Chapter 1. General Introduction

Multiple reflections have always been an important problem in exploration seismology. In marine data multiples can be especially severe, causing the misinterpretation of primaries and reducing the quality of velocity estimates. Their removal is essential to reliable velocity estimation and clean migrated sections. Some methods of multiple suppression (Goupillaud (1961), Treitel and Robinson (1966), Schneider, et.al. (1964), Sherwood and Trorey (1965), Claerbout (1968), Wuenschel (1960), etc.), including the most popular one of predictive deconvolution (Peacock and Treitel (1969), Riley (1973)) in many cases indeed do a reasonable job. Nevertheless, being derived primarily from a time-statistical basis or from a one-dimensional layered earth, they still disregard two major ingredients: 1) the angle-dependent effects due to the different angles of propagation of the seismic rays (waves), and 2) intrinsic wave phenomena, such as diffractions, usually present in the recorded seismograms. Probably only Taner's approach [22] to multiple suppression (radial traces' deconvolution), partially accounts for slanted propagation. Otherwise, his and the rest of the prevailing methods, are confined within the framework of ray theory approximations.

D. C. Riley [17] showed that a deterministic approach to the modelling and removal of multiples based on the two-dimensional scalar wave equation can be implemented in some practical situations. The advantage of this approach over the previous ones is that it correctly incorporates diffractions and other wave effects. The main idea behind this method is to decompose the scalar wave equation into two equations governing downgoing and upcoming waves separately (uncoupled equations). The separation is achieved through a coordinate transformation that implies a frame moving together with the wave front. The uncoupled equations, may be used to migrate surface wave fields down into the earth or to diffract them from within the earth up to the surface. Further, the up and downgoing equations are coupled at the reflector locations through the transmission and reflection coefficients. The obtained coupled equations allow us to solve both the forward and the inverse problems. The former refers to the computation of the wave fields recorded at the surface (reflection seismograms) given a distribution of reflection coefficients and a string of waveforms going down into the earth. The latter reverses the operation: given the reflection seismogram, defines the reflection coefficients. Therefore, by solving the forward problem we can synthetize reflection seismograms that include diffracted multiple reflections, while the solution to the inverse problem implies their cancellation from a surface seismogram. Riley's study, however, was limited to waves recorded at small offsets (up to 20 degrees propagation angles approximately).

This thesis expands Riley's theory to wider angles of propagation, thereby accounting for a whole new range of slanted propagation related phenomena. The advantages of this generalization are important:
1) For one thing it can enhance those offsets where the information is more reliable, overcoming one of Riley's main difficulties. Consider Figure 1.1, where the recording geometry of a typical marine seismic survey is illustrated. The combination of factors such as the finite length of the receiver cable, the shot to geophone distances

and the reflector depths, limits the offsets and propagation angles that can be registered. Thus, it is highly desirable that the theory is capable of handling the range of operational angles and offsets.

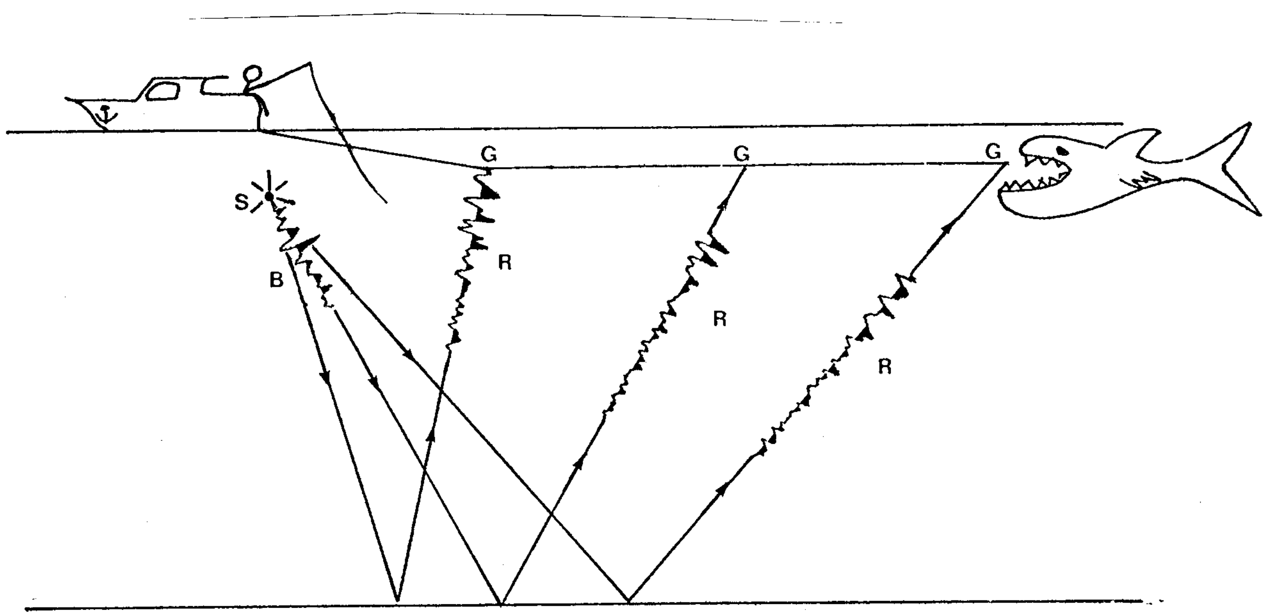

Figure 1.1. Recording geometry of a marine survey. A source (S), located just beneath the surface sends an acoustical signal (B) into the earth. This input waveform is reflected by the sub-surface reflectors and eventually recorded by a string of geophones (G) in the form of reflection (refraction) seismograms (R) .

2) The new theory allows also for variations of depth and reflection coefficients within the multiple paths. This fact alone accounts for several innovations. As we know, multiple reflections migrate differently than primaries, especially in the case of a dipping sea bottom or strong lateral velocity inhomogeneities. Thus, in order to

predict and subtract multiples, a theory has to properly model such migrations. Figure 1.2 clearly shows how the combination of slanted propagation and offset in a not so uncommon situation, will yield multiple arrivals quite different (both in color and in time) than the ones predicted by a theory that assumes vertical propagation.

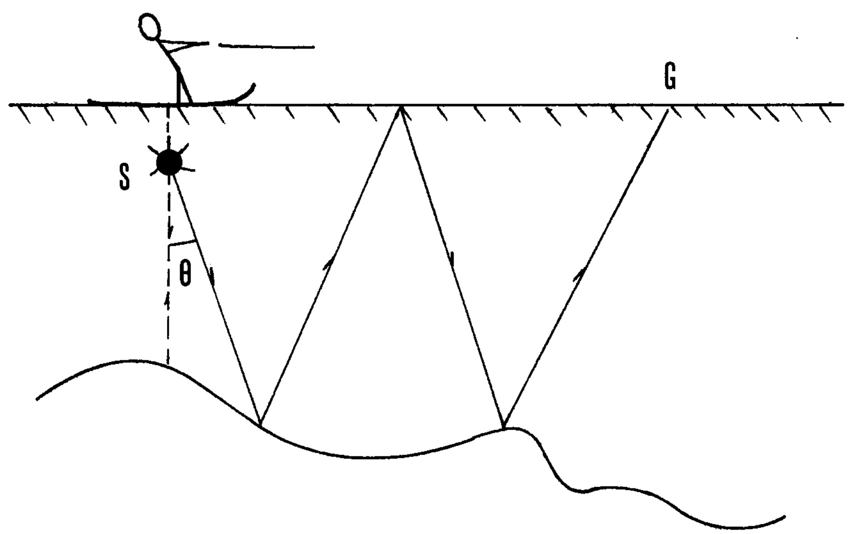

Figure 1.2. Slanted multiple reflections. The dashed line shows a vertically propagating wave, while the solid one corresponds to a wave traveling initially at an angle θ . Notice that the slanted multiple will differ from the vertical one in arrival times as well as in color, since in the slanted case each bounce images a different sector of the sea bottom.

In the case of peg-leg multiple reflections, we might expect still stronger effects. Usually it is accepted that different peg-leg paths of a given order produce a single arrival in the seismogram (Fig. 1.3a) Riley's theory predicted a splitting of the paths into different arrivals (short path diffracted and long path diffracted peg-legs) due to differences in their migration patterns. But since the major effect is actually due to the slanted propagation, the peg-legs do not separate that much in his case. Figure 1.3b shows, however, that in the case of a dipping, rough sea bottom, due to the non-vertical propagation, we should expect widely separated arrivals for each multiple path. The slant theory correctly models such separation. Furthermore, it also accounts for the proper amplitude corrections due to lateral variations of the reflection coefficients within the multiples paths.

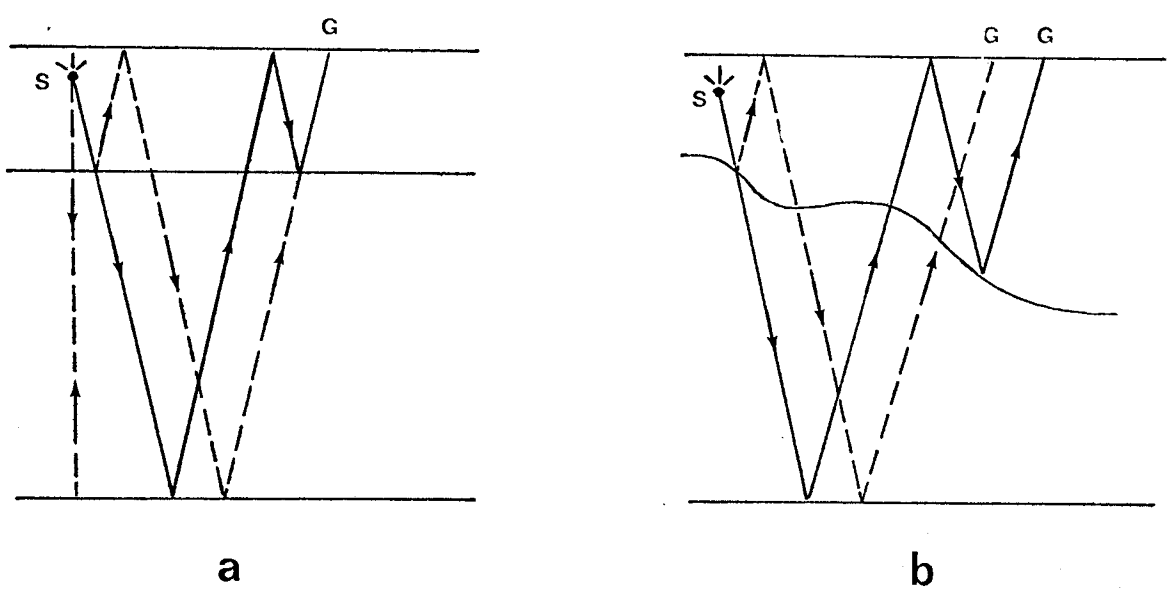

Figure 1.3. Slanted peg-leg multiple reflections. In the case of vertical propagation or flat reflectors (a), the different paths (dashed and solid lines) corresponding to reflections of a given order, will arrive at the same time. But if the reflectors are dipping and/or not flat (b), each path arrives at its own time and images a different sector of the sea bottom.

3) Experience with real data indicates that reflection coefficients are angle-dependent quantities. Thus, varying the illumination angle we could in principle enhance or attenuate particular subsurface reflectors. This interesting property, usually disregarded in the standard processing and migration theories, is partially incorporated in ours.

4) Finally, this theory properly accounts for the well established angular radiation pattern of the seismic sources.

Of course, using the scalar wave equation to model slanted incidences, still will leave some open questions in relation to additional effects such as the p to s conversions. And this certainly will limit our results, especially at near-critical angles. At the present, work is being done to overcome this limitation by the use of the more general elastic wave equation.

This thesis can be conceptually broken into two parts, the first being devoted to developing the mathematical and physical framework within which the theory operates, and the second devoted to its practical implementation.

In Chapter 2 we start by reviewing and expanding Riley's Noah deconvolution. Although it is a ray theory approximation, nevertheless, it includes some of the basic assumptions and slanted effects. It is shown how this theory already allows the modelling and suppression of an important class of multiples and peg-legs.

Chapter 3 develops the theory in terms of the two-dimensional scalar wave equation. The transformations related to a slanted propagation are derived and both the coupled and uncoupled equations are obtained. The chapter ends with synthetic examples and their implications.

The second part of the thesis relates to the practical implementation of this theory. Chapter 4 reviews some of the basic concepts connected with the definition and practical realization of slanted plane-wave stacks (p-stacks). P. Schultz (1976) introduced this notion as a way to synthetize recorded data whose source was a down-going slanted plane wave. Thus, they constitute the natural input data for our theory. The concept of the Fresnel zone is entered in an effort to define those values of p (ray parameter $p = \sin\theta / v$) which will produce the best stacked section for a given data. At the end, a real data example is analyzed.

Finally, in Chapter 5 we discuss several options for the estimation of the shot waveform, whose accurate knowledge seems to be essential to the routine application of this theory. Optimization schemes based on the minimization of the seismogram power are considered as a means to improve initial guesses.