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Email: gdz@sub.uni-goettingen.de

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# Global and Regional Phase Velocities of Long-Period Fundamental Mode Rayleigh Waves*

W. Mitronovas

Institute of Geophysics, ETH-Hoenggerberg (HPP), CH-8093 Zurich, Switzerland

**Abstract.** New data for the fundamental mode Rayleigh waves from 16 earthquakes recorded on special instruments are used here to determine phase velocities on regional and global basis in the period range of 15 s–350 s. Two types of special instruments are used here: (1) broad-band long-period system, and (2) ultra long period system. Data from the first type are used to determine phase velocities by the two-station method in the period range of 15 s – 260 s on a regional basis between Madeira Island (Funchal-FUN) and southern Portugal (Faro-FAR) and between Faro and Zurich (ZUR). The distances between the stations are 950 km and 1750 km, respectively. Based on seven events for each station pair, the determined phase velocities have an average standard error of the mean of 0.01 km/s. Data from both types of instruments are used in the one-station method to determine phase velocities in the period range of 100 s–350 s on a global basis using earth circling paths through ZUR from four earthquakes. The velocities, based on three determinations from each earthquake using various combination of $R_1$ through $R_6$, have an average standard error of about 0.005 km/s. Surface waves circling the earth in different places show clear differences in phase velocity up to 0.02 km/s, even at periods of 300 s.

**Key words:** Special LP instruments – Long-period Rayleigh waves – Regional phase velocities.

## 1. Introduction

To date systematic determination of surface wave velocities of the fundamental mode at very long periods ($T > 150$ s) has been possible only on a global scale. Such inforamtion on a regional basis would be very useful in outlining structural differences between (and within) continents and oceans to greater depths which

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in turn would be helpful in understanding the dynamics of the earth. The lack of proper instruments made such studies until recently very difficult.

The study of higher mode surface waves provides a way to reach greater depths using shorter periods. But the data analysis is, by comparison to the fundamental mode, considerably more complicated and is still being developed and improved. In any case, the study of higher modes should be used, if possible, not as an alternative but as a complimentary tool to the fundamental mode.

Recent developments in long-period (LP) seismometry, meanwhile are making it easier to determine surface wave velocities of the fundamental mode on a regional scale to a higher precision and at longer periods. In this study, first data from two types of new LP instruments are used to determine accurately phase velocities of the fundamental mode Rayleigh waves in the period range of 15 s–350 s on a regional as well as global scale. Before presenting and discussing the results, a brief description of the instruments will be given. For the purpose of discussion, the new instruments will be referred to as (1) broad-band long-period and (2) ultra long period seismographs.

## 2. Instrumentation

### *A. Broad-Band LP Seismograph*

The conventional long-period (LP) instruments of the type used in the WWSSN stations have been successfully used for many years to study surface wave dispersion on regional basis for periods up to 150 s (Knopoff, 1972). Only rarely was it possible to measure velocities at periods greater than 200 s (Biswas and Knopoff, 1974). When very low noise, large dynamic range DC amplifiers became available, it became possible to develop a new LP instrument that has several important advantages over the conventional type in its application to the study of surface wave propagation on a regional basis. This was done by replacing the LP galvanometer, photographic recording part of the conventional system by an electronic amplifier-filter, ink recording system. The low noise, large dynamic range are crucial requirements in an amplifier for such LP application. This seismograph has the following important advantages over the conventional system: (1) the transfer function is more stable with time and environmental conditions and can be determined more easily and accurately; (2) the amplitude response as a function of period is so flexible that it can be shaped to almost any desired form; (3) installation and operating costs are considerably lower because the photographic recording and its dark room are replaced by ink recording on cheap paper. In fact, such a system has been demonstrated to operate quite satisfactorily in any building with a basement where a person can be persuaded to change records regularly. This makes it possible to locate a recording station almost anywhere.

The first type of instrument from which data will be presented was designed especially to study surface wave dispersion on a regional basis in a broad period range (5 s–250 s). This was accomplished by combining a highly damped moving coil type seismometer with a natural period near 15 s with an electronic filter with a corner period near 200 s (equivalent to a galvanometer with a

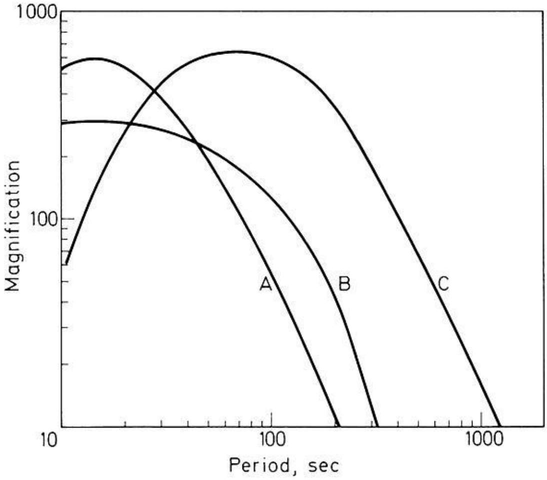

**Fig. 1 A–C.** Amplitude magnification as a function of period for three types of seismographs:
**A** Conventional seismometer-galvanometer LP system used in WWSSN.
**B** New broad-band LP system.
**C** New ultra long period system

period of 200 s). In addition, the magnification of the system was kept sufficiently low so that signals from larger earthquakes, with relatively more energy at long periods, would not be off scale. This system has been described in detail by Wielandt and Mitronovas (1976). A typical amplitude response of such a system is compared in Figure 1 to the response of a standard system (WWSSN) and to the second type (ultra long period) to be described below.

## *B. Ultra Long Period Seismograph*

The maximum magnification of the broad-band LP system described above is limited in practice primarily by the long period noise due not to ground motion but to environmental conditions at the seismometer. To substantially increase the gain at very long periods, it is necessary first to increase the output signal from the seismometer by replacing the velocity transducer by a displacement transducer, then to protect the seismometer from any magnetic, pressure, temperature and other fluctuations in the environment, and finally to reduce the signal at short periods (low-pass filter) if a high dynamic range recording (digital) is not available. It has been found in practice that the temperature variation is the most difficult to eliminate because the effect is normally not only very large but difficult to reduce at very long periods.

There have been many different approaches to solve the above problem. The approach in designing this seismometer has been to start with small dimensions using a flat spring suspension instead of the more conventional helical spring of the LaCoste type. The design of the flat spring suspension is described by Wielandt (1975). The temperature effect of the flat spring is adjusted to produce as small temperature effect as possible for the overall seismometer in the required period range. The small size of the instrument makes it easier and cheaper to reduce the magnetic, pressure and temperature effects of the environment to acceptable levels. Details for the overall system will be published in the near future.

It has been demonstrated in practice that an ultra long period system with the amplitude response and gain as shown in Figure 1 can be successfully operated in an office building with a normal basement, as is the case at our institute in Zurich where the data were obtained. The noise and dynamic range requirements of the electronic amplifier filters system depend on the shape of the transfer function. For that shown in Figure 1 the requirements are less stringent than for the broad-band seismograph. Recent improvements in the system made it possible to increase the gain about five times over that shown in Figure 1. So far there are only few data from the improved system.

## 3. Data and Method of Analysis

### *A. Two-Station Method*

Data from the broad-band long period system were digitized by hand at two seconds per sample from seismograms recorded at 60 mm/min. Time variable, band-pass filtering (Landisman et al., 1969) was used as an aid to separate the fundamental from the higher modes and to reduce the interference effects of the multipath propagation of surface waves. The filters were based upon a preliminary determination of dispersion (group) velocities inferred from a moving window analysis.

When more than one recording station is available, surface wave phase velocities have normally been determined either by a two-station method (Brune and Dorman, 1963) or by a tripartite (multipartite) array (Press, 1956). Knopoff et al. (1967) have demonstrated that in the presence of lateral heterogeneities the determined velocities, based on a tripartite net where the surface waves do not propagate parallel to one of the legs, may be significantly in error; but when the propagating vector is nearly parallel to the two stations of a tripartite net which are also used in the two-station method the results for the two methods are always similar. The only advantage of the tripartite over the two-station method would be in cases where the propagating vector deviates systematically from the great circle path. However, the examples of Knopoff et al. (1967) suggest that, in many cases, the deviation from the great circle path is not large. The results of Gjevik (1974) show more directly that, even for short periods ($T=20$ s), only for extreme cases is the propagation direction significantly different from the great circle path.

In this study a preliminary comparison between the two-station and the tripartite method indicated that the assumption of great circle propagation was satisfactory. This assumption was further substantiated by the observation that the results for the two-station method from opposite directions of wave propagation were in every case the same within expected errors (see Table 2). For these reasons the two station method was used throughout. To date sufficient data are available from two two-station pairs: (1) Funchal (FUN) and Faro (FAR), a distance of about 950 km; (2) Faro and Zurich (ZUR), a distance of about 1750 km (Fig. 2). The first line represents an oceanic path, the second line a continental path.

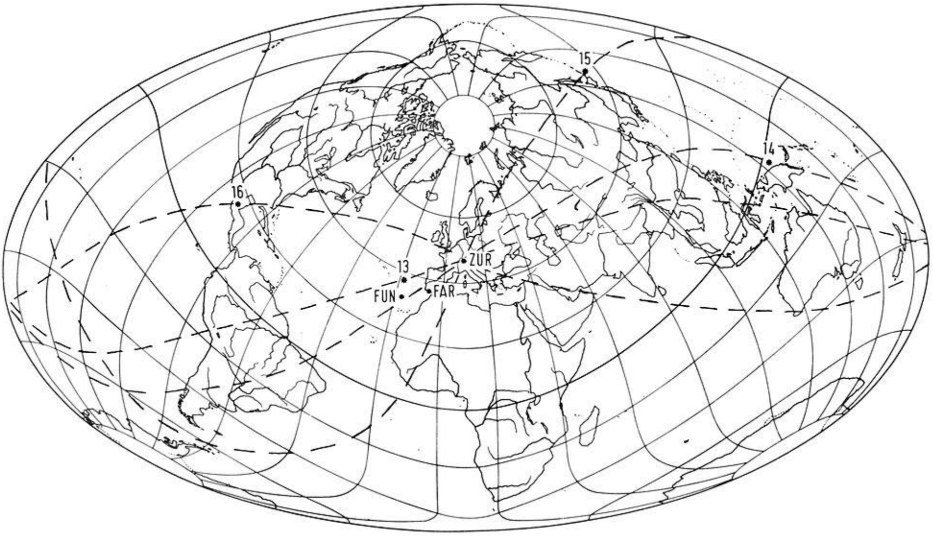

**Fig. 2.** The location of recording stations (dots) used in the regional phase velocity study (two-station method) and of earthquakes (stars with numbers) used in the one-station method for the globe circling paths (dashed lines) through Zurich (ZUR)

**Table 1**

| Event Number | Date | | | Origin Time | | | Location | | Magnitude | Stations used |
|---|---|---|---|---|---|---|---|---|---|---|
| | (D) | (M) | (Y) | (H) | (M) | (S) | (LAT) | (LONG) | ($M_b$) | |
| A. Events used in the two-station method | | | | | | | | | | |
| 1 | 2 | 1 | 74 | 10 | 42 | 29.9 | 22.5S | 68.4W | 6.4 | FUN-FAR |
| 2 | 9 | 5 | 74 | 23 | 33 | 25.2 | 34.5N | 138.7E | 6.0 | FUN-FAR |
| 3 | 23 | 10 | 74 | 6 | 14 | 54.8 | 8.4S | 154.0E | 6.1 | FAR-ZUR |
| 4 | 9 | 11 | 74 | 12 | 59 | 49.8 | 12.5S | 77.8W | 6.0 | FUN-FAR |
| 5 | 19 | 1 | 75 | 8 | 00 | 24.3 | 32.4N | 78.6E | 5.3 | FUN-FAR<br>FAR-ZUR |
| 6 | 7 | 2 | 75 | 4 | 51 | 44.0 | 7.3S | 149.5E | 6.3 | FAR-ZUR |
| 7 | 13 | 3 | 75 | 15 | 26 | 42.5 | 29.9S | 71.3W | 6.2 | FUN-FAR<br>FAR-ZUR |
| 8 | 27 | 3 | 75 | 5 | 15 | 06.2 | 40.4N | 26.1E | 5.7 | FUN-FAR |
| 9 | 10 | 5 | 75 | 14 | 27 | 40.5 | 38.1S | 73.1W | 6.4 | FAR-ZUR |
| 10 | 16 | 6 | 75 | 22 | 35 | 23.2 | 3.0S | 147.8E | 6.1 | FAR-ZUR |
| 11 | 10 | 7 | 75 | 18 | 29 | 16.0 | 6.5N | 126.6E | 6.2 | FAR-ZUR |
| 12 | 28 | 10 | 75 | 6 | 54 | 22.4 | 22.9S | 70.5W | 5.9 | FUN-FAR |
| B. Events used in the one-station method[a] | | | | | | | | | | |
| 13 | 26 | 5 | 75 | 9 | 11 | 49.8 | 35.9N | 17.6W | 8.0 | ZUR |
| 14 | 25 | 12 | 75 | 23 | 22 | 21.7 | 4.1S | 142.0E | 6.6 | ZUR |
| 15 | 21 | 1 | 76 | 10 | 05 | 14 | 43 N | 149 E | 6.4 | ZUR |
| 16 | 4 | 2 | 76 | 9 | 01 | 52 | 16 N | 90 W | 7.5 | ZUR |

[a] These events are located in Figure 2

**Table 2**

A. Results for the FUN-FAR path

| Period (s) | Phase velocity[a] (km/s) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | (#1) | (#2) | (#4) | (#5) | (#7) | (#8) | (#12) | Average |
| 15 | 3.88 | | 3.83 | | | | | $3.855 \pm 0.025^{b}$ |
| 20 | 3.93 | | 3.90 | | | | 3.90 | $3.910 \pm 0.010$ |
| 25 | 3.97 | | 3.94 | | | | 3.93 | $3.947 \pm 0.012$ |
| 30 | 3.99 | 4.01 | 3.97 | 4.02 | 3.98 | 3.97 | 3.96 | $3.986 \pm 0.008$ |
| 40 | 4.00 | 4.02 | 4.01 | 4.03 | 4.00 | 3.98 | 3.99 | $4.004 \pm 0.007$ |
| 50 | 4.01 | 4.03 | 4.02 | 4.04 | 4.02 | 3.99 | 4.00 | $4.016 \pm 0.007$ |
| 60 | 4.02 | 4.05 | 4.04 | 4.06 | 4.03 | 4.00 | 4.01 | $4.030 \pm 0.008$ |
| 80 | 4.04 | 4.08 | 4.06 | 4.09 | 4.06 | 4.04 | 4.05 | $4.060 \pm 0.007$ |
| 100 | 4.09 | 4.15 | 4.11 | 4.14 | 4.10 | 4.09 | 4.10 | $4.111 \pm 0.009$ |
| 120 | 4.17 | 4.22 | 4.18 | 4.20 | 4.15 | 4.14 | | $4.177 \pm 0.012$ |
| 140 | 4.26 | 4.31 | 4.29 | 4.29 | 4.23 | 4.23 | | $4.268 \pm 0.014$ |
| 160 | 4.35 | | 4.42 | 4.38 | 4.34 | 4.33 | | $4.364 \pm 0.016$ |
| 180 | 4.46 | | 4.57 | 4.49 | | 4.46 | | $4.495 \pm 0.026$ |
| 200 | 4.58 | | | 4.61 | | 4.60 | | $4.597 \pm 0.009$ |
| 220 | 4.71 | | | 4.74 | | | | $4.725 \pm 0.015$ |

B. Results for the FAR-ZUR path

| (s) | (#3) | (#5) | (#6) | (#7) | (#9) | (#10) | (#11) | Average |
|---|---|---|---|---|---|---|---|---|
| 20 | | | | | 3.60 | 3.70 | | $3.650 \pm 0.028$ |
| 25 | | | 3.73 | | 3.79 | 3.75 | | $3.757 \pm 0.018$ |
| 30 | | 3.88 | 3.81 | 3.86 | 3.87 | 3.79 | | $3.842 \pm 0.017$ |
| 40 | | 3.90 | 3.92 | 3.90 | 3.93 | 3.86 | | $3.902 \pm 0.012$ |
| 50 | | 3.94 | 3.97 | 3.94 | 3.95 | 3.91 | | $3.942 \pm 0.010$ |
| 60 | 3.98 | 3.98 | 4.01 | 3.96 | 3.96 | 3.97 | | $3.977 \pm 0.007$ |
| 80 | 4.05 | 4.03 | 4.06 | 4.03 | 4.00 | 4.05 | | $4.037 \pm 0.009$ |
| 100 | 4.11 | 4.10 | 4.11 | 4.08 | 4.06 | 4.12 | 4.05 | $4.090 \pm 0.010$ |
| 120 | 4.17 | 4.15 | 4.17 | 4.15 | 4.13 | 4.19 | 4.14 | $4.157 \pm 0.008$ |
| 140 | 4.26 | 4.24 | 4.25 | 4.22 | 4.25 | 4.27 | 4.23 | $4.246 \pm 0.006$ |
| 160 | 4.36 | 4.32 | 4.35 | 4.30 | 4.37 | 4.35 | 4.33 | $4.340 \pm 0.009$ |
| 180 | | 4.42 | 4.49 | 4.40 | 4.47 | 4.45 | 4.42 | $4.442 \pm 0.014$ |
| 200 | | 4.53 | | 4.53 | 4.57 | 4.58 | 4.53 | $4.548 \pm 0.011$ |
| 220 | | 4.67 | | 4.67 | 4.67 | | 4.64 | $4.663 \pm 0.008$ |
| 240 | | 4.85 | | 4.85 | 4.78 | | 4.74 | $4.805 \pm 0.027$ |
| 260 | | | | | 4.88 | | 4.85 | $4.865 \pm 0.011$ |

[a] The results are listed by event numbers. See Table 1 for identification

[b] Standard error of the mean

Because of lateral inhomogeneities of the earth and the resulting interference of spreading surface waves, a single determination of phase velocity from one earthquake is usually not very reliable for such small distances between recording stations. Seven events were found for each station pair where the signal was satisfactory on both stations and where the direction of surface wave propagation was in line with the stations to within ±10°. In addition, events were chosen

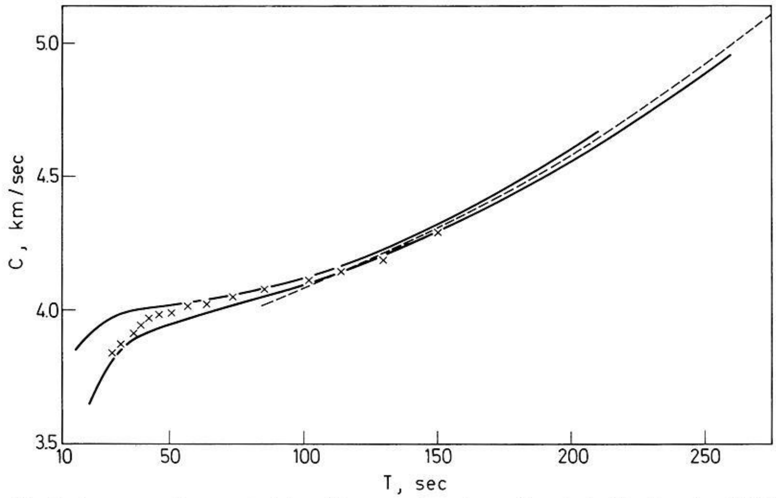

**Fig. 3.** Average phase velocities ($C$) as a function of period ($T$) for the FUN-FAR path (top solid line) and for FAR-ZUR path (bottom solid line); results for Western Europe ($X$'s) from Nolet (1976) and Seidl (1971); average values for globe circling paths using the one-station method (dashed line)

so that the wave propagation would be available from both directions. Table 1A presents the selected events and indicates which station pair was used.

The determined phase velocities were plotted as a function of period and then smoothed by fitting a curve through the data for each event. The smoothing was done by "eye". The results are presented at selected periods for each event in Table 2. The average values with their statistics for the two profiles are presented in Table 2 and Figure 3.

### *B. One-Station Method*

Data from the vertical component of the ultra long period and the broad-band seismographs at Zurich (ZUR) were used to determine phase velocities of the fundamental mode Rayleigh waves for the globe circling paths using the well known one-station method (Nafe and Brune, 1960; Brune et al., 1961). Data from the ultra long period system were digitized by hand at 10 s per sample from seismograms recorded at 6 mm/min. Similar filtering as used on the broad-band data was applied to these data, although it was found that, because of the nature of the data, filtering was not essential (see Fig. 5A). Table 1B presents the four earthquakes used in this study and Figure 2 shows the location of the events and the great circle paths through Zurich. The large earthquake (#13) was recorded on the low gain broad-band LP system, while the other three smaller events were recorded on the ultra long period system. Aside from a good signal, the only requirement for an event in such a study is that its location not be too close to the recording station or its antipode, in which cases waves travelling in opposite directions will arrive at the station about the same time and interfere.

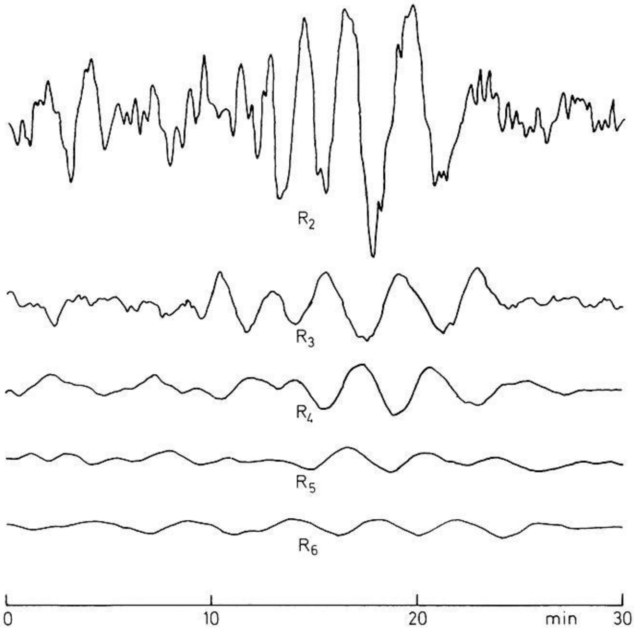

**Fig. 4.** Tracings of data from the ultra long period seismogram (vertical component) for Event #16. Pass $R_1$ was clipped

**Table 3.** Results for the one-station method

| Period (s) | Phase velocity[a] (km/s) | |
|---|---|---|
| | (#13) | Average |
| 101.05 | 4.0583 ± 0.0071[b] | 4.0753 ± 0.0369[c] |
| 111.63 | 4.1211 ± 0.0151 | 4.1277 ± 0.0321 |
| 120.00 | 4.1546 ± 0.0224 | 4.1670 ± 0.0180 |
| 129.73 | 4.2078 ± 0.0066 | 4.2100 ± 0.0145 |
| 141.18 | 4.2648 ± 0.0009 | 4.2627 ± 0.0147 |
| 150.00 | 4.3072 ± 0.0026 | 4.3041 ± 0.0154 |
| 160.00 | 4.3479 ± 0.0003 | 4.3503 ± 0.0125 |
| 171.43 | 4.4050 ± 0.0041 | 4.4106 ± 0.0092 |
| 181.13 | 4.4585 ± 0.0066 | 4.4639 ± 0.0089 |
| 192.00 | 4.5222 ± 0.0006 | 4.5251 ± 0.0111 |
| 200.00 | 4.5716 ± 0.0024 | 4.5736 ± 0.0103 |
| 208.70 | 4.6282 ± 0.0012 | 4.6289 ± 0.0097 |
| 218.18 | 4.6912 ± 0.0023 | 4.6916 ± 0.0088 |
| 228.57 | 4.7602 ± 0.0027 | 4.7606 ± 0.0088 |
| 240.00 | 4.8422 ± 0.0009 | 4.8433 ± 0.0088 |
| 252.63 | 4.9351 ± 0.0016 | 4.9368 ± 0.0102 |
| 266.67 | 5.0383 ± 0.0027 | 5.0397 ± 0.0113 |
| 282.35 | 5.1506 ± 0.0019 | 5.1535 ± 0.0114 |
| 290.91 | 5.2108 ± 0.0066 | 5.2160 ± 0.0132 |
| 300.00 | 5.2770 ± 0.0104 | 5.2841 ± 0.0147 |
| 309.68 | 5.3513 ± 0.0132 | 5.3591 ± 0.0147 |
| 320.00 | 5.4385 ± 0.0113 | 5.4423 ± 0.0147 |
| 331.03 | 5.5420 ± 0.0049 | 5.5357 ± 0.0232 |
| 342.86 | 5.6626 ± 0.0015 | 5.6443 ± 0.0433 |

[a] Results only for event #13 given here. Results for the other three events can be reconstructed by using these results in conjunction with Figure 5

[b] Standard error based on 3 determinations: $R_4$-$R_2$, $R_5$-$R_3$, $R_6$-$R_4$

[c] Standard error based on all data from four events (12 determinations)

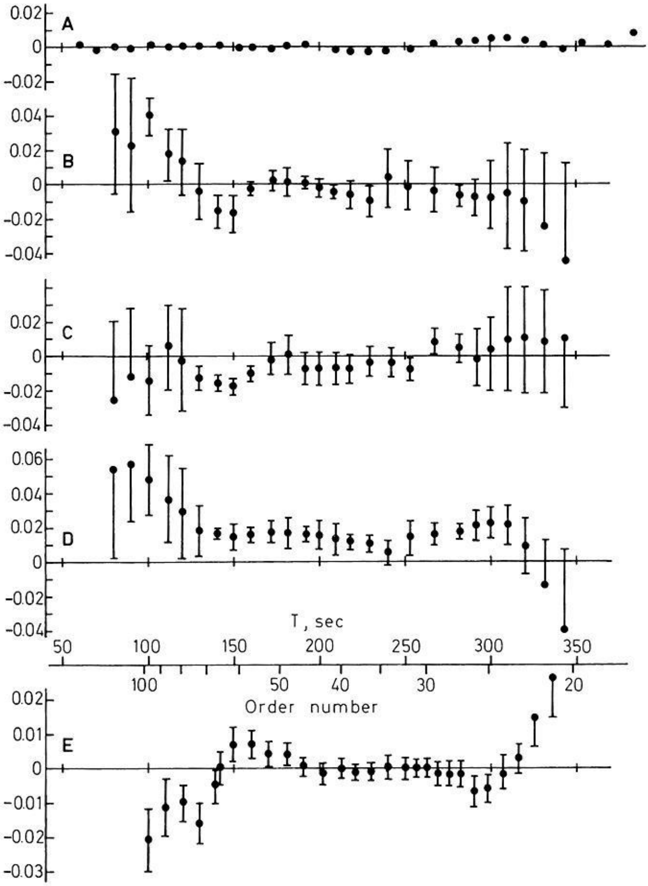

**Fig. 5A–E.** Differences in phase velocities (km/s) as a function of period ($T$) for the following cases: **A** Typical errors resulting from data analysis: $R_2$ and $R_4$ passes from Event #16 were digitized twice (10 s intervals) and also filtered and unfiltered. **B** Event #14–Event #13. **C** Event #16–Event #13. **D** Event #15–Event #13. **E** Average for this study (interpolated)–free oscillation data (Gilbert and Dziewonski (1975) for $T > 140$ s; Derr (1969) for $T < 140$ s). Bars in cases B, C and D indicate the sum of standard errors; in case E the sum of standard errors of the mean. The period and order number scales apply to all cases

In this study either $R_1$ to $R_5$ (events #14, #15) or $R_2$ to $R_6$ (events #13, #16) pases were used, depending on whether $R_1$ was on scale or not, to form three independent determinations ($R_3$-$R_1$, $R_4$-$R_2$, $R_5$-$R_3$ or $R_4$-$R_2$, $R_5$-$R_3$, $R_6$-$R_4$) of phase velocity for each great circle path. Figure 4 shows how the typical data look on the ultra long period seismogram. Table 3 presents the average phase velocities at selected periods based on Event #13 (3 determinations) as well as the average values based on all four events (12 determinations). Most of the data in the last column are also plotted in Figure 3 for comparison with the regional results. Figure 5 presents the differences between Event #13 and the other events in a graphical form on an expandes scale (B, C. D). Using Table 3 in conjunction with this figure, it is possible to reconstruct the phase velocity values for all four great circle paths. Finally, a comparison is made between the present results and the best free oscillation results (*E*).

## 4. Discussion

Lateral heterogeneities within the earth lead to interference patterns in the amplitude and phase of surface waves as they spread from a source. This underlines the need to determine velocities on regional basis but at the same time makes it more difficult to do so. The interference patterns in phase lead to errors ("oscillations") in the determined surface wave velocity as a function of period (Pilant and Knopoff, 1964). Such "oscillations" in general tend to increase with decreasing distance between recording stations.

In the course of this study it was found that, for a given station pair, the oscillations can vary considerably from one event to the next, even when the two events are from the same general (but not identical) region. (So far there have been no cases with more than one event from the same region and same focal mechanism to check if the patterns are repducible). In the best examples the maximum oscillations about the average are of the order of ±0.03 km/s for the FAR-ZUR line and about ±0.05 km/s for the FUN-FAR line. In this study results for events with oscillations up to ±0.15 km/s were accepted, provided the patterns were sufficiently regular so that a reliable smooth curve could be drawn through the data. Such smoothing was done by eye because it was found difficult to propose a good objective procedure to fit all cases. As the amount of data increases, however, the exact smoothing procedure for each event becomes less important to the final estimate. Seven such independent determinations for each line is probably a minimum number when the exact nature of the smoothing procedure starts to become unimportant. In this case, I feel that it is better to have sufficient data, even though not all of it of the highest precision, than to rely on a single precise determination of unknown accuracy. In other words, it is safer to have large random errors than to have small errors with an unknown systematic bias. It is in order to guard against systematic bias that effort was made to use events from opposite sides of each station pair and to determine accurately the phase respsonse of the instruments (Mitronovas and Wielandt, 1975).

Assuming no systematic errors in the data, the occuracy in the average values can be represented realistically by the standard error of the mean. The results summarized in Table 2 indicate that the standard error of the mean is on the average about 0.010 km/s in the period range from 30 s–200 s for the FAR-ZUR path and in the period range from 30 s–160 s for the FUN-FAR path. The results outside these ranges are less reliable either because of larger scatter in the data or because of insufficient data.

Comparing the phase velocities from the two regions (Fig. 3), it can be seen that for periods up to 80 s there exist large and well determined differences corresponding to the well known differences between the oceanic and continental crust and upper mantle. Systematic and significance differences in phase velocity persist up to the longest periods (210 s), although the slight increase in the difference beyond 160 s is probably not significant because the data is less reliable here as pointed out above. The *x*'s are the composite results of Nolet (1976) and Seidl (1971) and reflect the average values for Western Europe. Nolet's results extend from 28 s–about 110 s, Seidl's from 60 s–about 150 s. The differences between their results from 60 s–110 s are negligible. The systematic differences in the period range from 40 s–100 s between their results and the results for the FAR-ZUR line probably reflect regional differences within Western Europe. The nature of the earth structure reflecting the observed differences in the phase velocities will not be discussed in this paper.

The precision in the determined phase velocities, based on one event, is at least one order of magnitude higher for the one-station method using the globe circling paths than for the regional results. This is mainly due to the much larger distances involved in the one-station method (~40,000 km). The combined effects of the instrumental response, selective attenuation of energy at short periods, and the nature of the minimum in the group velocity for Rayleigh waves between 200 s and 300 s limited the useful period band between 100 s and 350 s in this study. This happens to be the period range where the observations from free oscillations are more difficult because of problems in separating and identifying various modes. Compared to the free oscillation results, the one-station method results are more sensitive to earth properties close to the great circle path of wave propagation, so that regional nature of the earth can be better studied. Finally, the data analysis in the one-station method is relatively easy.

The precision in the results from Event #13 (Table 3), based on 3 determinations, is typical for the other three events (not presented). Typical standard errors for the average values from all four events, based on 12 determinations, are considerably larger, however, suggesting significant differences in phase velocity for different great circle paths. It can be inferred from Figures 2 and 5 that the difference in velocities increases as the distance between the great circle paths increases. Such data can be used to study the earth on a smaller scale regional basis. The results from the one-station method using the globe circling paths are even better suited to study the earth structure on a global scale by averaging many observations. In this way the results from the free oscillations can be improved at shorter periods. A comparison is made (Fig. 5E) between the present results and the best free oscillation results. The comprehensive results of Gilbert and Dziewonski (1975) extend only down to a period of 141 s. The results of Derr (1969) are used for comparison at shorter periods. Such a comparison will be more meaningful when more data become available from the one-station method. It is already clear that eventually the one-station observations will not only help define the average standard earth mode, but will at the same time indicate the extend of regional variations within the real earth.

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