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Ray synthetic seismograms: a useful tool in the International Data Center environment

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Abstract
In this paper some of the results of a feasibility study on ray synthetic seismograms usage are reported. A computational method, ways of composing synthetic traces, an application of the source wavelet and the radiation pattern and integration of such an approach into the Center for Seismic Studies (CSS) revision 3.0 structure are outlined. Further on, results obtained for model examples, nuclear explosions, and earthquakes are presented. Conclusions of the undertaken feasibility study help to understand that ray synthetic seismograms represent a very fast tool (results in «no time») and simultaneously represent a complex tool with all needed features. The ray synthetic seismograms can be implemented in various ways: to be computed automatically and used within the Intelligent Monitoring System, to be computed automatically and provided to the analyst, to provide a database of master events, to be computed interactively by an analyst during routine daily analysis.

Key words *seismology – synthetic seismograms – data processing – nuclear explosions*

1. Introduction

Synthetic seismograms have been attracting attention of seismologists since the advent of modern computing facilities. A lot of different approaches were applied to compute synthetic seismograms for quite different goals (*e.g.* Alterman and Loewenthal, 1972; Lysmer and Drake, 1972; Červený *et al.*, 1977; Wenzel *et al.*, 1990; Zahradnik *et al.*, 1993).

The most straightforward derivation of algorithms for synthetic seismograms computation is based on full (numerical) solutions of the elastodynamic equation. These approaches can be applied to a very broad class of models of elastic media. Results obtained may be very close to those obtained by field measurements. These approaches are, however, very computer intensive and are hardly directly applicable to global seismology in the sense that we would compute synthetic seismograms repeatedly in their full complexity for any arbitrarily selected set of observational stations deployed on the Earth's surface and for any arbitrary source. On the other hand, the ray theory has been found very useful not only in seismology, but generally in physics, and, in particular, in optics. Applications of the ray theory became particularly useful when it became clear how to compute rays in inhomogeneous media (Babich and Alekseev, 1958; Karal and Keller, 1959; Červený *et al.*, 1977; Kravstov and Orlov, 1980). This is important for seismology both on global and regional scales.

Once the ray theory was developed for generally inhomogeneous *1D*, *2D* and *3D* media, this theory found immediately its applications in analysing the most interesting features of seismic waves propagation due to various anomalies in the Earth's interior. This approach became known as ray tracing (in laterally inhomogeneous media). The second important impetus to popularity of ray methods was due to the success in developing algorithms for computation of amplitudes of various wave groups known as dynamic ray tracing (Červený, 1983; Červený and Pšenčík, 1983; Červený, 1985a,b). During the worldwide experiment GSETT-2 the waveforms were transmitted to the Experimental International Data Centers (EIDC) and used for interactive data analysis (see Ringdal, this volume). A paper by Ryall (1992) demonstrates very nicely how the availability of waveforms contributed to improving the quality of data analysis.

In this paper some questions related to the application of ray synthetic seismograms to practical problems of global seismology and analysis of the related data will be discussed. It will be shown that the ray synthetic seismograms are useful in everyday routine analysis. The advantages of the ray synthetic seismograms compared to other algorithms for synthetic seismogram calculations will be mentioned.

The paper will focus on the results of one feasibility study when one very efficient algorithm for ray synthetic seismogram computation based on the method of Červený and Janský (1985) was tested in the environment of an Experimental International Data Center. Various source wavelets used for synthetic seismogram calculation were implemented. In particular, the stress was laid on composing the synthetic trace, not only in a very fast manner, but also on the fact that the synthetic trace should be fully comparable with measured data, in the sense that all commonly used digital processing procedures can be applied equally to the measured seismograms and to synthetic traces. Some examples of the computations of ray synthetic seismograms will be given both for earthquakes and for nuclear explosions.

2. Synthetic seismograms: a useful tool for analysts

Everybody who has worked routinely with seismological data has come across synthetic seismograms. A lot of seismic analysts have had a wish to be able to compare their ideas immediately with some synthetic seismograms. Anybody who has ever tried to interpret a measured seismogram of an unknown earthquake using seismological tables has dreamt about a more comfortable form of these tables and about a way of depicting, not only the kinematic information (travel-times), but also the amplitudes of individual wave groups (synthetic seismograms).

It can be summarized that synthetic seismograms find their application as a useful tool for an analyst in the following situations:

— when learning to analyse the seismograms;

— when getting accustomed to a new seismic region, *i.e.* analysing data from a new array or concentrating on a new epicentral area;

— when getting accustomed to a new epicentral distance range, *i.e.* when changing the focus of everyday work from/to local, regional, and teleseismic epicentral distance range;

— as a reference in everyday analysis, *i.e.* in phase identification, particularly for strong events with secondary phases which are not quite common, in identifying and using the depth phases, in analysing complicated seismograms comprising overlapping events, multiple events and mixed events. The usage of synthetic seismograms for analyzing suspicious cases (negative evidence) is also very important.

3. Synthetic seismograms: a useful tool for waveform modelling

Synthetic seismograms can be used for various types of in-depth studies. However, when suitably applied and properly computed, they may be successfully used to model:

— a source type, *i.e.* distinguishing between the explosive and tectonic (double couple) type of source;

— a source area, *i.e.* using and getting first level information on the type of rock at the source (geological setting) and on the source coupling;

— a local structure in the source vicinity, *i.e.* using the regional velocity model including the crustal interfaces and the Moho depth, and perhaps also upper mantle anisotropy;

— anomalies along the global propagation path, *i.e.* taking into account travel time anomalies, multiple raypaths between a source and a receiver, geometrical spreading, frequency-dependent attenuation, and the ellipticity of the Earth;

— a local structure in the receiver vicinity, *i.e.* using the regional velocity model including the crustal interfaces and the Moho depth, and also the upper mantle anisotropy;

— receiver site characteristics, *i.e.* topography, elevation, sedimentary cover, station type (single station, array), etc.;

— recording equipment characteristics;

— processing procedures influence.

However, the most important fact for the analyst is that he or she can directly visually compare the synthetic seismogram(s) with measured trace(s). This enables him or her to take into account, not only the absolute values of the recorded signal, but additionally, it is sometimes even more useful to compare the ratios of amplitudes of individual wave groups on one channel, between all the channels of one station or an array or between two different stations. The usage of all this information in the course of routine analysis, particularly for complex and suspicious events, definitely increases the quality of interpretation tremendously and makes the results of any interpretation less subjective. Having synthetic seismograms at hand makes the requirement for employing an excellent analyst, with long-term experience in routine interpretation of seismological data, less stringent.

The travel-times find their usage in «automated» or «intelligent» systems. The same is surely also true for synthetic seismograms usage in these systems. However, first the ways of how to use all the above mentioned information contained in a suitable type of synthetic seismograms have to be found and, above all, fast and efficient ways of how to compute the seismograms in «no time» have to be developed.

4. Advantages of ray synthetic seismograms compared to travel time curves

Besides the kinematic information comprised in the travel time curves (tables), the synthetic seismograms offer additional useful information on amplitude properties (and sometimes also phase properties) of individual wave groups.

The synthetic seismograms can be computed not only for a single component, but for all the three components Z, N, and E. They can also be rotated to get other more suitable representations, *e.g.* Z, R, and T.

5. Advantages of ray synthetic seismograms compared to non-ray synthetic seismograms

The ray synthetic seismograms present a great advantage over all other types of synthetic seismograms from the point of view that the ray synthetic seismograms are already «analysed», *i.e.* the computational algorithm itself inherently provides very valuable information on identification of all phases on the synthetic waveform. This includes even identification of all multiple onsets for the same wave type which are very close in time to each other (*e.g.* due to some lateral inhomogeneity or a vertical gradient change).

Ray synthetic seismograms may be computed for an arbitrary number of stations, *i.e.* the seismograms may be computed for one channel of a station, for all channels of a station, or for a sparse or dense set of stations. Each of these tasks can be suitably optimized without the need to compute the complete wavefield in an extensive part of the Earth.

One of the main advantages of ray synthetic seismograms, compared to all other types of synthetic seismograms, is that they can be computed very fast. The amount of the computer time demanded for ray synthetic seismogram calculation, when compared to that needed for application of some other methods, may differ by an order of magnitude.

When computing the ray synthetic seismograms, we also obtain, besides the seismograms themselves, some additional valuable supplementary information. This additional information is not only represented by the travel times, amplitudes and phases for individual wave groups, but as a by-product, the ray algorithm can provide the complete ray path information. This is very important for understanding complicated secondary arrivals, multiple arrivals of the same wave group, etc.

The approach which is applied for ray synthetic seismogram calculation can be considered very modern from today's point of view. It is modular and flexible. In principle it is suitable even for parallel computing. All this enables one to consider the ray seismograms calculation algorithm as a skeleton where additional non-ray features may be easily appended via hybrid approaches, perturbation schemes and linearization. This also enables one to tailor the algorithm to provide, on request, either routine or advanced information suited to the purpose (routine analysis by an analyst, advanced analysis of suspicious or complex events by an analyst, usage within intelligent systems, etc.).

6. Feasibility study on ray synthetic seismograms

This section will focus on one tentative implementation of a fast algorithm for ray synthetic seismograms calculation which was undertaken at the CSS, Washington, in the environment of the Experimental International Data Center.

6.1. *Velocity model*

The type of the velocity model which can be used for ray synthetic seismograms calculation is in principle rather arbitrary. For the purpose of this study, the one-dimensional global model, known as IASPEI91 (Kennett and Engdahl, 1991a,b) was used. This model, however, has some unpleasant features as, for example, the absence of any low velocity zone in the upper mantle. As this model does not contain any information on attenuation properties, the Q values from the PREM model (Dziewonski and Anderson, 1981) were used after slight modification (Zedník *et al.*, 1993).

6.2. *Computational method*

The computational method depends on the dimensionality of the velocity model used and on its parametrization. It was shown by Červený and Janský (1985) that one of the most suitable parametrizations of a one-dimensional velocity model with interfaces can be based on cubic splines approximation applied not to velocity as a function of depth, but to depth as a function of the square of velocity. Such dependence must be derived from the velocity information for each of the layers. The ray tracing algorithm (Červený *et al.*, 1977) is based on the application of the well known shooting method. However, in particular, the suitable media parametrization mentioned above makes this approach very fast.

As a starting point for this feasibility study, a program ZESMO (Zedník, Janský and Červený, 1993) was used. In this program the routines for ray tracing (Červený and Pšenčík, 1981; Janský and Červený, 1979) are used and the classical Earth flattening transformation (EFT) (see *e.g.* Aki and Richards, 1980) was applied. The ZESMO program was designed to compute travel-times and amplitudes for a set of waves and to assign the traditional seismological labels (*e.g. PKP*) to them.

The travel-times and amplitudes of individual waves need to be converted into ray synthetic seismograms by a procedure which will be referred to as «composing synthetic trace». For this purpose a test program has been written in the frame of this feasibility study. It covers multiple choice for the suitable source wavelet, application of the radiation patterns for an explosion and double couple source mechanism (Aki and Richards, 1980; Červený and Pšenčík, 1981). The program was optimized for the speed of computation and, in particular, attention was paid to produce synthetic traces, not only for visual comparison with the recorded traces, but to produce such synthetic traces to which any digital processing (polarization analysis, filtration) can be applied without creation of false artifacts.

To make the results of this feasibility study directly comparable with global seismological data available at the Experimental International Data Center, the program for composing the synthetic trace was coded to be compatible with the standard Center for Seismic Studies revision 3.0 format (Anderson *et al.*, 1990). It became quite clear already at the stage of getting the first results that the applied algorithm was well suited for the purpose to be achieved and the speed of the complete synthetic trace production on SUN workstations was quite impressive.

It is worth mentioning that the implementation described enables one to use all multiple onsets of one wave group; computes amplitudes either for *Z-R-T* or *Z-N-E* systems; it enables one to use different prevailing frequencies for wavelets modelling different wave types; and, above all, the attenuation using the t-star method is also applied. This enables to come closer to realistic amplitude ratios between various phases. The computational approach is tuned to keep «full dynamic range» on each trace and at all traces belonging to one station. A later application of all advanced digital processing procedures as polarization analysis, polarization and frequency filtering, etc. becomes thus feasible. The modularity and flexibility of the approach were kept in mind to enable us a later addition of non-ray features and the generation of synthetic traces for multiple events and overlapping events.

6.3. *Source wavelet*

A source wavelet should be represented by an analytical signal. Generally, we show only the real part of the analytical signal, the complementary imaginary part being its Hilbert transform. To repeatedly compute the Hilbert transform (even using FFT) is a rather computer intensive task and it is of value if it can be somehow bypassed. This is the reason why some special source wavelets are of such a high practical value. These special source wavelets enable us to approximate the imaginary part of the analytical signal without computing the Hilbert transform repeatedly.

Suitable approximations of reasonable analytical signals are, for example, the Berlage wavelet and the Gabor wavelet (Berzon *et al.*, 1962). These wavelets have various free parameters which can be used to make the signal wavelet closely approximate real signals. Generally speaking, the most important free parameters of any synthetic source wavelet have to comprise the prevailing frequency of the signal, a number of «visible» swings or a number of «side lobes» in the wavelet (or the signal duration), and the position of signal envelope maximum. Besides the parameters typically used in the definition of a wavelet, more «human friendly» parameters should be at the disposal of the analyst.

6.3.1. Berlage wavelet

The Berlage wavelet is usually defined using the formula

$$s(t) = \exp\left(- \frac{2\pi f(t - t_{\text{onset}})}{\gamma} \right) \cdot$$

$$\cdot (t - t_{\text{onset}})^{\text{exponent}} \cdot \sin(2\pi f(t - t_{\text{onset}}) + \Psi)$$

The main characteristic features of this wavelet are:

- exponential envelope with ramp;
- harmonic carrier.

The free parameters are frequency, onset time, γ, exponent, and ψ. Besides these «mathematical» parameters, it is suitable to introduce more human friendly parameters comprising:

- position of the maximum in the signal wavelet envelope;
- duration of the «visible» part of the wavelet.

Various examples of Berlage wavelets are shown in figs. 1a-c. It can be shown that this sort of synthetic source wavelet is suitable from the seismological point of view as its usage results in rather clear onsets of the synthetic signals (moreover, they are one-sided).

6.3.2. Gabor wavelet

The Gabor wavelet is usually defined using the formula

$$s(t) = \exp\left[- \left(\frac{2\pi f(t - t_{\text{onset}})}{\gamma}\right)^2 \right] \cdot$$

$$\cdot \cos(2\pi f(t - t_{\text{onset}}) + \Psi)$$

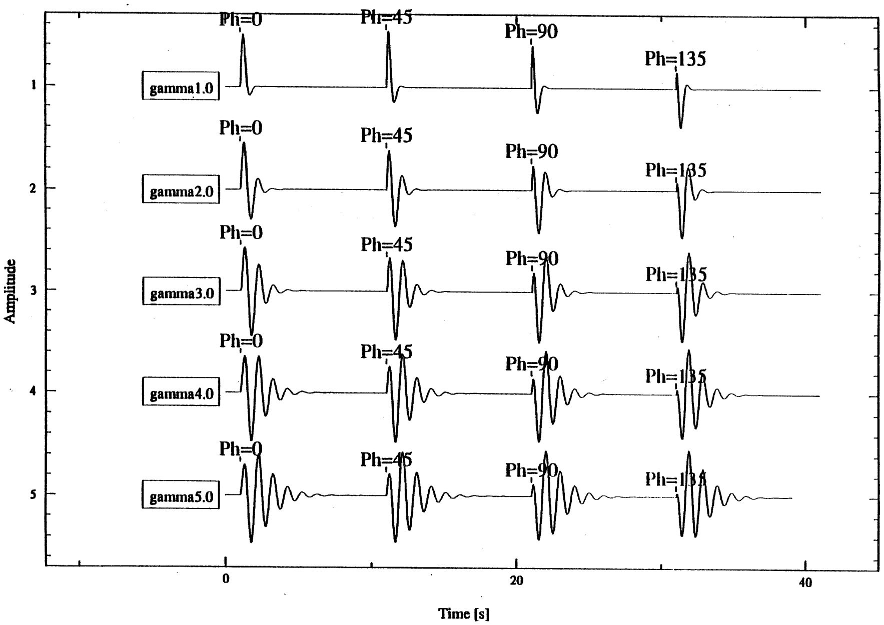

Fig. 1a. Berlage wavelet – different signals for exponent 1, period 1 s, gamma 1-5 and phase shifts 0-180 degrees.

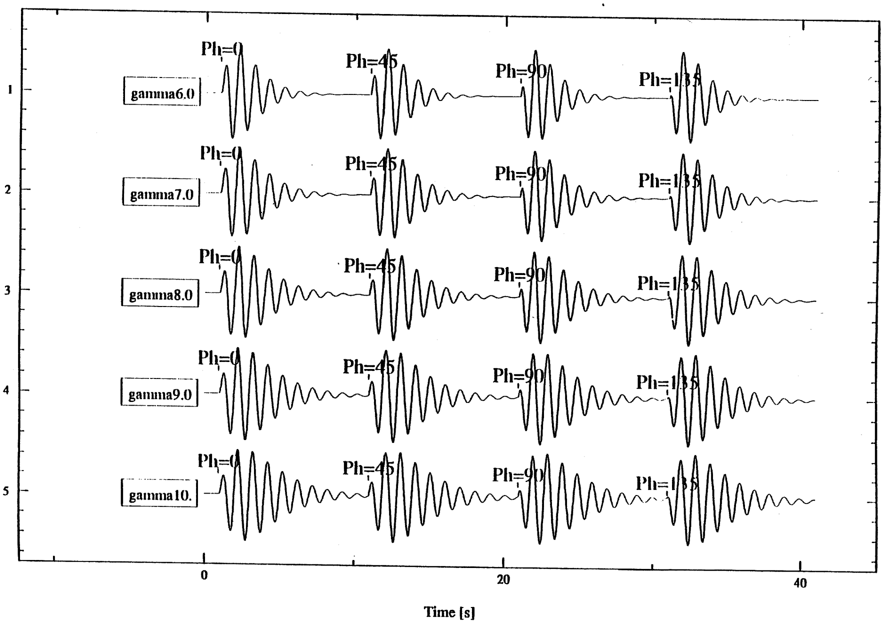

Fig. 1b. Berlage wavelet – different signals for exponent 1, period 1 s, gamma 6-10 and phase shifts 0-180 degrees.

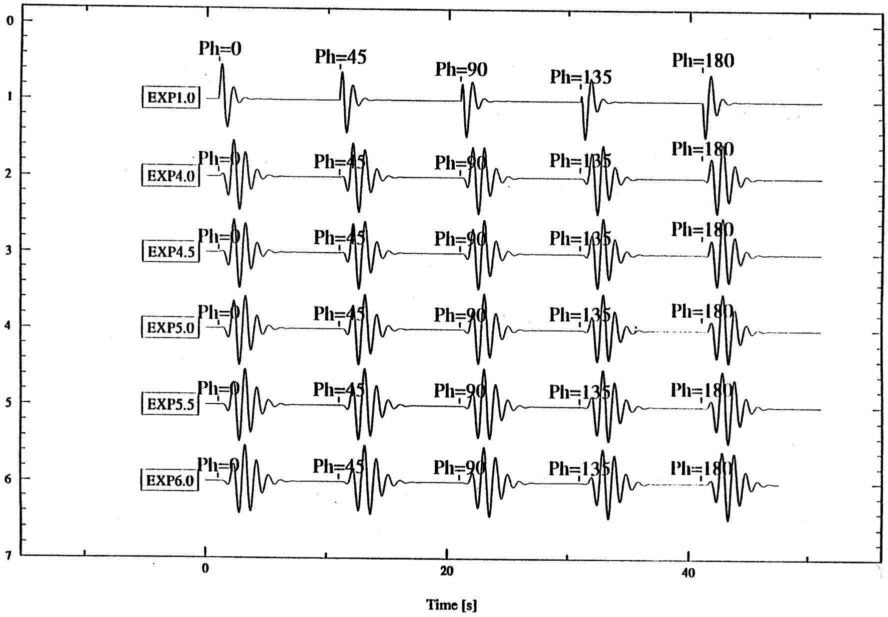

Fig. 1c. Berlage wavelet – different signals for exponents 1-6, period 1 s, gamma 2.27 and phase shifts 0-180 degrees.

The main characteristic features of this wavelet are:

- Gaussian envelope;
- harmonic carrier.

The free parameters are γ and ψ. Besides these «mathematical» parameters, it is suitable to introduce a more human friendly parameter which can be called *«number of side lobes»*. Various examples of Gabor wavelets are shown in figs. 2a,b. The Gabor type of synthetic source wavelet has various suitable properties for wavefield modelling, *e.g.* it fits very well into the Gaussian beam approach (Červený and Pšenčík, 1983; Červený, 1985b) and that is why this type of synthetic source wavelet has often been used in reflection seismic modelling. In this case, the time of maximum amplitude of the signal wavelet is of particular use.

In seismology, where the stress is laid on the onset of a wave group, this sort of source wavelet is less suitable due to its time symmetry (the signal is «two-sided»). To come closer to the observed wavefield, an additional time shift must be applied to retain «positive» onset direction for explosive sources and to approximate a «one-sided» signal. This type of signal is thus less suitable compared to the Berlage wavelet, *e.g.* for the testing of detectors on synthetic data.

6.4. *Interaction of the test software for synthetic trace composition with the standard CSS format*

As mentioned earlier, the test software was written to produce the synthetic waveforms in such a form that they can be fully used within the Experimental International

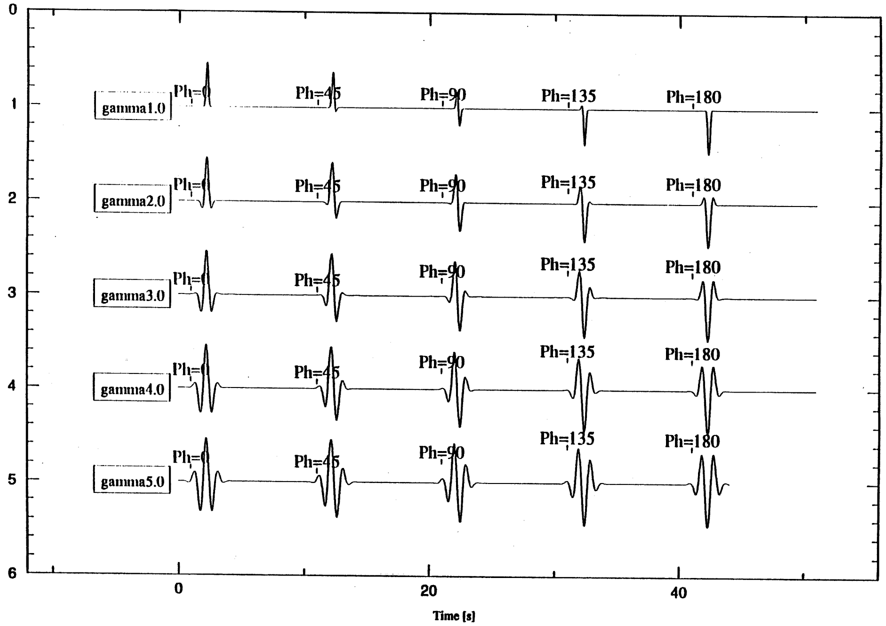

Fig. 2a. Gabor wavelet – different signals for period 1 s, gamma 1-5 and phase shifts 0-180 degrees.

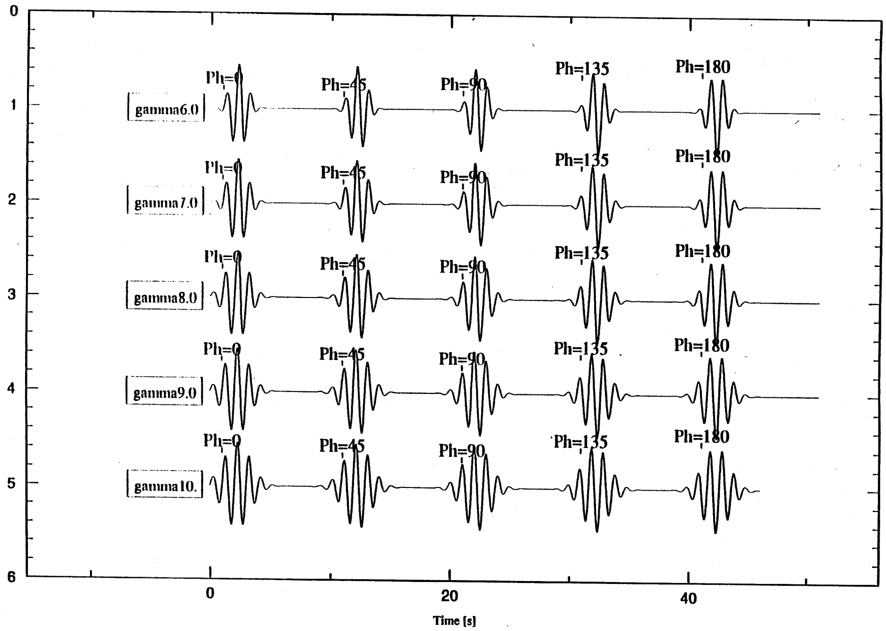

Fig. 2b. Gabor wavelet – different signals for period 1 s, gamma 6-10 and phase shifts 0-180 degrees.

Data Center data base system and so that all processing procedures can be applied equally to them as to measured seismograms. The software for synthetic trace composition was written so that the resulting synthetic trace would also fully conform to the CSS revision 3.0 format. For external use, the plain ASCII output is possible as well. The additional information used for synthetic seismograms calculation is adequately stored in the CSS 3.0 tables «wfdisc», «arrival», «event», «origin» and «remark». Data produced in this way may be directly loaded in the Center for Seismic Studies data base.

6.5. *Examples of synthetic traces*

In the following, some figures will be commented showing various features of the results. In a lot of the presented figures, IASPEI91 travel-time curves, as used in the Geotool program (Henson and Coyne 1993), are depicted for orientation and comparison.

In fig. 3 a very general overview picture of synthetic seismograms for «an explosive source» is shown covering epicentral distances from 10 to 170 degrees. Due to the scale used for the time axis the signal shape is not resolved in the picture. In this case no labels identifying individual phases are shown, but there are some IASPEI91 travel-times overlaid.

In fig. 4 another very general overview picture of synthetic seismograms is shown covering the epicentral distances from 20 to 160 degrees, but this time all the labels identifying individual phases (originating from the synthetic seismograms calculation algorithm) are shown. It is clear that there

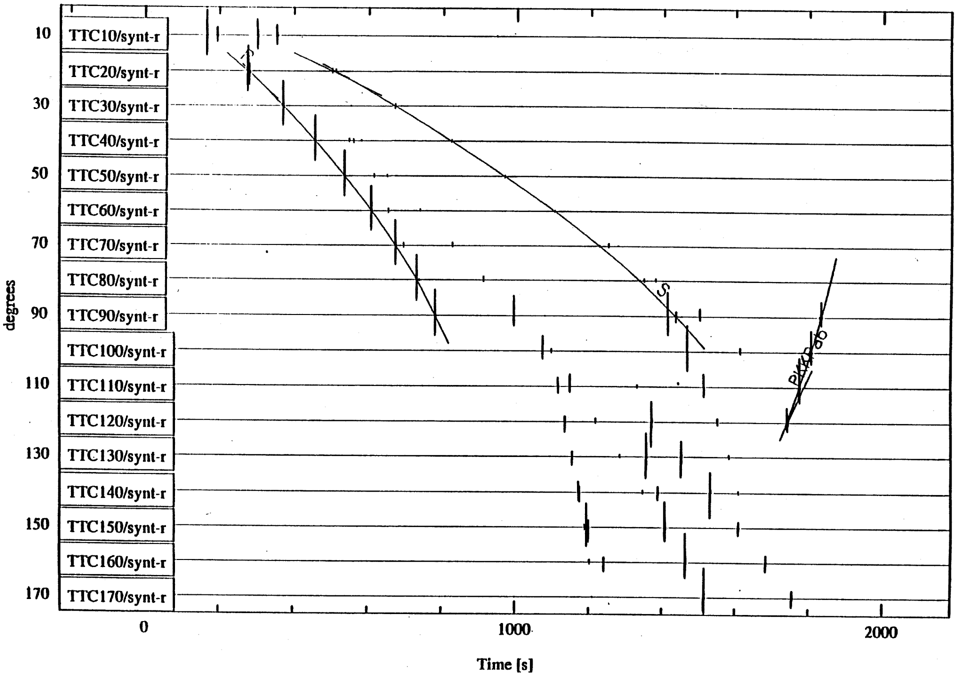

Fig. 3. Overview of ray synthetic seismograms for epicentral distances 10-170 degrees overlaid with selected IASPEI91 travel-time curves.

should be an approach applied to select only those labels for plotting which correspond to waves with reasonably high amplitudes. This approach was also programmed into the test package.

In figs. 5, 6 and 7 three images in subsequently increasing details are shown. Please note how the multiple *P*-onset around 20 degrees becomes resolved. The existence of all these multiple onsets in synthetic data should, however, be carefully studied as they may also exist due to the model parametrization only.

In fig. 8 there is a detailed picture for the most popular PKP caustic area showing various PKP branches and the PKiKP branch of the IASPEI91 travel-times, along with the computed ray synthetic seismograms using the Berlage wavelet.

6.6. *Synthetic seismograms for the LOP NOR underground nuclear test*

In fig. 9 the record of the LOP NOR underground test of May 21, 1992, as recorded by ARCESS array, is shown along with the synthetic trace using the IASPEI91 velocity model and a simple Berlage wavelet. The synthetic trace fits very well in the general features of the recorded trace. In principle the «signal generated noise», or the «coda», may at least be partly modelled when the facts mentioned in section 3 would be taken into account and the approaches mentioned in section 5 would be applied. The «later arriving» phases on the synthetic trace show us where to expect them on the measured trace.

In fig. 10 a detailed picture of the waveform of the measured signal and that of the synthetic one are shown. A very high similarity of both of these waveforms demonstrates how suitable the Berlage wavelet with its free parameters may be. The same wavelet as fitted to the first arrival is then appropriately used (and transformed for wave groups exhibiting a non-zero phase shift) for the later arriving wave groups.

Figure 11 shows a detail of the time section where the secondary wave groups are expected. It seems that the *PcP* wave group may be resolved with high precision. The multiple arrival of *PP* waves is questionable and would deserve further studies. It has to be mentioned that, in this case, no extra corrections were applied, taking into account the facts mentioned in section 3; and thus it can be expected that after application of these approaches the precision of fitting individual wave groups can even increase.

6.7. *Synthetic seismograms for complex signals*

In this section an example of the GSETT-2 prominent Caucasus earthquake

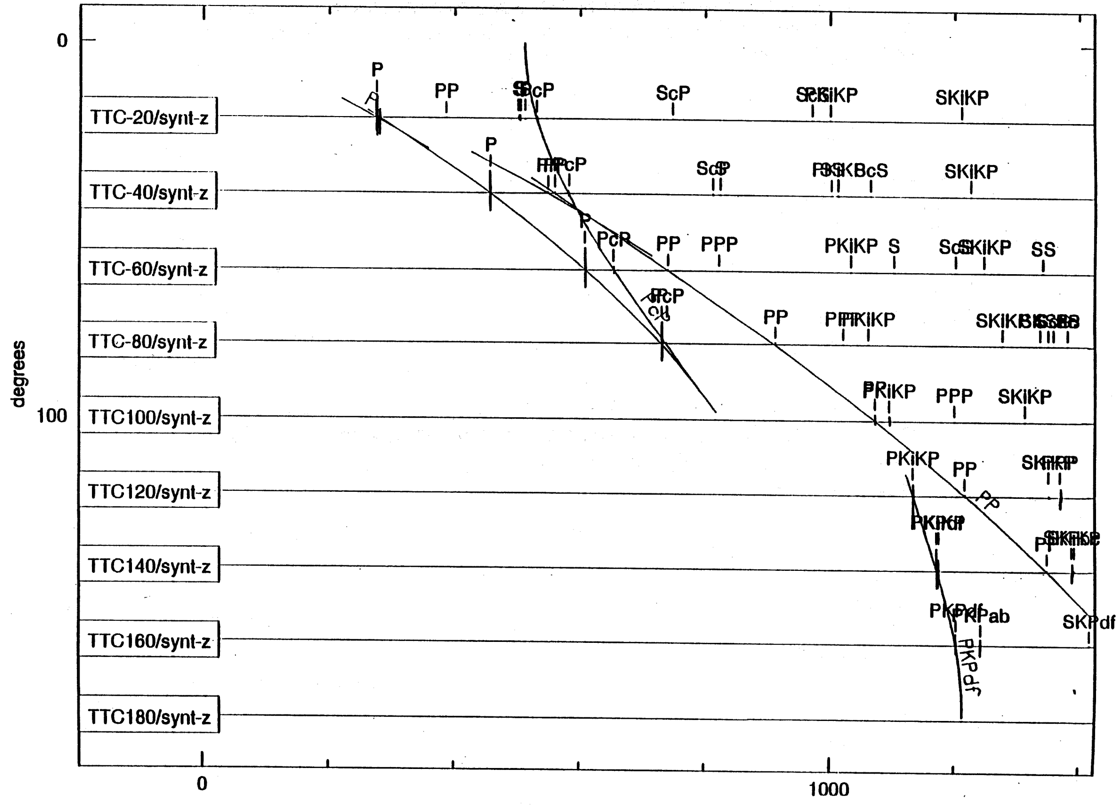

Fig. 4. Overview of ray synthetic seismograms (including the labels of all computed phases) for epicentral distances 20-170 degrees overlaid with selected IASPEI91 travel-time curves. It is possible to see the complexity of arrivals which the analyst has to face not having the information on amplitudes and just using kinematic information.

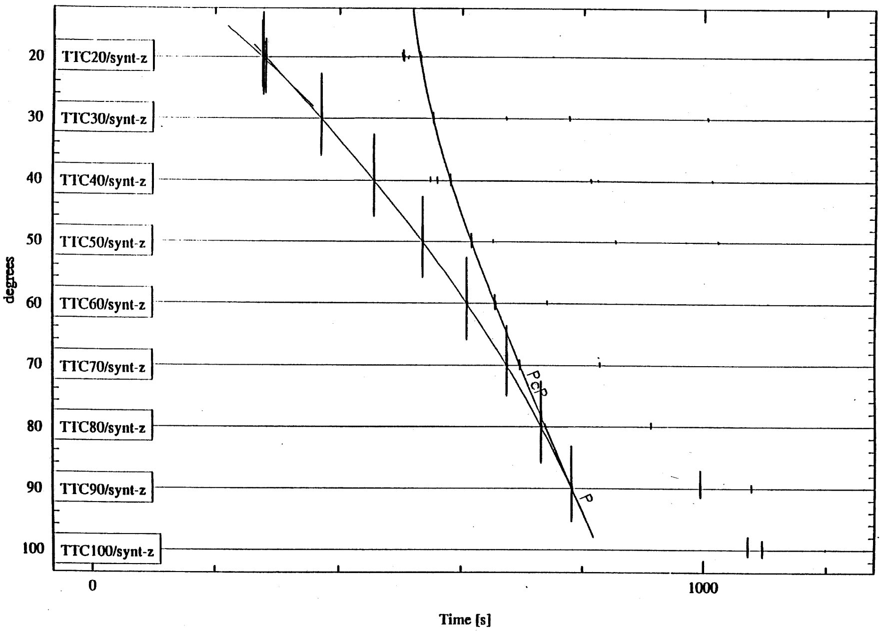

Fig. 5. Overview of ray synthetic seismograms for epicentral distances 20-100 degrees overlaid with selected IASPEI91 travel-time curves.

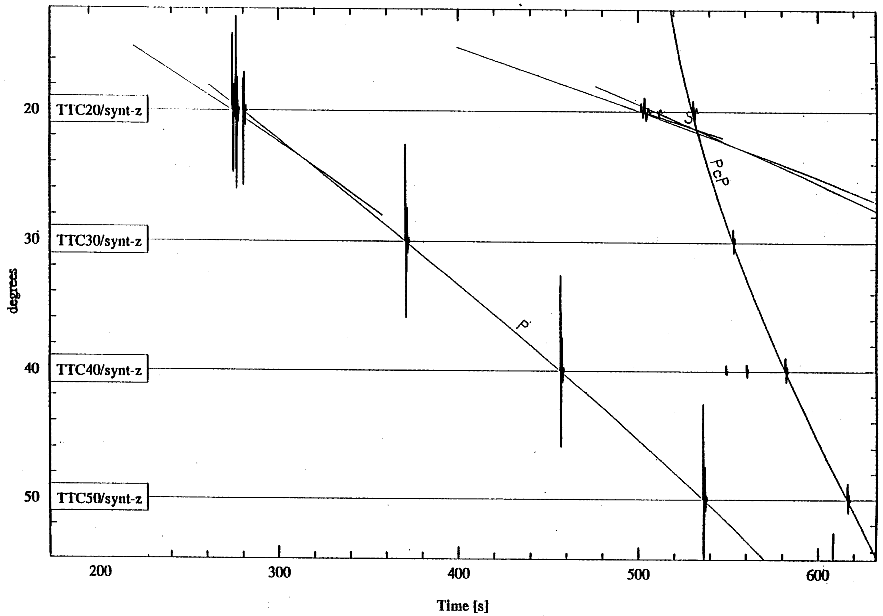

Fig. 6. Overview of ray synthetic seismograms (including the labels of computed phases) for epicentral distances 20-50 degrees overlaid with selected IASPEI91 travel-time curves.

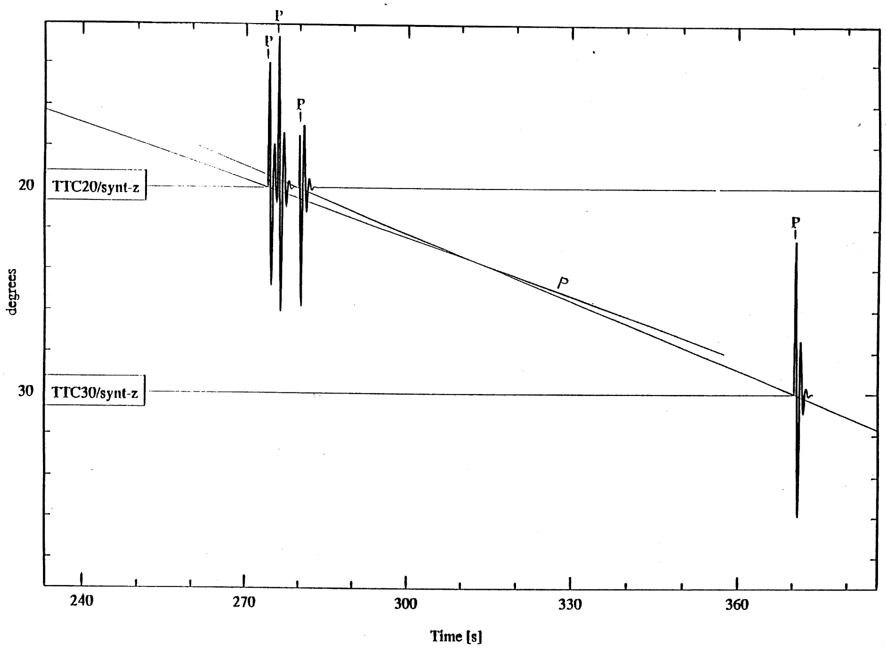

Fig. 7. Overview of ray synthetic seismograms (including the labels of computed phases) for epicentral distances 20-30 degrees overlaid with selected IASPEI91 travel-time curves.

of April 29, 1991, origin time 9:12 is shown. First let us show a composite picture of seismic traces for this earthquake as recorded by some European GSETT-2 stations.

Figure 12 shows how important the knowledge of the structure in the vicinity of the recording station may be. The records from SQTA station in Austria and KSP station in Poland show very strong phases just after the first arrival. However, these phases are not seen on the GEC2 (array in Germany) and VRAC (station in the Czech Republic) records. One of the interpretations of these phenomena may be that these phases originate within the geological structure in the vicinity of these stations. This hypothesis can be supported by the homogeneity of the Bohemian Massif where both GERESS and VRAC are situated. On the contrary, stations SQTA and KSP are situated either within or close to inhomogeneous mountainous area. These secondary arrivals represent features which may be studied by means of ray synthetic seismograms using the approaches outlined above. It is worth mentioning that strong phases generated locally represent a threat for efficiency of an automated «intelligent» system which does not take into account all these «fine details».

In the case of this prominent earthquake, it is quite interesting to study records of the Japanese station MAT as various secondary phases, *e.g. PP*, *PPP*, *SS*, *SSS* were picked and reported at MAT, but they were not correlated at the Experimental International Data Centers operating during GSETT-2. Using synthetic seismograms could help in this case as well to see whether these phases may have amplitudes high enough to be picked up by an automated system or by an analyst. It is worth mentioning that for this exceptional

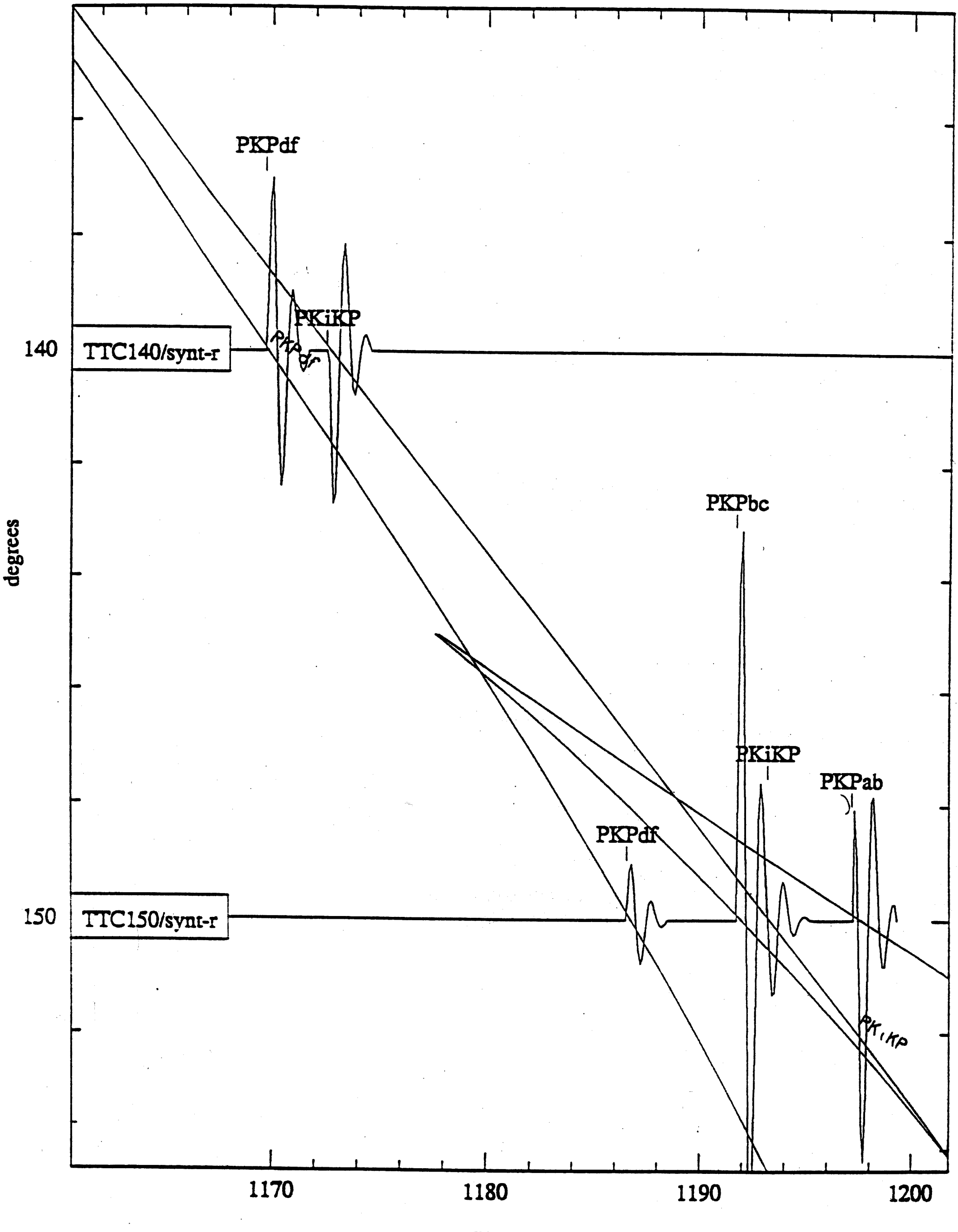

Fig. 8. Overview of ray synthetic seismograms (including the labels of computed phases) for epicentral distances 140-150 degrees overlaid with selected IASPEI91 travel-time curves.

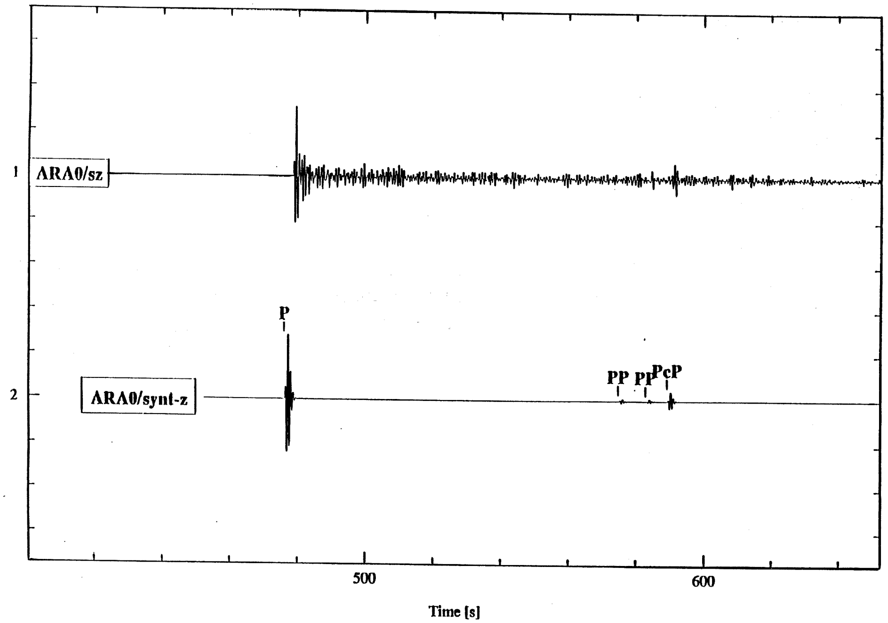

Fig. 9. Signal of the LOP NOR underground nuclear test of May 21, 1992 as recorded by ARCESS and the corresponding ray synthetic seismogram-overview.

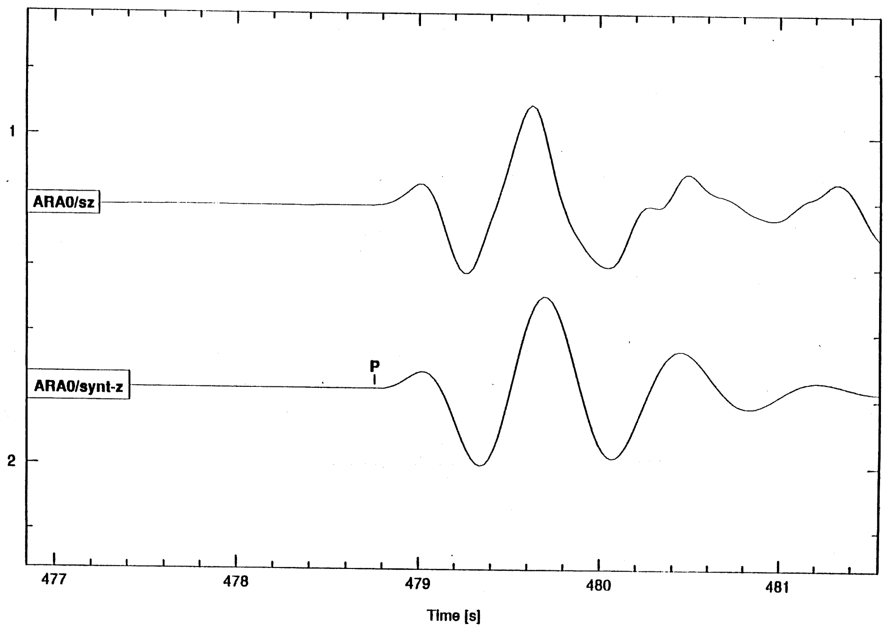

Fig. 10. Signal of the LOP NOR underground nuclear test of May 21, 1992 as recorded by ARCESS and the corresponding ray synthetic seismogram-*P* onset.

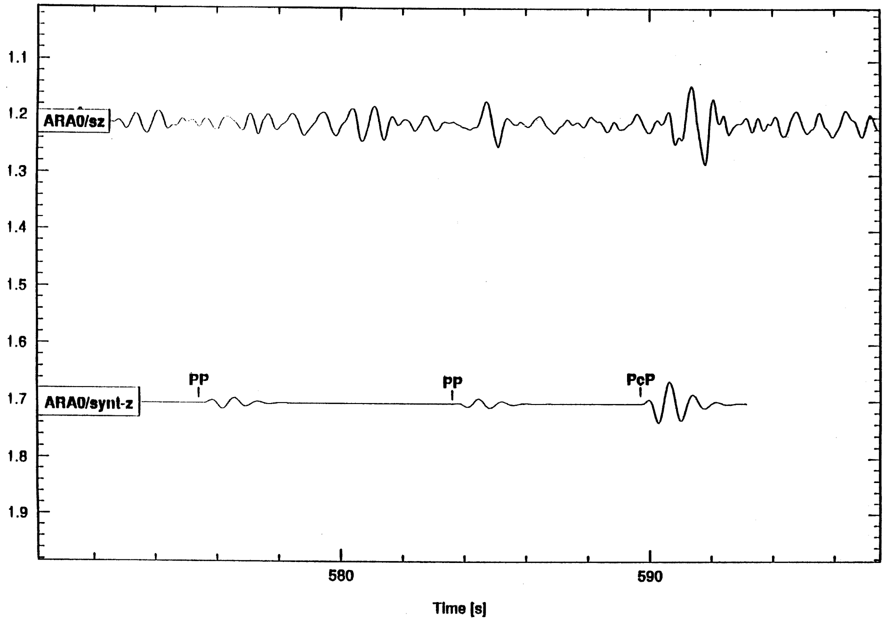

Fig. 11. Signal of the LOP NOR underground nuclear test of May 21, 1992 as recorded by ARCESS and the corresponding ray synthetic seismogram-secondary *PP* and *PcP* phases.

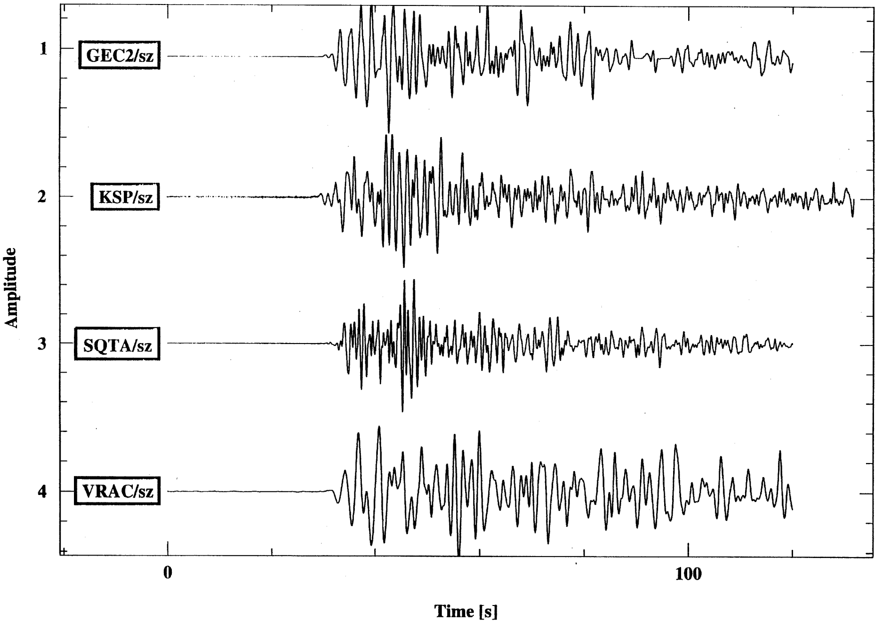

Fig. 12. Signal of the Caucasus earthquake of April 29, 1991, 9:12 UTC as recorded by some selected GSETT-2 stations in Europe.

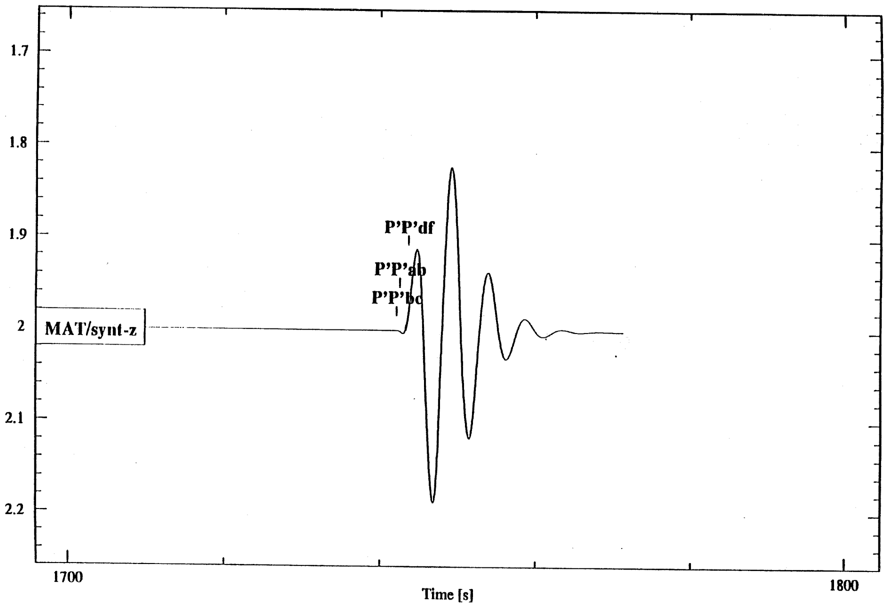

Fig. 13. Part of the ray synthetic seismogram for the Caucasus earthquake of April 29, 1991, 9:12 UTC-interference of various *P'P'* branches at MAT.

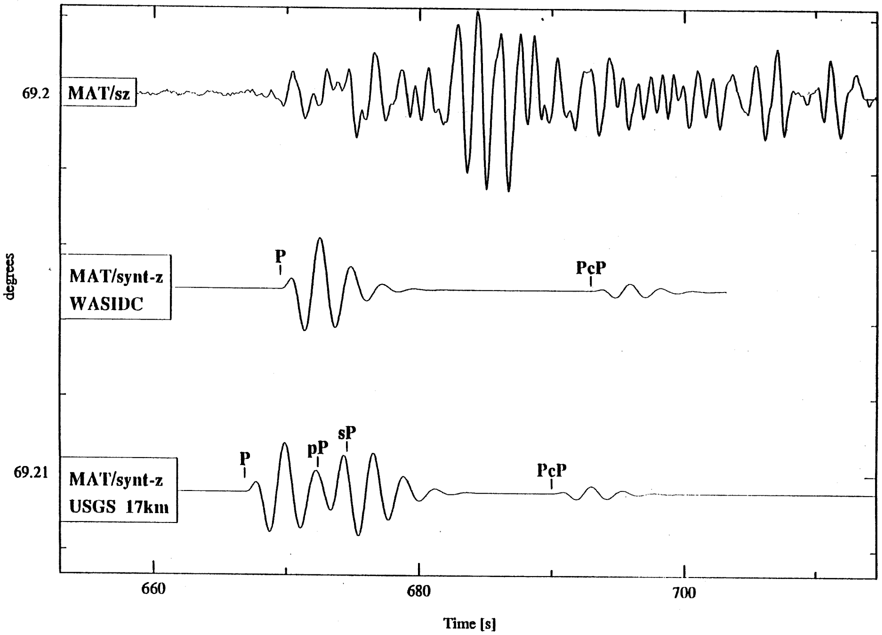

Fig. 14. Signal of the Caucasus earthquake of April 29, 1991, 9:12 UTC as recorded by MAT along with two ray synthetic seismograms computed for two available hypocenter solutions, *i.e.* for the «best» GSETT-2 hypocenter solution of WAS EIDC and for the USGS hypocenter solution with hypocentral depth of 17 km and thus with developed depth phases *pP* and *sP*.

strong event at the particular epicentral distance of MAT quite an interesting coincidence occurs for *P′P′ab, P′P′bc*, and *P′P′df* phases (see fig. 13) as modelled by ray synthetic seismograms.

Another interesting usage of ray synthetic seismograms may be demonstrated in the case of this event when comparing the original MAT record with two ray synthetic seismograms: one for the GSETT-2 hypocenter solution where no depth phases should occur, with the other one, *i.e.* the USGS solution with hypocentral depth of 17 km and with expected depth phases *pP* and *sP*. From the comparison with the MAT recorded trace, a very prominent secondary arrival, some 13 s after the first onset, can be seen. Such a phase, again, does not find a clear interpretation in the set of typically used teleseismic phases either. This may represent just another topic for a more detailed study using ray synthetic seismograms (fig. 14).

7. Conclusions

Based on the presented results of the ray synthetic seismograms study, though being very preliminary (as only results of a feasibility study are reported), it can be concluded that ray synthetic seismograms represent a useful tool, not only for routine usage by analysts in the IDC environment, but that they also represent a useful tool for more detailed analyses and modelling of complex seismograms.

It can be concluded that ray synthetic seismograms can find their application within the International Data Center environment, *e.g.*:

— to be used as a very fast tool (results can be provided in «no time»);
— to be used for analyses of complex waveforms;
— to be used to provide some background information, being much more informative than simple travel-time curves.

Ray synthetic seismograms represent a useful tool for analysts in many situations:

— when learning to analyse seismograms;
— when getting accustomed to a new seismic region;
— when getting accustomed to a new epicentral distance range;
— as a reference in everyday analysis.

Ray synthetic seismograms represent a useful tool for waveform modelling enabling one to take into account specifics of the source type, source site characteristics, local structure in the source vicinity, global propagation path, local structure in receiver vicinity, receiver site characteristics, recording instrument and processing procedures.

Comparing ray synthetic seismograms to non-ray synthetic seismograms, we can see a lot of advantages of the latter ones:

— all phases on the synthetic waveform are identified;
— they may be computed for arbitrary number of stations;
— they can be computed fast;
— they provide raypath information;
— they may serve as a skeleton where additional features can be implemented via perturbation schemes and linearization;
— they can be tailored to provide routine/advanced information.

It can be concluded that ray synthetic seismograms within the International Data Center environment can:

— be computed automatically and used within the intelligent system;
— be computed automatically and provided to the analyst;
— be used to create a data base of master events (reference events) for various epicentral distances, various epicentral areas, various types of events;

— be computed interactively by an analyst during routine analysis.

Further on, it can be pointed out that the usage of level II data (waveform segments) during GSETT-2 experiment was very valuable and it enabled us to use more advanced interactive data processing procedures relying exclusively on waveform data. The advantages of synthetic seismograms over those of travel-time curves can help to make data interpretation even more reliable and less ambiguous. However, it became clear that the usage of waveform segments only limits the application of advanced processing tools which are based on the knowledge of the full three-component waveforms/complete array data.

The lessons learned from GSETT-2 and conclusions to be implemented in the forthcoming experiments are that, either the data have to be transmitted continuously to the International Data Center or they must remain available for a reasonably long period of time at the station to be readily available on request. For some purposes, either complete array data or complete three-component waveforms are needed and thus these data should be readily available as well.

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