INTRODUCTION

Since the earliest days of marine seismic prospecting, geophysicists have recognized and had to contend with the problem of hard-bottom multiple reflections. This phenomenon is widespread on surveys shot in northern latitudes such as offshore-Labrador, Alaska, and the North Sea. There are at least two geological reasons why these areas have acoustically hard bottoms. The first reason is that glacial erosion has prevented soft sediment accumulation on these seafloors. A second reason is that high impedance gas hydrate deposits are often found in Arctic seabottoms because of the near-freezing temperatures. Also, large parts of these seafloors are strewn with glacial boulders - the legacy of the last glaciation. Many of these boulders have the dimensions of seismic wavelengths and effectively back-scatter much of the source energy. They give rise to complex multiple diffraction patterns which become more and more confused as recording time increases. In all of these cases multiple interference is often strong enough to completely overpower primary reflections making interpretation impossible.

Multiple reflections fall into one of three basic categories (Figure 0.1). There is much disagreement in the literature on these classifications but the terminology we will introduce here is internally consistent. "Water bottom" multiples are those multiples whose raypaths lie entirely within the water layer (Fig 0.1a). They have very strong amplitudes since the seafloor has much higher reflectivity than deeper geological horizons. "Pegleg" multiples (Fig 0.1b) have raypaths which undergo exactly one reflection in the sedimentary sequence. The upcoming rays of "surface" multiples always reflect off the sea-surface before going down again. Surface multiples include both water bottom and pegleg multiples as well as multiples such as the one shown in Figure 0.1c. A raypath representative of yet another class of multiples called "short-path" or "intra-bed" multiples is drawn in Figure 0.1d. Their presence is fairly subtle in marine seismic data since the geological horizons involved are much weaker reflectors than the seafloor.

Several practical solutions to the multiple problem have been developed which work well when the mean velocities of the multiple and primary raypaths are distinct. This is most often the case for water bottom multiples since water velocity is usually much lower than acoustic velocities in sediments. Some pertinent references are Naess (1977) ("Super-stack"), Wehrhahn and Titchkosky (1978) ("Answers"), and Schneider, Prince and Giles

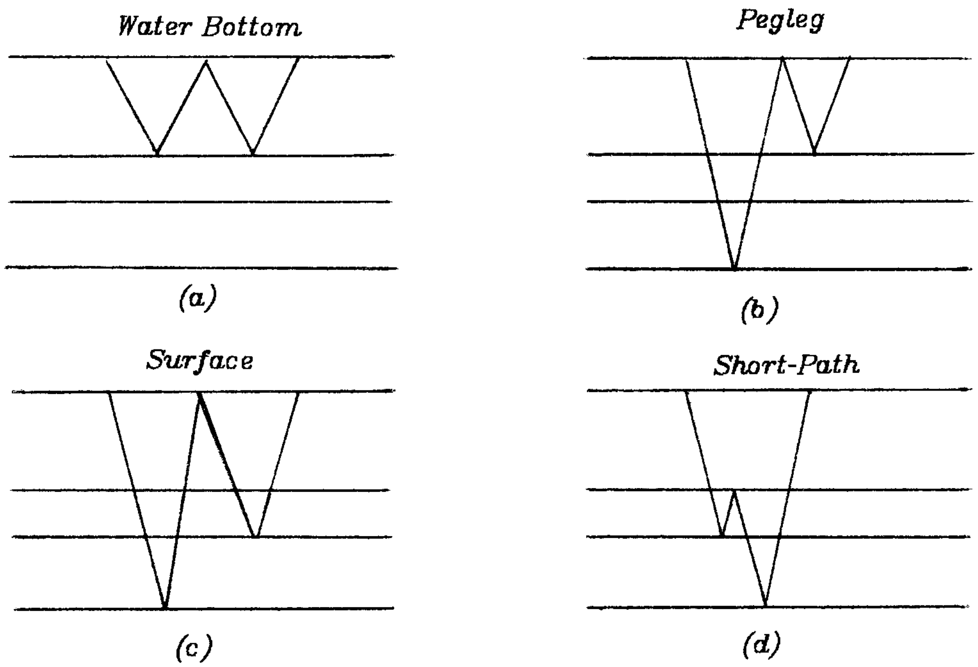

FIG. (0.1). Raypaths are displayed for (a) water-bottom multiple, (b) pegleg multiple, (c) general surface multiple, and (d) short-path multiple.

(1965). Such velocity discrimination methods may be classified into one of two groups - those that attempt to attenuate multiples of known velocity from the data and those which enhance the primaries directly. The former approach works best when multiple velocities are well known and clustered far away from primary velocities. The latter technique is preferable when primary velocities are well defined and we wish to suppress a broad spectrum of multiple velocities. To use a military analogy - something with which the electrical engineering literature is replete - we can choose to wage a war by either wiping out the enemy or aiding our allies. If the enemy is in one spot it is probably most expedient to conduct a concentrated bombing raid. If the enemy is widely dispersed it may be wiser to send help to our friends.

When multiple reflections cannot be discriminated from primaries on the basis of velocity, the geophysicist must resort to "predictive" techniques of multiple suppression. Such techniques commonly involve estimating where the space-time trajectories of the multiples should lie before subtracting them in an appropriate manner from the data. Predictive techniques are not as widely developed at the practical level as the velocity filtering methods mentioned above. They are usually needed to attenuate *pegleg* multiples which tend to have velocities much closer to primary reflectors than water-bottom multiples. Long period pegleg multiples - usually defined as peglegs associated with water depths in the hundreds of meters rather than tens of meters - can be a particularly severe problem when they show up deep in the section among very weak primaries.

It should be noted that predictive methods are *complementary* to - not an *alternative* to velocity filtering methods of multiple suppression. Any improvement realized in the primary/multiple ratio with a predictive scheme is usually further enhanced by velocity filtering and vice-versa.

To those familiar with seismic data processing the predictive method of multiple suppression which comes most immediately to mind is "predictive deconvolution" (c.f. Peacock & Treitel (1969) and Robinson & Treitel (1980). There is a rich literature surrounding this topic which probes many facets of one-dimensional wave propagation theory. Predictive deconvolution uses the "Wiener-Levinson" (W-L) recursion to solve a system of normal equations derived from a least squares prediction-error criterion. The use of the W-L recursion is so widespread in seismic data processing that the algorithm may fairly be called the bread and butter of the industry. This thesis will cover a number of marine environment predictive techniques which go *beyond* predictive deconvolution.

We have already suggested that there are two aspects to the predictive multiple suppression problem. The first is the prediction procedure itself or the generation of a multiple model; the second is the multiple suppression part of the algorithm. The distinction between these two phases is not always clear-cut, but the division applies to most methods. In general, the suppression phase involves statistically fitting the multiple model to the original data. (We can usually expect some correlation between these two datasets - if not, there is probably not much of a multiple problem to begin with). We would like to perform this second step with as few independent fitting parameters as possible. These parameters are typically the values of a matched filter or some other cross-correlation filter. There is a temptation at this point to either use a large number of filter parameters in a time-stationary model or to use a time-adaptive filter with an adaptation time that is small with respect to the multiple reverberation period. In either case we run a very real risk of "throwing the baby out with the bath water" and attenuating the primaries as well as the multiples.

The required number of free fitting parameters depends on how well the physics of the reverberation process is modelled by the first stage.

What, then, are some useful models for multiple reverberation? Previous refinements to predictive deconvolution have centred around the so-called "Noah's" model which added the effects of low amplitude surface multiples of the type shown in Figure 0.1c. (e.g., Riley and Claerbout (1976), Mendel (1978), Lee and Mendel (1981), and Morley (1979)). Such an approach is limited to zero offset and does not directly deal with the seafloor reflector whose influence on the seismic data is all-pervasive. In other words, zero offset models do not address the fact that the near-surface response at the shot and at the geophone may be quite different.

To deal with the problem of non-zero offset, Estevez (1977) developed a "slant frame" theory of multiple reflections. His simple theory, without diffractions, included the effects of wide offset and a narrow range of dip. The more general theory - including diffraction terms - allowed for a broader range of dips. Unfortunately, this approach did not advance beyond the forward modelling stage.

An even simpler step beyond the strictly one-dimensional assumptions of predictive deconvolution is a model which relaxes the zero offset, zero dip requirement for primaries yet assumes vertical incidence propagation of multiple wavefronts in the water. This assumption is poor for water bottom multiples but in many cases is surprisingly good for peglegs. This is because the velocity contrast at the seafloor is often so big that a small angle of incidence in the water can imply a large propagation angle in the sediments. Such a model is introduced in this thesis as a "Split-Backus" model. Backus (1959) developed a theory of multiple reverberation which laid the groundwork for predictive deconvolution. The "splitting" refers to the two different periods in the multiple reverberation train resulting from the possibly different water depths at shot and geophone locations.

Perhaps the most important contribution of this thesis is a technique called "seafloor-consistent multiple suppression". Each seismic trace is modelled as a convolution of shot, geophone, midpoint, offset and average response functions. In the log-frequency domain this becomes a separable additive model which can be solved for each frequency in a manner analogous to the "surface-consistent statics" problem of exploration seismology. The shot and geophone components of the solution provide an automatic statistical estimate of the Split Backus reverberation model for each trace. A most important feature of the process is that the number of free parameters in the model is vastly reduced when compared with trace-by-trace predictive deconvolution. Thus, the primary reflections emerge relatively unscathed after multiple suppression.

If it is necessary to model wide-angle multiple wavefront propagation, a wave equation approach is more appropriate. This thesis also develops the theory for this type of approach and presents results of some preliminary applications.

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