Travel times in the INRIA Marmousi models

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Summary

The possibility and accuracy of the calculation of the first–arrival travel times and the ray–theory travel times is demonstrated on two INRIA bench–mark versions of the 2-D Marmousi model. The two models differ considerably in the degree of global smoothness.

Sort of calculated travel times

We consider here the theoretical travel times defined in terms of the eikonal equation. Within this class of travel times, we should especially distinguish between the first–arrival travel times and the ray–theory travel times. It is known that the first–arrival travel times differ considerably from the ray–theory travel times in general block models with structural interfaces.

The *first–arrival travel times* do not correspond to the ray–theory high–frequency asymptotic approximation, they describe the fastest possible propagation of information and are often connected with a negligible amount of energy. The first–arrival travel times are the property of the exact solution of elastodynamic equation. In this way, they are related rather to the full–wavefield finite differences than to the ray method. In dispersive media, the first–arrival travel times correspond to the maximum propagation velocities over the frequency range. The calculation of the first–arrival travel times is much easier than the calculation of the ray–theory travel times.

The *ray–theory travel times* ("multivalued" travel times) correspond to a selected elementary wave in the asymptotic decomposition of the wavefield. They describe the propagation of energy in the high–frequency asymptotic approximation. In dispersive media, the ray–theory travel times correspond to the velocities at the prevailing frequency.

In a special case of a nondispersive, smooth medium, the first–arrival travel times are the minimum travel times selected of the ray–theory travel times. Theoretically, not in practice. As a smooth medium becomes more complex, the number of multiple travel time branches exponentially increases with the number of smooth heterogeneities: each triplication of the wavefront caused by a small heterogeneity spreads further in a large angle, approaches many other small heterogeneities and is again triplicated at each of the heterogeneities and so on. In practice, we cannot calculate millions of travel–time branches and millions of multiple arrivals at a receiver. The multivalued ray–theory travel times may thus be calculated just in models which are *sufficiently globally smooth*, i.e. they are not only locally smooth but also contain just a reasonably small number of distinct heterogeneities. In more complex models, the statistical properties of the multivalued ray–theory travel times instead of the individual values have to be estimated.

Test models, source, receivers

The results of the calculation of the first–arrival travel times and the ray–theory travel times in two smooth models, which differ considerably in the degree of global smoothness, are summarized.

The two smooth continuous bench–mark 2-D models without structural interfaces, based on the Marmousi model, have been prepared for the workshop "Computation of multi–valued traveltimes" held in INRIA Rocquencourt, France, on September 16–18, 1996 (Benamou 1996). The "hard" model is globally quite rough and is smooth on the scales of the order of several metres, whereas the "smoothed" model is a considerably smoothed version of the "hard" model, see Klimeš & Bulant (1996).

The point source is situated at distance $x_1 = 6.000\,\mathrm{km}$ from the left–hand side of each 2-D model of dimensions $9.192\,\mathrm{km} \times 2.904\,\mathrm{km}$, at the depth of $x_2 = 2.800\,\mathrm{km}$. The receivers are located along the top of the model ($x_2 = 0.000\,\mathrm{km}$), with spacing 24 metres ($x_1 = 0.000\,\mathrm{km}$, $0.024\,\mathrm{km}$, $0.048\,\mathrm{km}$, ..., $9.192\,\mathrm{km}$).

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First–arrival travel times in the Marmousi "smoothed" and "hard" models (Figure 1)

The first–arrival travel times are, as a rule, calculated on regular rectangular grids of points, using the discretized versions of seismic models. The calculation by means of a stable causal algorithm usually makes no problems, with exception of the accuracy. The accuracy is dependent on the algorithm used (and, naturally, on the efficient coding) and on the density of the grid.

Grids of various densities have been considered and methods of different accuracy have been compared, see Klimeš (1996b). Let us name, e.g., the first–order network shortest–path ray tracing according to Klimeš & Kvasnička (1994) and the second–order method by Klimeš (1996a). For very accurate reference travel times refer to Klimeš (1996c).

Ray–theory travel times in the Marmousi "smoothed" model (Figure 2)

The ray–theory travel times at given receivers in the "smoothed" model were calculated by the *shooting method* based on the initial–value algorithm by Červený, Klimeš & Pšenčík (1988). Even the "smoothed" model is not sufficiently smooth for the shooting method: the geometrical spreading, especially at the leftmost part of the receiver profile, is so great that there is no take–off angle available within the single precision real numbers to shoot the ray to that region. Thus, the shooting method cannot catch all the two–point rays in this model. On the other hand, if the two–point ray is found, the calculated ray–theory travel time is probably very accurate. *Wavefront tracing* would probably be reliable in this model. The question remains whether the price for it would be the loss of accuracy.

Ray–theory travel times in the Marmousi "hard" model (Figure 3)

The ray–theory travel time curve in the "hard" model is so complex that the two–point ray tracing makes no sense. For illustration, travel times corresponding to several of the initial–value rays are shown in Figure 3. The cloud of points in Figure 3 is far from starting to form the complete travel–time curve.

Acknowledgements

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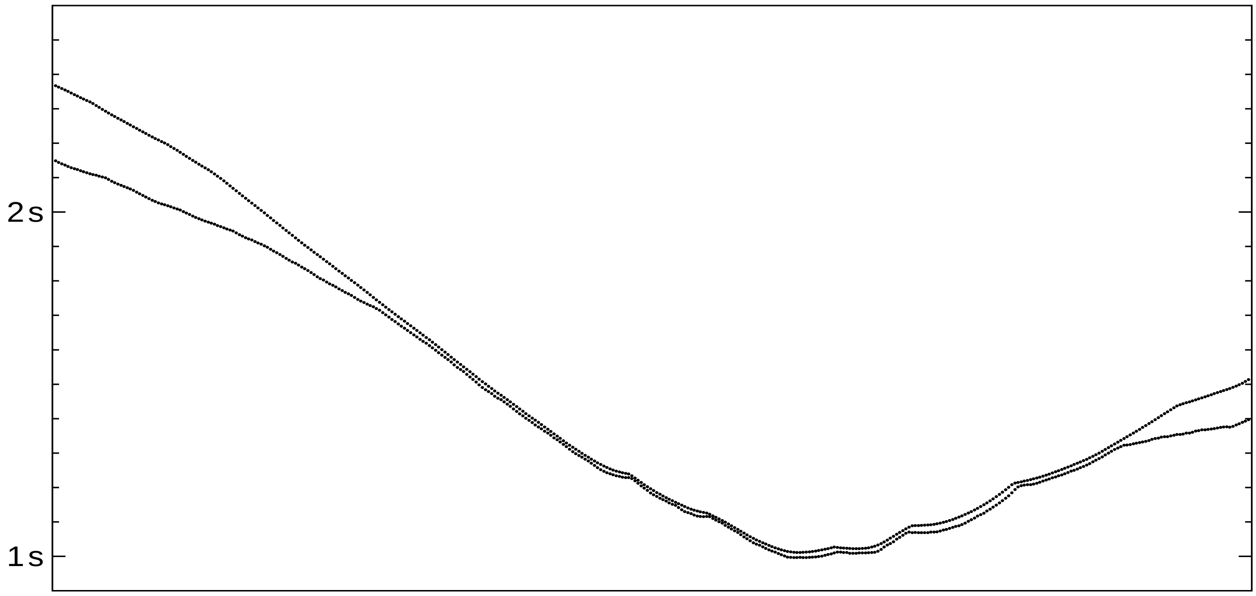

Figure 1. The first–arrival travel times in the "smoothed" (upper curve) and "hard" (lower curve) INRIA bench–mark versions of the 2-D Marmousi model.

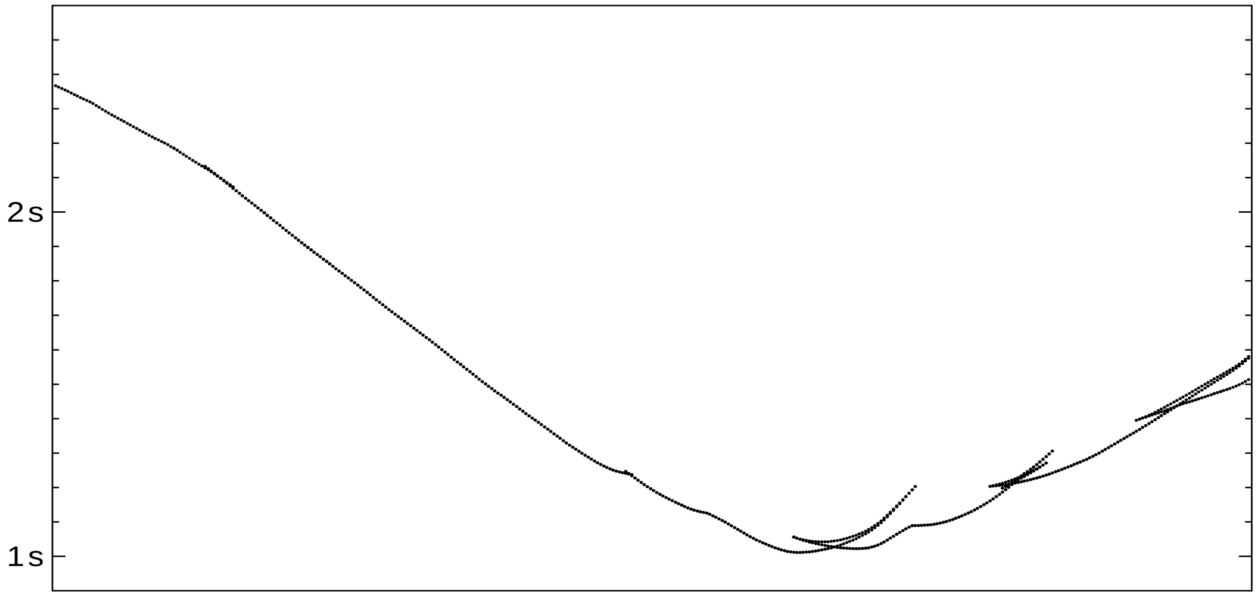

Figure 2. The first–arrival travel times and the two–point ray–theory travel times in the "smoothed" INRIA bench–mark version of the 2-D Marmousi model.

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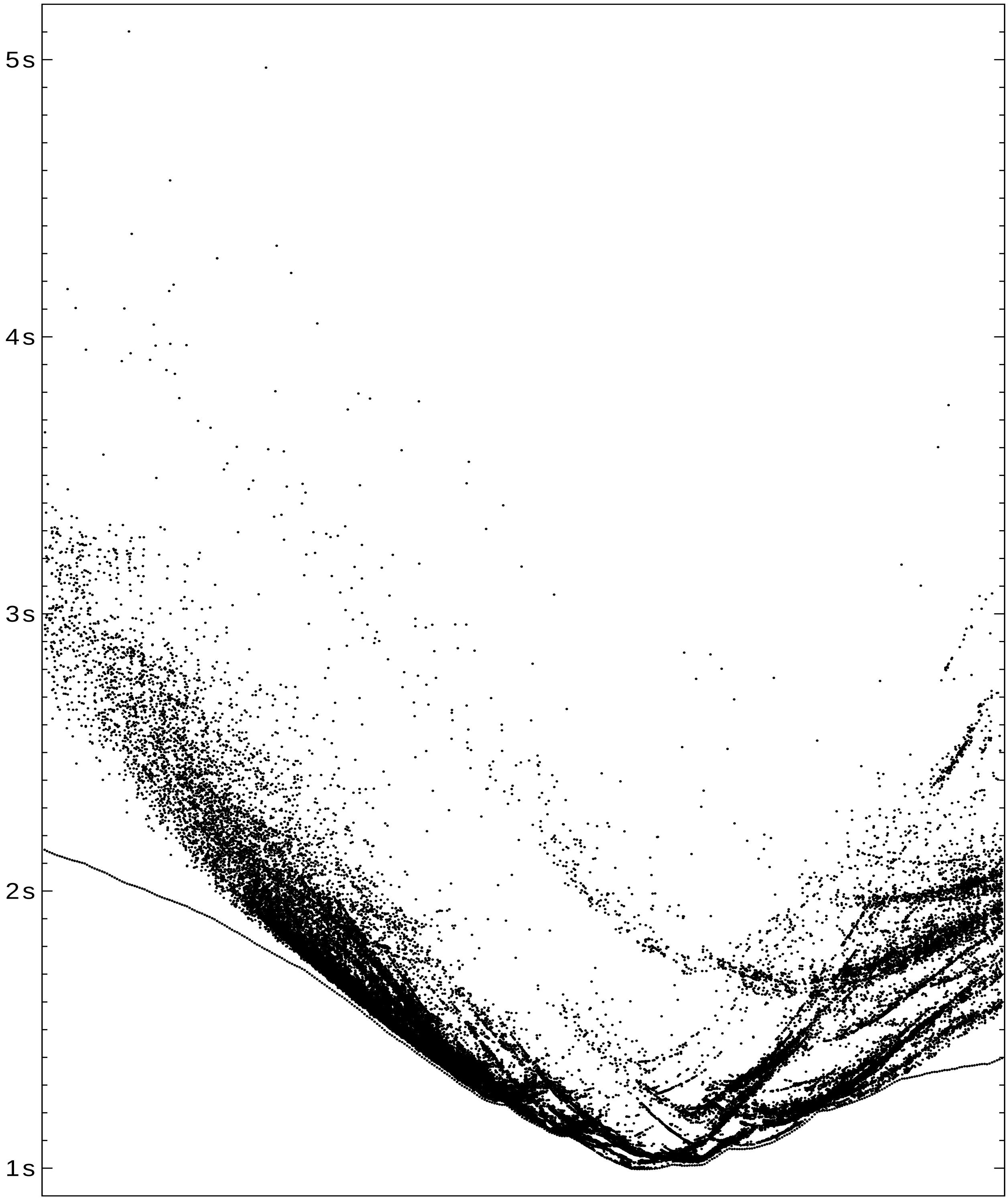

Figure 3. The first–arrival travel times and 136 818 initial–value ray–theory travel times in the "hard" INRIA bench–mark version of the 2-D Marmousi model. 136 818 of 244 302 initial–value rays, shot with the angular increment of 0.000 010 radians, hit the receiver profile.