CHAPTER 1
Overview of Low Frequency data

1.1 Introduction. At long periods, it is convenient (and quite accurate) to think of a seismogram simply as a sum of decaying cosinusoids:

\[ u(t) = \sum_{k=1}^{\infty} A_k \cos (\omega_k t + \phi_k) e^{-\alpha_k t} \] (1.1)

where \( u(t) \) is the observed time series, \( A_k \) and \( \phi_k \) are the initial amplitude and phase of the \( k \)'th mode of oscillation, and \( \omega_k \) and \( \alpha_k \) are the frequency and attenuation rate. The usual analogy that is made is that of a bell. When we hit a bell, the resulting sound consists of certain discreet frequencies - the tones of the bell. These frequencies and the rate at which the oscillations decay are properties of the structure of the bell. The actual sound we produce depends upon how we hit the bell. Obviously, the harder we hit the bell, the larger the initial amplitude of the oscillations. Depending upon where and how we hit the bell, we can excite some oscillations more than others. In terms of 1.1, \( \omega_k \) and \( \alpha_k \) tell us about Earth structure and \( A_k \) and \( \phi_k \) tell us about the Earthquake source.

The attenuation rate is sometimes specified by the “quality factor” of the oscillation, \( Q_k \), where

\[ \alpha_k = \omega_k / 2Q_k. \] (1.2)

If \( Q_k \) is large, \( \alpha_k \) is small and the oscillation rings on for a long time. Conversely, an oscillation with a small \( Q_k \) is rapidly damped out. The low frequency oscillations which we are considering (i.e., frequency less than 10 mHz) have \( Q_k \) between about 100 and 6000. Thus \( \alpha_k \ll \omega_k \) and attenuation is weak.

A seismogram is the interference pattern of a sum of many decaying sinusoids (Fig 1.1). To see the individual modes of oscillation we work in the frequency domain by Fourier transforming. Our definition of the forward Fourier transform (i.e., time to frequency) is

\[ f(\omega) = \int_{-\infty}^{\infty} f(t) e^{-i\omega t} dt. \] (1.3)

\( f(\omega) \) is a complex quantity called the “spectrum” of \( f(t) \).

We are interested in the spectrum of a decaying cosinusoid. Let

\[ C_k(t) = \cos (\omega_k t) e^{-\alpha_k t} \quad \text{for} \quad t \geq 0, \]
\[ C_k(t) = 0 \quad \text{for} \quad t < 0. \]

then
\[ C_k(\omega) = \int_0^\infty \cos(\omega_k t) e^{-\alpha_k t} e^{-i\omega t} \, dt, \]

\[ = \frac{1}{2} \int_0^\infty (e^{(-\alpha_k + i(\omega_k - \omega))t} + e^{(-\alpha_k - i(\omega_k + \omega))t}) \, dt, \]

\[ = \frac{1}{2} \frac{1}{\alpha_k - i(\omega_k - \omega)} + \frac{1}{2} \frac{1}{\alpha_k + i(\omega_k + \omega)}. \]

For \( \omega \simeq \omega_k \), the first term is large whilst the second term is much smaller. Thus, if we only consider positive frequencies in the vicinity of \( \omega_k \), we have

\[ C_k(\omega) \simeq \frac{1}{2} \frac{1}{\alpha_k - i(\omega_k - \omega)} \quad (1.4) \]

or, in terms of real and imaginary parts,

\[ C_k(\omega) = \frac{1}{2} \frac{\alpha_k}{\alpha_k^2 + (\omega_k - \omega)^2} + i \frac{1}{2} \frac{(\omega_k - \omega)}{\alpha_k^2 + (\omega_k - \omega)^2} \quad (1.5) \]

\( C_k(\omega) \) is plotted in Fig. 1.2. Note that the real part falls off from its peak value as \((\omega_k - \omega)^2\) whereas the imaginary part falls off only as \((\omega_k - \omega)\). This latter property means that the spectrum of a decaying sinusoid falls off quite slowly from its peak value \((\approx 6\, \text{db/octave})\).

![Fig 1.2 Spectrum of a decaying cosinusoid in a small frequency band surrounding the center frequency, \( \omega_k \). Frequency is in units of \( \alpha_k \)](image)

**Problem 1.1** Show that the width of the power spectrum of \( C_k(\omega) \) at the half power points is \( 2\alpha_k \).

The seismogram is a sum of such spectra all centered at different frequencies so a plot of the modulus
of the spectrum of 1.1 looks something like the following sketch:

You should note a couple of things. First, each spectral peak falls off quite slowly so modes of oscillation which are close together in frequency may not be resolvable as separate peaks. Second, the width of a spectral peak is related to $\alpha_k$ (actually, the width of a peak at the half-power points is $2\alpha_k$). Thus, weakly attenuated modes have narrow spectral peaks while strongly attenuated modes have broad peaks.

An application of this procedure to a real time series is shown in Fig 1.3. The only difference between this result and our previous analysis is that, for obvious reasons, we did not use an infinite record length. Peaks are clearly visible but their long tails overlap and the result is quite messy. The result can be improved by using a data window (or taper). The procedure is to multiply the finite data series by some chosen function of time before Fourier transforming. The very act of taking a finite record length is equivalent to multiplying an infinite record by a boxcar function but such a function has very poor spectral leakage characteristics. To illustrate what this means, consider the result of multiplying the time series by a Hanning taper (which is illustrated in Fig 1.5) before Fourier transforming. The result, shown in Fig 1.4, is much less jagged than before and the peaks are more clearly defined. The simplest way to understand this result is in terms of convolution. Convolution is discussed in all text books on time series analysis and so will only be given brief consideration here.

The convolution of two functions of time, $a(t)$ and $b(t)$, is defined by:

$$a(t) * b(t) = \int_{-\infty}^{\infty} a(t-t')b(t') \, dt'.$$

Then

$$F.T.(a * b) = a(\omega) \cdot b(\omega)$$

$$F.T.(a \cdot b) = a(\omega) * b(\omega)$$

where $F.T.$ stands for “Fourier transform of”

Taking a finite record length of data is equivalent to multiplying the infinite record by a boxcar, $B(t)$
of length $T$:

In the frequency domain, this is equivalent to convolving $u(\omega)$ with $B(\omega)$. Now

$$B(\omega) = \int_{-\infty}^{\infty} B(t)e^{-i\omega t}dt = \int_{0}^{T} e^{-i\omega t}dt = \frac{e^{-i\omega T} - 1}{-i\omega} = Te^{i\omega T/2} \frac{\sin(\omega T/2)}{(\omega T/2)}$$

The spectrum $B(\omega)$ is a phase shift multiplied by a sinc function. If we sketch the modulus of this function it looks like

Convolutions with a peak-like function ($i.e.$, the spectrum of a decaying sinusoid) gives a spectrum very much like that of a boxcar, $i.e.$,

Thus, with a finite record length, we do not see the spectrum of a resonance function, but we see a function with sidelobes. Energy originally at a frequency $\omega_k$ now appears at other frequencies, $i.e.$, the frequencies of the sidelobes. This phenomenon is called spectral leakage and is responsible for
the jagged appearance of the spectrum in Figure 1.3 (and is partially responsible for the appearance of energy between the peaks corresponding to the free oscillation frequencies).

If we do not use a data window, we are implicitly using a boxcar function but obviously we can choose any function we like. The choice of an optimal window is quite complicated as there are trade-offs involved. In particular, we would like to choose a data window with a spectrum which has very small sidelobes to reduce spectral leakage. At the same time, we would like the central lobe of the spectrum of the data window to be narrow so that we have as much frequency resolution as possible. The log-modulus of the spectrum of several data windows are shown in Figure 1.5. (The log helps to emphasize the size of the sidelobes.) A cosine data window suppresses the sidelobe level but broadens the central lobe. A \( \cos^2 \) data window suppresses sidelobes even more but the central peak is further broadened. Other tapers can be devised which essentially have no sidelobes but are too broad for our application. Harris, (1978) reviews many of the tapers in common usage. Some work has been done on finding optimal tapers for a time series of decaying sinusoids and a general (but difficult) review of spectrum estimation and harmonic analysis is by Thomson (1982). Figure 1.6 shows spectra of a time series using some of these windows. These tapers are quite difficult to compute and we content ourselves here with choosing a compromise data window such as the Hanning window.

The desirability of using a data window is illustrated in Figure 1.7 by a synthetic example (Dahlen 1982). The top panel illustrates the spectrum of a time series consisting of ten modes of oscillation with frequencies indicated by the vertical lines. If we were simply to estimate the mode frequencies by picking peaks, it is clear that we would get significantly biased estimates. The application of the Hanning window (\( \cos^2 \)) gives the result in the middle panel. The peaks are now separated and centered at their true frequencies. Another window (Blackman-Harris 4-term, BHV) has been applied in the lower panel. The spectral leakage is much less than for the Hanning taper but the peak widths are broader and two closely spaced lines would not be as well resolved as with the Hanning taper. The Hanning taper is therefore a reasonable compromise.

The application of a data window has two desirable effects. It reduces spectral leakage and it modifies the shape of the spectrum of a decaying cosine making it more concentrated in frequency. This latter property means that individual peaks in the spectrum can be more clearly identified (though peak widths are now no longer simply related to \( \alpha_k \)).

### 1.2 Estimation of peak frequencies

To learn about Earth structure, we would like to measure \( \omega_k \) and \( \alpha_k \) and similarly, to learn about the earthquake source, we would like to measure \( A_k \) and \( \phi_k \). An obvious way to measure \( \omega_k \) is to just take the peak value of the spectrum. This is not a very good procedure as the peak value can be biased when modes are closely spaced in frequency. Furthermore, we obtain no estimate of the uncertainty in our estimate of \( \omega_k \). An obvious way to measure \( \alpha_k \) is to use a “moving window” analysis. The amplitude of the spectrum of a segment of data is estimated and then the amplitude of a later segment of data is estimated. The drop in amplitude is related to \( \alpha_k \). Again, it turns out that this is not a good procedure and our resulting estimate of \( \alpha_k \) is more uncertain than it need be.

An overview of measurement techniques can be found in Masters and Gilbert, (1983) and we briefly describe two of these here. For simplicity, we consider a single isolated mode of oscillation though it is desirable that any measurement technique can handle modes which overlap in frequency. We have

\[
u(t) = A_k \cos(\omega_k t + \phi_k) e^{-\alpha_k t}
\]

Fourier transforming gives

\[
u(\omega) = a_k C_k(\omega)
\]

(1.7)
where \( a_k \) is a complex number with

\[
A_k = |a_k| \quad \text{and} \quad \phi_k = \tan^{-1} \left( \frac{\text{Im}(a_k)}{\text{Re}(a_k)} \right)
\]

\( C_k(\omega) \) is given approximately by 1.4.

You should note that \( a_k \) is linearly related to \( u(\omega) \) in 1.7 whereas \( \omega_k \) and \( \alpha_k \) are nonlinearly related to \( u(\omega) \). If \( \omega_k \) and \( \alpha_k \) are known it is therefore easy to recover \( a_k \). In practice we work with a data window, \( d(t) \) say, such as the Hanning taper and 1.7 becomes

\[
u(\omega) * d(\omega) = a_k C_k(\omega) * d(\omega)
\]

or

\[
u'(\omega) = a_k C_k'(\omega)
\]

We evaluate \( u'(\omega) \) and \( C_k'(\omega) \) at a small number of frequencies, \( \omega_i \), about the peak of interest, i.e.,

\[
\begin{bmatrix}
\text{Re}(u_1') \\
\text{Im}(u_1') \\
\text{Re}(u_2') \\
\text{Im}(u_2')
\end{bmatrix} =
\begin{bmatrix}
\text{Re}(C_1') & -\text{Im}(C_1') \\
\text{Im}(C_1') & \text{Re}(C_1') \\
\text{Re}(C_2') & -\text{Im}(C_2') \\
\text{Im}(C_2') & \text{Re}(C_2')
\end{bmatrix}
\begin{bmatrix}
\text{Re}(a_k) \\
\text{Im}(a_k)
\end{bmatrix}
\]

Equation 1.9 is a set of simultaneous equations to be solved for \( a_k \) and may be solved by any of a number of techniques. We write 1.9 as

\[
u' = C' \cdot \mathbf{a}
\]

and the solution symbolically as

\[
\mathbf{a} = C'^{-1} \cdot \mathbf{u}'
\]

(The least squares solution is \( \mathbf{a} = (C'^T C')^{-1} C'^T \mathbf{u}' \). Of course we need to know \( \alpha_k \) and \( \omega_k \) so that \( \mathbf{C}' \) can be calculated but then \( \mathbf{a} \) can easily be recovered. Equation 1.9 can also be easily modified if more than one mode is present in the spectrum.)
If we do not know $\alpha_k$ and $\omega_k$, we can make an initial guess and solve for a first estimate of $a_k$. Equation 1.8 can then be linearized so that a better estimate of $\omega_k$ and $\alpha_k$ can be found. We form

$$u'(\omega) = u'_0(\omega) + \frac{\partial u'_0(\omega)}{\partial \omega_k} \delta \omega_k + \frac{\partial u'_0(\omega)}{\partial \alpha_k} \delta \alpha_k$$

(1.10)

where $u_0(\omega)$ is formed using our initial estimates of $\omega_k$, $\alpha_k$ and $a_k$. In the time domain it is easy to show that

$$\frac{\partial u'_0(t)}{\partial \omega_k} = -tA_k \sin (\omega_k t + \phi_k) e^{-\alpha_k t} \delta \omega_k$$
$$\frac{\partial u'_0(t)}{\partial \alpha_k} = tA_k \cos (\omega_k t + \phi_k) e^{-\alpha_k t} \delta \alpha_k$$

(1.11)

Equation 1.11 can be easily Fourier transformed and 1.10 can then be cast into matrix form when all the terms dependent upon frequency are evaluated at a few frequency points about the peak of interest, i.e.,

$$u' - u'_0 = \delta u' = D \cdot s$$

(1.12)

where $s = [\delta \omega_k, \delta \alpha_k]^T$ and $D$ is a matrix of derivatives $\partial u'/\partial \alpha_k$, $\partial u'/\partial \omega_k$ evaluated at a few frequency points.

Solution of 1.12 follows the solution of 1.9. Once $\delta \omega_k$ and $\delta \alpha_k$ have been estimated, we form new estimates of $\omega_k$ and $\alpha_k$ (i.e., $\omega_k \rightarrow \omega_k + \delta \omega_k$ and $\alpha_k \rightarrow \alpha_k + \delta \alpha_k$) and repeat the whole procedure until no improvement in fit to the data is obtained. Various tricks can be played to speed up convergence – see Masters and Gilbert (1983) for details.

An alternative technique (the autoregressive technique) which allows the estimation of $\omega_k$ and $\alpha_k$ in a noniterative fashion is based upon the recursion relations satisfied by a decaying cosinusoid. This method is described in detail by Chao and Gilbert (1980). Consider a single oscillation, i.e.,

$$u(t) = A_k \cos (\omega_k t + \phi_k) e^{-\alpha_k t}$$

(1.13)

Using trigonometric identities gives

$$u(t + \delta t) = y_1 u(t) + y_2 u(t - \delta t)$$

(1.14)

where $\delta t$ is a time increment and

$$y_1 = 2 \cos (\omega_k \delta t) e^{-\alpha_k \delta t}$$
$$y_2 = -e^{-2 \alpha_k \delta t}$$

(1.15)

Suppose our time series is specified at evenly spaced time points, $t_i$, where $t_1 = 0, t_2 = \delta t, t_3 = 2\delta t$ etc. Then 1.14 can be written as

$$u(t_3) = y_1 u(t_2) + y_2 u(t_1)$$
$$u(t_4) = y_1 u(t_3) + y_2 u(t_2)$$
$$u(t_5) = y_1 u(t_4) + y_2 u(t_3)$$

(1.16)

which again can be cast in matrix form as

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\[
\begin{bmatrix}
u(t_3) \\ u(t_4) \\ u(t_5) \\ \vdots 
\end{bmatrix} = \begin{bmatrix}
u(t_2) & u(t_1) \\ u(t_3) & u(t_2) \\ u(t_4) & u(t_3) \\ \vdots & \vdots 
\end{bmatrix} \begin{bmatrix} y_1 \\ y_2 
\end{bmatrix}
\]

(1.17)

All the columns in 1.17 can be multiplied by a data window and Fourier transformed so that we need only use a few frequency points about a peak. Equation 1.17 can be solved for \(y\) then \(\omega_k\) and \(\alpha_k\) recovered from

\[
\alpha_k = -\frac{1}{2\delta t} \ln (-y_2)
\]

\[
\omega_k = \frac{1}{\delta t} \cos^{-1} \left( \frac{y_1}{2\sqrt{-y_2}} \right).
\]

This technique can be extended to handle more than one oscillation if our frequency band contains several modes. Both techniques described above have error analyses (Dahlen, 1982; Chao and Gilbert, 1980) so, in the presence of noise, we can assign uncertainties to our estimates of \(\omega_k, \alpha_k, A_k\) and \(\phi_k\). These error analyses also give an indication of the optimal record length to use for a particular data window. For a Hanning taper, a record length of 1.1 \(Q\) cycles is optimal for the recovery of \(\alpha_k\) and \(\omega_k\).

A successful application of these techniques is shown in Figure 1.8. The dashed line is the original amplitude spectrum. The solid line is the residual after subtracting out a decaying sinusoid with the best estimates of \(A_k, \phi_k, \omega_k\), and \(\alpha_k\). Figure 1.9 is an example of what happens when the spectrum does not correspond to that of a single decaying cosine and the retrieved values of \(\omega_k\) and \(\alpha_k\) are unreliable. Another way of diagnosing failure of the techniques is to vary the record length used in the analysis. If the retrieved values of \(\alpha_k\) and \(\omega_k\) vary as the record length is changed, we are probably observing an interference effect and the spectrum again cannot be adequately modeled by a single decaying cosine.

In successful cases, all techniques give the same answers as illustrated in Figure 1.10 (in the second panel we have plotted \(1000/Q\) instead of \(\alpha_k\)). Each point is an estimate made from a different seismic record of a mode of oscillation (in this case, \(0S_{13}\)). If the Earth was truly spherically symmetric, \(0S_{13}\) would have the same frequency (~2.113 mHz) on every recording. The resolvable variation in measured frequency of this mode (2.1095 \(\rightarrow\) 2.1162 mHz) is a consequence of the fact that the Earth is not quite spherically symmetric. Each seismic recording dominantly gives a sampling of the Earth which corresponds to the average structure under the great circle joining source and receiver. Thus each source-receiver pair samples a slightly different structure – faster paths give higher frequencies. In our example of \(0S_{13}\) there are 27 closely spaced modes of oscillation. The interference between the 27 oscillations results (usually) in a single peak which looks like a single resonance function. The peak frequency is variable (depending upon which great circle we are sampling) and the apparent attenuation that we measure is a mixture of true attenuation and beating effects.

At very long periods (~1000 seconds), the Earth’s rotation is the dominant cause of splitting. The effect is so strong that we do not see a single peak anymore but a set of closely spaced peaks (Figure 1.11). The exception to this is at the South Pole where a vertical component recording should still show a single peak if rotation is the dominant cause of splitting. The lower panel in Figure 1.11 demonstrates this to be the case (look particularly at \(1S_4\)). Unfortunately, at very low frequencies the South Pole is a noisy station so that no modes of oscillations are visible with frequencies less then \(\sim\)4 mHz.

Splitting can lead to very strange estimates of apparent attenuation and it makes it very difficult to learn about the attenuative properties of the Earth.

As noted above, the techniques for measuring the properties of an oscillation of the Earth \((A_k, \phi_k, \alpha_k, \omega_k)\) can be easily extended to simultaneously measure the properties of several oscillations. An
example of fitting two peaks is shown in Figure 1.12. Unfortunately, there are trade-offs between the parameters of the oscillations and it is difficult to obtain reliable estimates. There are two ways of avoiding multiple-peak estimation. One arises if the two modes have very different attenuation rates. If we choose a sample of data which starts late in the record, the strongly attenuated mode will have decayed much more than the weakly attenuated mode and, if we start late enough, we will effectively be left with a single mode. This is illustrated in Figure 1.13. The spectra are of 125 hours of recording but starting 2 hours, 27 hours, and 52 hours respectively after the origin time of the event. In the last panel we have almost removed the lower frequency, more highly attenuated mode. This is an example of the use of the Earth as an attenuation filter.

An alternative way of avoiding multi-peak estimation is to use many recordings and add them together in such a way as to emphasize a single mode of oscillation. We shall be developing the machinery required to perform this “array-processing” of data as the book progresses. For now, reconsider 1.8 when more than one mode is present, \( i.e. \)

\[
u'(\omega) = \sum_k a_k C'_k(\omega)
\]

Now \( a_k \) is a function of the source-receiver geometry and the earthquake source mechanism, so for the \( j \)th recording we can write

\[
u'_j(\omega) = \sum_k a_{kj} C'_k(\omega)
\]

(1.18)

If \( a_{kj} \) can be computed, we can solve 1.18 for \( C'_k(\omega) \), \( i.e. \), the resonance function of individual modes of oscillation. Figure 1.14 shows a plot of \( |C'_k(\omega)| \) in a small frequency band where a few modes of oscillation are present. About 800 recordings were used to solve for the \( C'_k(\omega) \) and we have done a good job of isolating individual modes. We can now measure \( \alpha_k \) and \( \omega_k \) from the isolated resonance functions. With some assumptions, it is possible to compute \( a_{kj} \) for individual resonance functions within a nearly degenerate multiplet. Figure 1.15 shows an application to the nine closely spaced singlets of \( {}^1S_4 \) again showing that fine-scale isolation of singlets is possible.

1.3 References.


