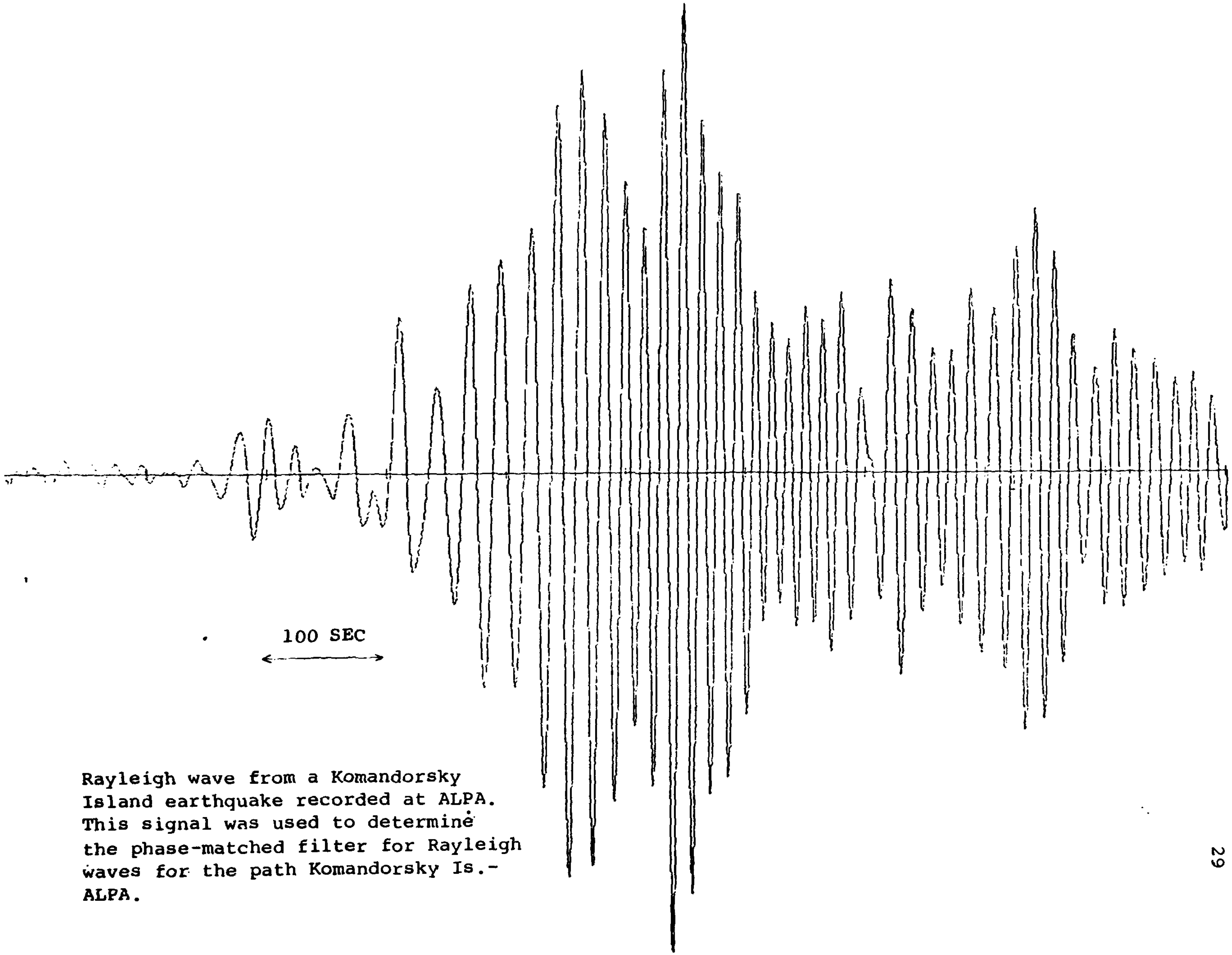
ANDREANOF IS. (51.60N, 173.50W) - ALPA (65.40N, 147.90W)

C = 0.0 cycles

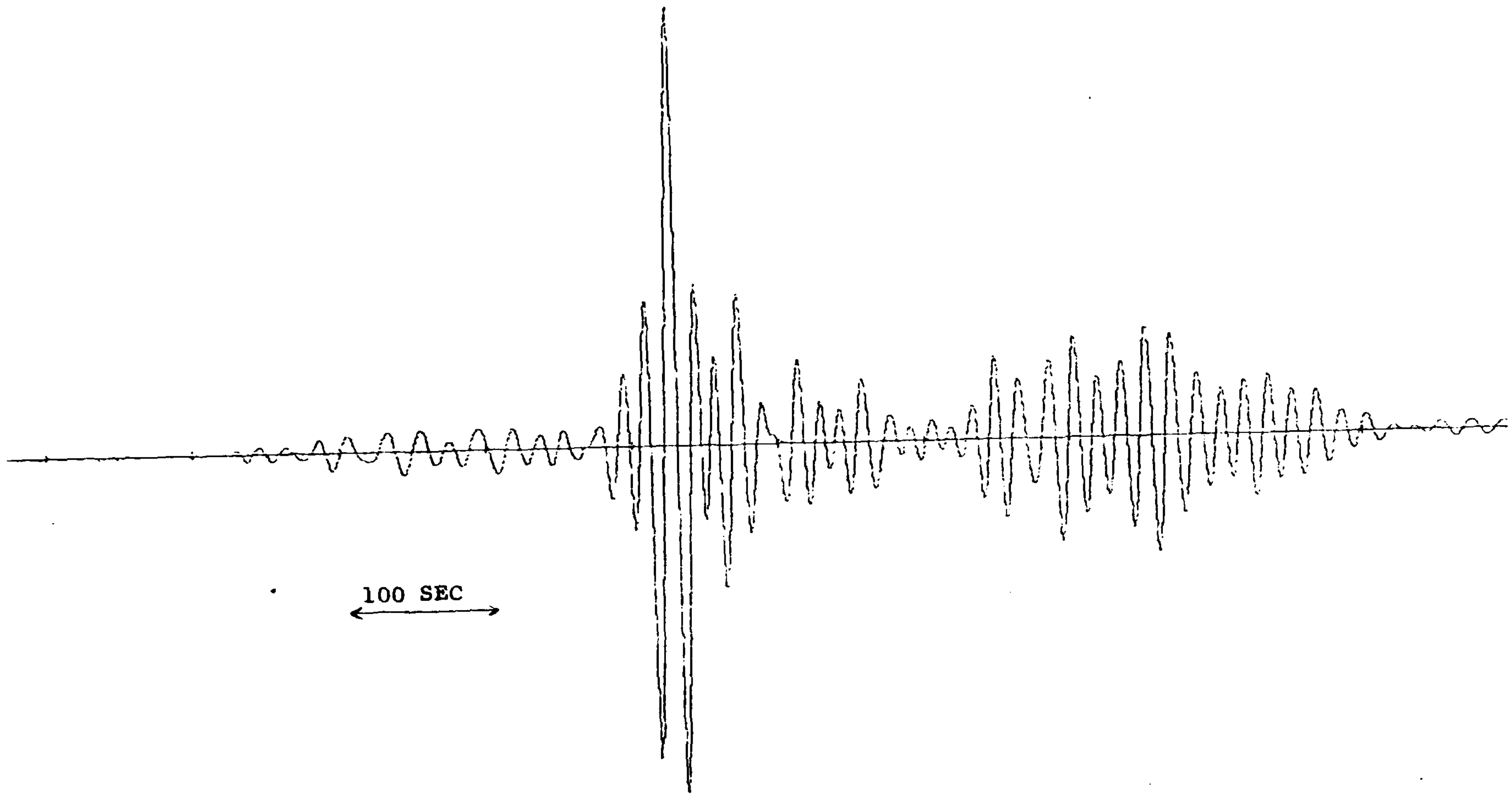
FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)	FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)
.00049	3.99[illegible]	.02100	3.7387
.00098	3.9151	.02148	3.7346
.00146	3.8010	.02197	3.7290
.00195	3.6943	.02246	3.7221
.00244	3.6217	.02295	3.7141
.00293	3.5662	.02344	3.7051
.00342	3.5445	.02393	3.6954
.00391	3.5352	.02441	3.6849
.00439	3.5465	.02490	3.6742
.00488	3.5592	.02539	3.6630
.00537	3.5715	.02588	3.6509
.00586	3.5876	.02637	3.6383
.00635	3.6043	.02686	3.6250
.00684	3.6185	.02734	3.6112
.00732	3.6297	.02783	3.5967
.00781	3.6427	.02832	3.5816
.00830	3.6569	.02881	3.5659
.00879	3.6690	.02930	3.5497
.00928	3.6781	.02979	3.5330
.00977	3.6864	.03027	3.5159
.01025	3.6947	.03076	3.4985
.01074	3.7034	.03125	3.4809
.01123	3.7131	.03174	3.4629
.01172	3.7227	.03223	3.4448
.01221	3.7307	.03271	3.4265
.01270	3.7364	.03320	3.4079
.01318	3.7408	.03369	3.3890
.01367	3.7442	.03418	3.3701
.01416	3.7475	.03467	3.3512
.01465	3.7504	.03516	3.3324
.01514	3.7527	.03564	3.3137
.01563	3.7542	.03613	3.2952
.01611	3.7550	.03662	3.2769
.01660	3.7551	.03711	3.2589
.01709	3.7545	.03760	3.2411
.01758	3.7531	.03809	3.2236
.01807	3.7513	.03857	3.2065
.01855	3.7497	.03906	3.1898
.01904	3.7478	.03955	3.1735
.01953	3.7462	.04004	3.1585
.02002	3.7440	.04053	3.1438
.02051	3.7416	.041[illegible]	3.1295

FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)	FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)
.04150	3.1155	.06494	2.7581
.04199	3.1019	.06543	2.7558
.04248	3.0887	.06592	2.7537
.04297	3.0759	.06641	2.7516
.04346	3.0633	.06689	2.7496
.04395	3.0511	.06738	2.7476
.04443	3.0392	.06787	2.7457
.04492	3.0277	.06836	2.7439
.04541	3.0165	.06885	2.7421
.04590	3.0055	.06934	2.7404
.04639	2.9949	.06982	2.7387
.04688	2.9846	.07031	2.7370
.04736	2.9744	.07080	2.7353
.04785	2.9646	.07129	2.7335
.04834	2.9548	.07178	2.7317
.04883	2.9454	.07227	2.7300
.04932	2.9360	.07275	2.7282
.04980	2.9265	.07324	2.7265
.05029	2.9169	.07373	2.7248
.05078	2.9076	.07422	2.7232
.05127	2.8984	.07471	2.7216
.05176	2.8893	.07520	2.7200
.05225	2.8806	.07568	2.7185
.05273	2.8721	.07617	2.7170
.05322	2.8638	.07666	2.7155
.05371	2.8557	.07715	2.7139
.05420	2.8480	.07764	2.7123
.05469	2.8405	.07813	2.7109
.05518	2.8336	.07861	2.7093
.05566	2.8276	.07910	2.7078
.05615	2.8220	.07959	2.7063
.05664	2.8167	.08008	2.7048
.05713	2.8117	.08057	2.7032
.05762	2.8069	.08105	2.7016
.05811	2.8023	.08154	2.7001
.05859	2.7981	.08203	2.6985
.05908	2.7940	.08252	2.6967
.05957	2.7902	.08301	2.6950
.06006	2.7865	.08350	2.6935
.06055	2.7831	.08398	2.6865
.06104	2.7798	.08447	2.6851
.06152	2.7767	.08496	2.6837
.06201	2.7738	.08545	2.6824
.06250	2.7708	.08594	2.6810
.06299	2.7681	.08643	2.6797
.06348	2.7654	.08691	2.6784
.06396	2.7629	.08740	2.6772
.06445	2.7605	.08789	2.6760

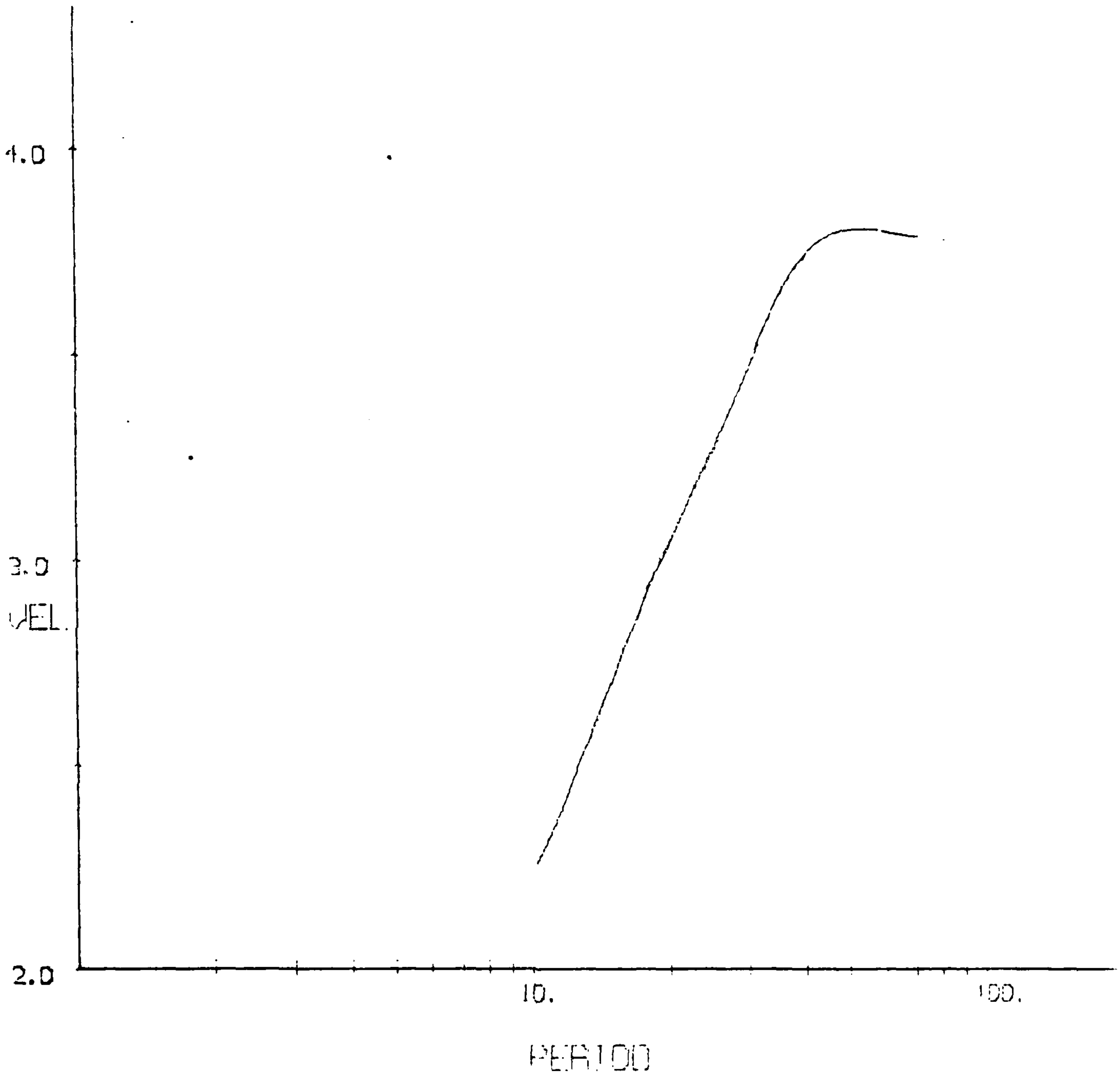
FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)
.08838	2.6748
.08887	2.6736
.08936	2.6725
.08984	2.6713
.09033	2.6702
.09082	2.6691
.09131	2.6681
.09180	2.6670
.09229	2.6660
.09277	2.6650
.09326	2.6640
.09375	2.6630
.09424	2.6621
.09473	2.6612
.09521	2.6603
.09570	2.6594
.09619	2.6585
.09668	2.6577
.09717	2.6568
.09766	2.6560
.09814	2.6552
.09863	2.6544
.09912	2.6536



Rayleigh wave from a Komandorsky Island earthquake recorded at ALPA. This signal was used to determine the phase-matched filter for Rayleigh waves for the path Komandorsky Is.-ALPA.



Pseudo-autocorrelation function obtained by the application of the Komandorsky Is.-ALPA phase-matched filter to the Komandorsky Island Rayleigh wave.



Plot of the apparent Rayleigh group velocity dispersion curve obtained for the Komandorsky Is.-ALPA path.

TABLED VALUES FOR THE APPARENT RAYLEIGH GROUP VELOCITY DISPERSION CURVE FOR THE PATH KOMANDORSKY ISLAND (54.40N, 167.5E)-ALPA (65.03N, 147.20W).

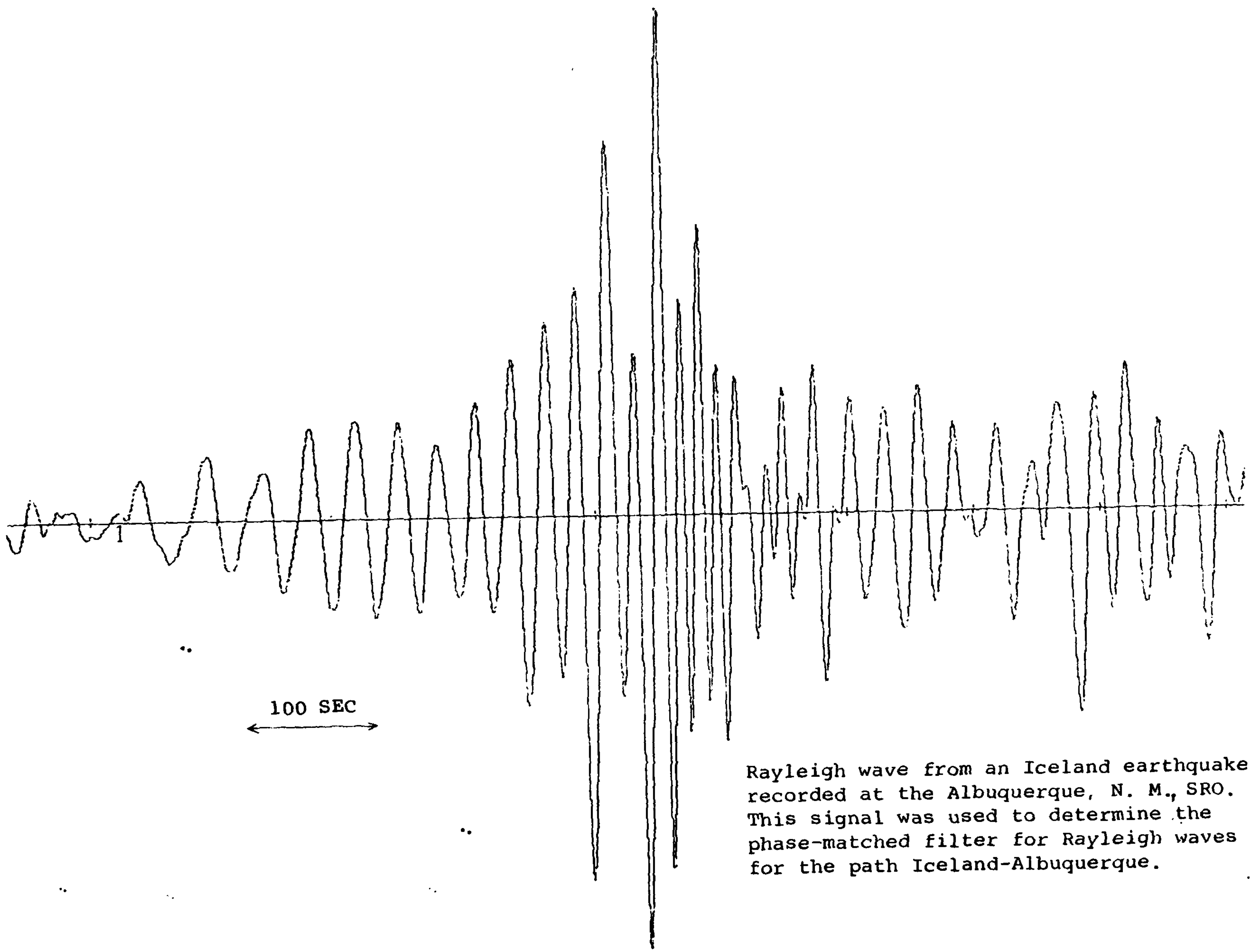
KOMANDORSKY IS. (54.40N, 167.50E) - ALPA (65.03N, 147.20W)

C = +0.425 cycles

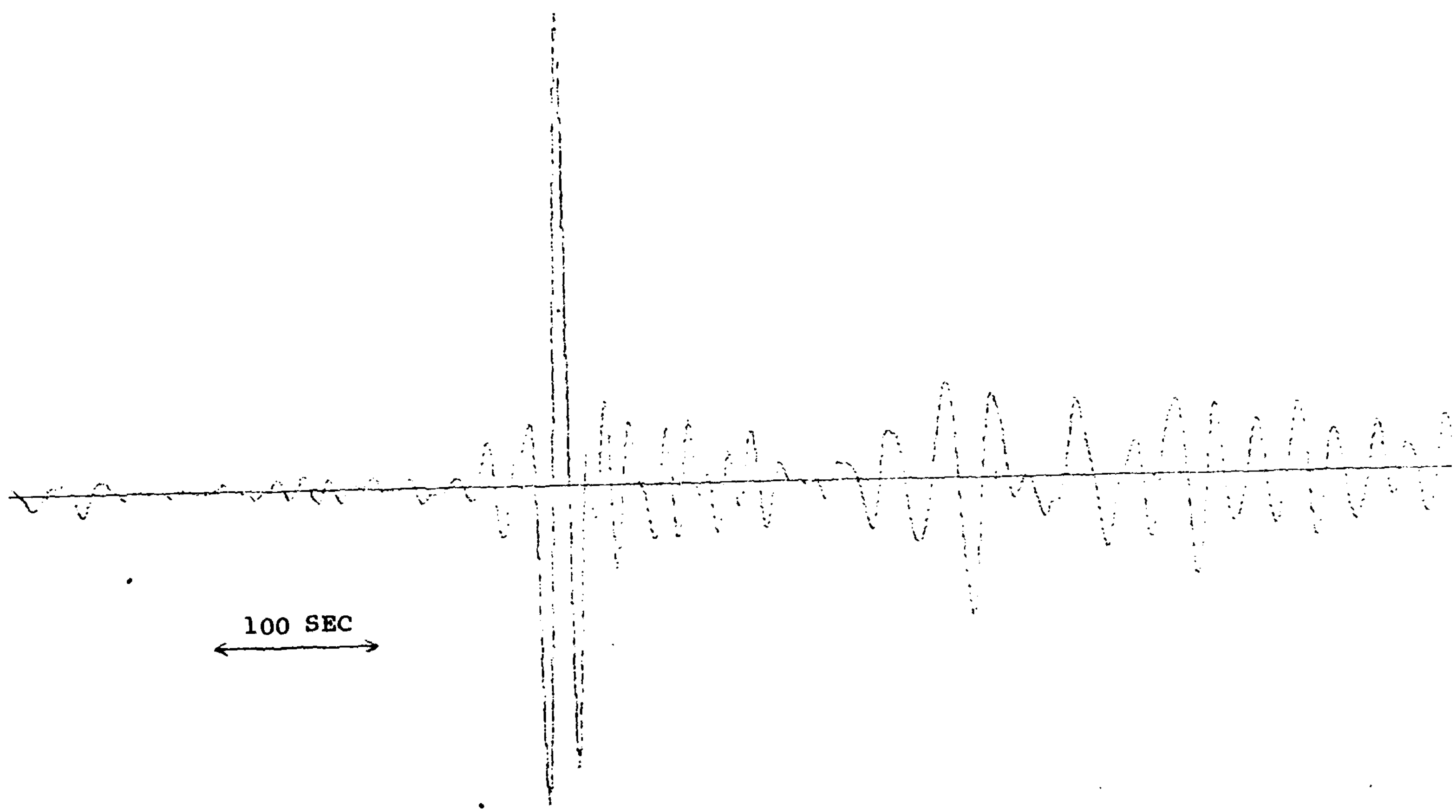
FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)	FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)
.00049	3.9801	.02148	3.7942
.00098	3.9932	.02197	3.7898
.00146	3.9502	.02246	3.7841
.00195	3.8082	.02295	3.7775
.00244	3.7015	.02344	3.7700
.00293	3.6324	.02393	3.7614
.00342	3.5992	.02441	3.7519
.00391	3.5850	.02490	3.7415
.00439	3.5927	.02539	3.7304
.00488	3.6101	.02588	3.7182
.00537	3.6308	.02637	3.7055
.00586	3.6469	.02686	3.6919
.00635	3.6617	.02734	3.6779
.00684	3.6771	.02783	3.6631
.00732	3.6933	.02832	3.6477
.00781	3.7062	.02881	3.6316
.00830	3.7163	.02930	3.6151
.00879	3.7267	.02979	3.5982
.00928	3.7383	.03027	3.5811
.00977	3.7477	.03076	3.5637
.01025	3.7545	.03125	3.5462
.01074	3.7602	.03174	3.5285
.01123	3.7654	.03223	3.5108
.01172	3.7698	.03271	3.4932
.01221	3.7737	.03320	3.4759
.01270	3.7771	.03369	3.4588
.01318	3.7802	.03418	3.4416
.01367	3.7827	.03467	3.4251
.01416	3.7848	.03516	3.4086
.01465	3.7868	.03564	3.3922
.01514	3.7889	.03613	3.3762
.01563	3.7916	.03662	3.3605
.01611	3.7949	.03711	3.3450
.01660	3.7979	.03760	3.3299
.01709	3.8007	.03809	3.3152
.01758	3.8028	.03857	3.3008
.01807	3.8039	.03906	3.2865
.01855	3.8040	.03955	3.2733
.01904	3.8035	.04004	3.2611
.01953	3.8024	.04053	3.2493
.02002	3.8014	.04102	3.2377
.02051	3.7996	.04150	3.2264
.02100	3.7974	.04199	3.2153

FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)	FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)
.04248	3.2045	.06641	2.7166
.04297	3.1939	.06689	2.7066
.04346	3.1833	.06738	2.6967
.04395	3.1730	.06787	2.6870
.04443	3.1628	.06836	2.6774
.04492	3.1526	.06885	2.6679
.04541	3.1417	.06934	2.6585
.04590	3.1310	.06982	2.6494
.04639	3.1203	.07031	2.6404
.04688	3.1098	.07080	2.6315
.04736	3.0993	.07129	2.6230
.04785	3.0891	.07178	2.6146
.04834	3.0791	.07227	2.6065
.04883	3.0692	.07275	2.5986
.04932	3.0594	.07324	2.5908
.04980	3.0505	.07373	2.5833
.05029	3.0422	.07422	2.5759
.05078	3.0341	.07471	2.5687
.05127	3.0261	.07520	2.5617
.05176	3.0181	.07568	2.5542
.05225	3.0102	.07617	2.5540
.05273	3.0023	.07666	2.5464
.05322	2.9943	.07715	2.5386
.05371	2.9863	.07764	2.5309
.05420	2.9781	.07813	2.5231
.05469	2.9699	.07861	2.5154
.05518	2.9612	.07910	2.5077
.05566	2.9513	.07959	2.5001
.05615	2.9412	.08008	2.4924
.05664	2.9309	.08057	2.4848
.05713	2.9204	.08105	2.4773
.05762	2.9098	.08154	2.4698
.05811	2.8990	.08203	2.4623
.05859	2.8881	.08252	2.4549
.05908	2.8771	.08301	2.4475
.05957	2.8660	.08350	2.4402
.06006	2.8548	.08398	2.4329
.06055	2.8436	.08447	2.4257
.06104	2.8324	.08496	2.4185
.06152	2.8211	.08545	2.4114
.06201	2.8099	.08594	2.4044
.06250	2.7993	.08643	2.3975
.06299	2.7887	.08691	2.3906
.06348	2.7782	.08740	2.3839
.06396	2.7678	.08789	2.3772
.06445	2.7574	.08838	2.3706
.06494	2.7471	.08887	2.3641
.06543	2.7368	.08936	2.3577
.06592	2.7266	.08984	2.3514

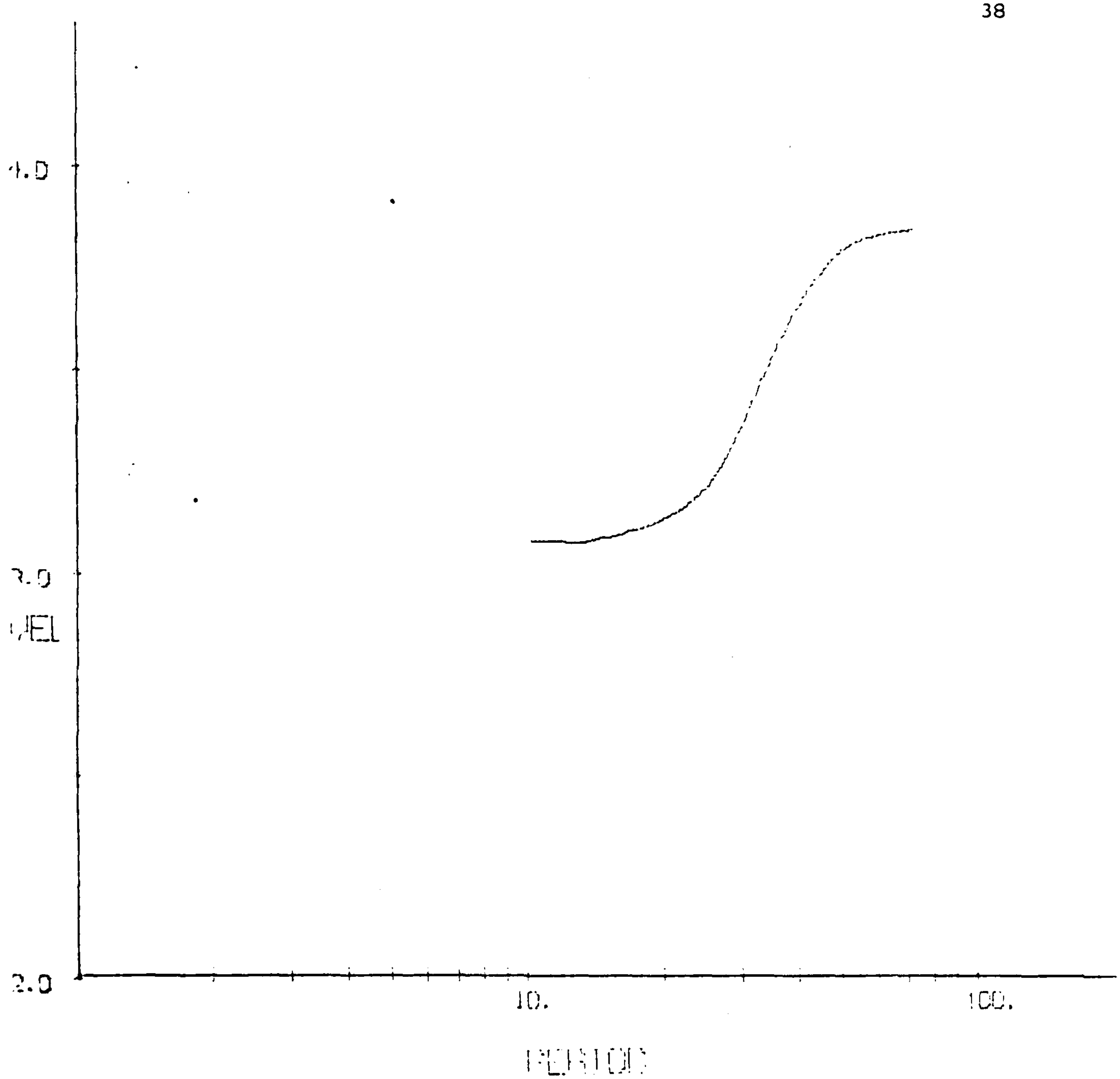
FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)
.09033	2.3451
.09082	2.3393
.09131	2.3336
.09180	2.3280
.09229	2.3225
.09277	2.3171
.09326	2.3118
.09375	2.3065
.09424	2.3014
.09473	2.2963
.09521	2.2913
.09570	2.2864
.09619	2.2815
.09668	2.2767
.09717	2.2720
.09766	2.2673
.09814	2.2627
.09863	2.2581
.09912	2.2536



Rayleigh wave from an Iceland earthquake recorded at the Albuquerque, N. M., SRO. This signal was used to determine the phase-matched filter for Rayleigh waves for the path Iceland-Albuquerque.



Pseudo-autocorrelation function obtained by the application of the Iceland-Albuquerque phase-matched filter to the Iceland Rayleigh wave.



Plot of the apparent Rayleigh group velocity dispersion curve obtained for the Iceland-Albuquerque path.

TABLED VALUES FOR THE APPARENT RAYLEIGH GROUP VELOCITY DISPERSION CURVE FOR THE PATH ICELAND (66.05N, 16.69W) - ALBUQUERQUE (34.93N, 106.45W).

ICELAND (66.05N, 16.69W) - ALBUQUERQUE (34.93N, 106.45W)

ϵ = -0.180 cycles

FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)	FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)
.00049	3.9958	.02100	3.7816
.00098	3.9883	.02148	3.7699
.00146	3.9796	.02197	3.7577
.00195	3.9693	.02246	3.7448
.00244	3.9610	.02295	3.7313
.00293	3.9532	.02344	3.7172
.00342	3.9454	.02393	3.7026
.00391	3.9379	.02441	3.6875
.00439	3.9307	.02490	3.6715
.00488	3.9241	.02539	3.6553
.00537	3.9180	.02588	3.6386
.00586	3.9123	.02637	3.6216
.00635	3.9069	.02686	3.6045
.00684	3.9018	.02734	3.5871
.00732	3.8970	.02783	3.5697
.00781	3.8925	.02832	3.5522
.00830	3.8884	.02881	3.5347
.00879	3.8844	.02930	3.5172
.00928	3.8807	.02979	3.4997
.00977	3.8773	.03027	3.4824
.01025	3.8741	.03076	3.4652
.01074	3.8712	.03125	3.4483
.01123	3.8683	.03174	3.4316
.01172	3.8656	.03223	3.4152
.01221	3.8630	.03271	3.3992
.01270	3.8603	.03320	3.3835
.01318	3.8578	.03369	3.3682
.01367	3.8552	.03418	3.3534
.01416	3.8526	.03467	3.3392
.01465	3.8501	.03516	3.3253
.01514	3.8481	.03564	3.3129
.01563	3.8458	.03613	3.3006
.01611	3.8434	.03662	3.2887
.01660	3.8405	.03711	3.2774
.01709	3.8372	.03760	3.2666
.01758	3.8334	.03809	3.2563
.01807	3.8290	.03857	3.2466
.01855	3.8240	.03906	3.2374
.01904	3.8182	.03955	3.2288
.01953	3.8116	.04004	3.2215
.02002	3.8023	.04053	3.2147
.02051	3.7923	.04102	3.2084

FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)
.04150	3.2026
.04199	3.1971
.04248	3.1921
.04297	3.1873
.04346	3.1829
.04395	3.1788
.04443	3.1750
.04492	3.1712
.04541	3.1675
.04590	3.1641
.04639	3.1608
.04688	3.1577
.04736	3.1545
.04785	3.1520
.04834	3.1493
.04883	3.1467
.04932	3.1443
.04980	3.1417
.05029	3.1391
.05078	3.1366
.05127	3.1342
.05176	3.1319
.05225	3.1297
.05273	3.1276
.05322	3.1256
.05371	3.1236
.05420	3.1218
.05469	3.1202
.05518	3.1189
.05566	3.1178
.05615	3.1167
.05664	3.1156
.05713	3.1145
.05762	3.1137
.05811	3.1128
.05859	3.1117
.05908	3.1109
.05957	3.1099
.06006	3.1085
.06055	3.1071
.06104	3.1057
.06152	3.1042
.06201	3.1028
.06250	3.1015
.06299	3.1001
.06348	3.0988

FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)
.06396	3.0976
.06445	3.0964
.06494	3.0957
.06543	3.0952
.06592	3.0947
.06641	3.0942
.06689	3.0938
.06738	3.0934
.06787	3.0930
.06836	3.0926
.06885	3.0921
.06934	3.0917
.06982	3.0909
.07031	3.0899
.07080	3.0888
.07129	3.0877
.07178	3.0867
.07227	3.0856
.07275	3.0846
.07324	3.0836
.07373	3.0826
.07422	3.0817
.07471	3.0810
.07520	3.0805
.07568	3.0802
.07617	3.0799
.07666	3.0796
.07715	3.0795
.07764	3.0794
.07813	3.0793
.07861	3.0794
.07910	3.0794
.07959	3.0795
.08008	3.0798
.08057	3.0800
.08105	3.0804
.08154	3.0807
.08203	3.0810
.08252	3.0814
.08301	3.0817
.08350	3.0821
.08398	3.0824
.08447	3.0827
.08496	3.0828
.08545	3.0828
.08594	3.0829

FREQUENCY (Hz)	RAYLEIGH GROUP VELOCITY (KM/SEC)
.08643	3.0329
.08691	3.0329
.08740	3.0329
.08789	3.0329
.08838	3.0328
.08887	3.0328
.08936	3.0327
.08984	3.0327
.09033	3.0327
.09082	3.0327
.09131	3.0327
.09180	3.0327
.09229	3.0327
.09277	3.0327
.09326	3.0327
.09375	3.0327
.09424	3.0327
.09473	3.0327
.09521	3.0327
.09570	3.0327
.09619	3.0327
.09668	3.0327
.09717	3.0327
.09766	3.0327
.09814	3.0327
.09863	3.0327
.09912	3.0327