Topic	Animation of seismic ray propagation and seismogram formation
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1 Introduction

Presented are 10 movies with animations of seismic ray propagation and the formation of seismic recordings in the distance range from 0.1° to 167°. Below we comment on each of these movies, which complement record sections presented in the Chapters 2 and 11 of this Manual. The animations can be opened by right mouse click on the file name **printed in bold blue letters** and then follow the instructions given below in section 2. The animation files can also be downloaded via the summary listing *Download Programs & Files* (see Overview on the NMSOP-2 cover page).

The development of such movies began at the University of Leipzig more than 20 years ago. Dr. Bernd Tittel, now retired from the University´s Geophysical Observatory Collm, was an expert in identifying late and very late core phases. Therefore, the idea was born to produce an animation of the propagation of the seismic rays for such very late phases through a simple standard 1-D Earth model. The related seismic recordings of station Collm (CLL) were later added as standing pictures at the end of the movie. More than a decade ago one of us (S. Wendt) revived these earlier efforts by extending these animations to crustal, mantle and core phases in the local, regional and teleseismic distance range and by "writing" the sequence of records at several stations of local or regional networks as soon as the respective seismic phase rays arrive at these stations.

All ray paths and travel-time curves were calculated with the program TauP of H. P. Crotwell (1998) on the basis of the IASP91 Earth model (Kennett and Engdahl, 1991).

2 Software requirements and handling

The animations run on a Windows-PC with QuickTime Player 4 to 7. Quick Time Player can be downloaded from www.apple.com. After its installation, activate the event record file you wish to see in *Download Programs & Files*. Move with the cursor in front of the bold blue file name you wish to open. A right-mouse click opens a window which offers also the choices "copy hyperlink" and "open hyperlink". When you confirm with a left mouse click "open hyperlink" then - after a while - the cover page of the respective movie file appears in a frame. Start the movie by pressing the start-button ▶ in the middle of the lower frame ridge. If this button is not visible then you have to reduce the frame size in the Quick Time Player menu line which appears above the movie cover frame. Click "Display Size" in order to adopt the movie frame to the size of your screen and then start the movie. The moving marker above the lower command line will start running and the movie will show up. If you wish to hold-on the movie or control its speed at will then just catch the moving marker with your cursor and move it as you wish.

If lines, letters and numbers in the movie appear broken or blurred, the screen resolution has to be increased before starting QuickTime. Click “Start” in the desktop area, then “Settings”, and then “Display” on the appearing “Control Panel”. When “Display Properties” appears click “Settings” and there you may change the pixel number in the desktop area. Usually, a resolution of 1280x1024 pixels should be sufficient to resolve all details. Then return to the desk top, go back to *Download Programs & Files* and start the movie file again or select another such demonstration.

Yet, sometimes a much easier way works even when the film is already running. Go to “Display Size” and change there from “adopt to screen size” to “normal size”.

3 General structure and contents of the movies

Each movie file shows first a cover page in the start-frame, which gives the data, origin time, source co-ordinates and name of the source region of the earthquake. After starting the movie you will see, for all teleseismic earthquakes, the propagation of seismic rays of different phases, coded in different color, through a simplified cross section of the Earth. Shown are only those rays which will reach stations of the German Regional Seismic Network (GRSN). As soon as the different rays arrive at these stations, the onsets and associated waveforms will be “written” according to the original seismograms recorded at these stations from the considered earthquake. The response filters applied to the original velocity broadband records are given together with the record component in the record frames. The station codes and the epicentral distances to the stations are written on the ordinates and the travel times are marked on the abscissas of the record section frames. For all depicted phases, the theoretical travel-time curves according to the IASP91 Earth and travel-time model are also plotted in the respective phase color into the record frames.

Exceptions are the two local earthquake recordings (Files 1 and 2). Here the propagation of the Pg and Sg wavefronts and the formation of the related records at stations of the GRSN in different azimuths from the source are either shown in conjunction with the formation of the local travel-time curve (File 1) or on separate map projections.

4 Movie files and peculiarities of the recordings shown

Below the following information is given for each animation:

- file name;
- geographical region of epicenter;
- source parameters date, origin time OT, co-ordinates, source depth h;
- magnitude and data center which has provided these source data;
- the size of each animation file in megabyte (MB);
- the interval of epicentral distances D of the recording stations shown;
- remarks about the depicted seismic phases and recording frames;

- complementary remarks about the peculiarities of the records shown and the lessons learned from this demonstration.

For the definition of seismic phase names and complementary ray diagrams see IS 2.1. The original velocity broadband records have been filtered according to the response characteristics of standard seismographs, e.g., of type Kirnos SKD, SRO-LP, WWSSN-SP and WWSSN-LP. Their response curves are shown in Chapter 11, section 11.3.2 together with complementary record examples.

Note, that in the following the file names are printed in bold black, since they are not hyperlinked with IS 11.3.

File 1: wendt_vogtland1_qt
NW- Bohemia, Czech Republic, Novy Kostel
17.09.2000 OT=15:14:33.5 50.22N 12.47E h=10km Ml=3.1 (SZGRF)
23.0 MB
D=10–130km
Pg and Sg
Left: propagating wave fronts of Pg (blue) and Sg (red); **right:** records of some stations of the GRSN. Traces are sorted according to distance. At the moment of wave-front arrival at a station the onset and related waveform of this arrival is written in the record of the seismic station.
Note that the depicted travel-time curves for an average 1-D local crustal model match well with the onsets at the stations WERN, MOX and CLL but the onsets recorded at the stations GFRO and WET are about 2 to 4 s later than the onset times expected according to this model. This illustrates the need for improved local travel-time curves which may also be azimuth-dependent.

File 2: wendt_vogtland2_qt
NW-Bohemia, Czech Republic, Novy Kostel
04.09.2000 OT=00:31:45.2 50.21N;12.44E h=10km Ml=3.2 (BGR)
28.3 MB
D = 10–240km
Phases: Pg and Sg

Left: developing records at several GRSN-stations; **right:** propagating wave fronts of Pg (blue) and Sg (red).
When a wave front arrives at a station the respective onset and original waveform recorded at this station is written in the seismogram. The amplitude ratio Pg/Sg strongly varies with azimuth due to the different source radiation pattern for P and S waves with respect to the station azimuth (see Figs. 3.25 and 3.26).

File 3: wendt_slovenia_qt
Slovenia
12.07.2004 OT=13:04:06.3 46.30N; 13.64D h=2km mb=5.0 (NEIC)
190.2 MB
D = 80-910km
Phases: Pn, (Pb?), Pg, Sn, Sb and Sg

Presented are the Z-component (above) and EW-component records (below) of WWSSN-SP filtered records of 8 stations of the German Regional Seismic Network (GRSN) (see diagram upper right) and a schematic crustal cross section (lower right) with the assumed ray-paths of the standard crustal phases Pg, Pb, Pn, Sg, Sb, and Sn. The following should be noted:

1.) Up to about 780km distance Pg is here the dominant phase onset in the early parts of the Z-component records;
2.) Yet, at the most distant station RGN Pn amplitudes are clearly larger than that of Pg which fall already in the signal-generate noise level;
3.) Pb, the critically refracted P wave from the mid-crustal Conrad discontinuity is not recognizable clearly in any record with the exception of the station RGN Z-component record, where it may be associated with slightly earlier than predicted arrival of a wave group with increased amplitude but no sharp onset;
4.) The P-wave onsets in the horizontal component records are generally smaller than in the Z component.
5.) Sg is the onset of the most prominent wave group with the largest amplitudes in the whole event record train;
6.) Sn is a clear earlier shear-wave arrival prior to Sg only in the horizontal component records and there also Sb has occasionally recognizably increased amplitudes, in this case at records of stations GRFO and CLL even with distinct onsets.

However, in the majority of earthquake records Pb and Sb are not well developed with clear onsets and significant SNR above the signal-generated noise between Pn and Sg.

File 4: wendt_hindukush_qt
Afghanistan-Tajikistan border region
30.06.1994 OT=09:23:21.4 36.3N;71.1E h=227km mb=6.1 (NEIC)
54.0 MB
D=43° - 47°
Phases: P, pP, sP, PcP, PP, pPP, PPP, sPP, ScP

Strong phases P, sP and sPP on KIRNOS displacement BB Z-component records (top traces) of a deep Hindukush earthquake, whereas the reflections at the core-mantle boundary PcP and ScP are more clear in WWSSN-SP-filtered traces (bottom traces).The travel-time curves of PcP and PP intersect near 43° epicentral distance. This overlap distance is depth-dependent. Also note the simple impulsive P-wave onset from this deep source as well as the different amplitudes of the depths phases pP and pPP on the one hand and the much stronger depth phases sP and sPP on the other hand. This is due to the different P- and S-wave radiation pattern in the direction of the short up-going rays p and s, respectively (see Fig. 2.43). Stations situated in another azimuth from the same source may observe a different amplitude ratio of these depth phases.

File 5: wendt_india_qt
W- India
26.01.2001 OT=03:16:40.7 23.3N;70.3E h=22km Ms=7.9 (NEIC)
63.5 MB
D=51.5°-55.5°
Phases: P, PP, S, ScS, SS, PKPPKPdf, and PKKKKP (P4KP)
Top: vertical (Z) component records; and middle: transverse (T) component records; both SRO-LP filtered; **bottom:** zoomed windows with Z-component short-period filtered records (4^{th} order band-pass, 0.5 – 1.7 Hz) of the multiple reflected core phases PKPPKPdf (P'P') and

PKKKKP (P4KP), which have travel times of more than 39 min and 46 min, respectively. Note that PKPPKP arrives from the opposite azimuth as compared to the direct P wave and has a negative slowness (i.e., the travel-time to stations at larger D is shorter).

File 6: wendt_russlchina_qt
E-Russia-NE-China border region
28.06.2002 OT=17:19:30.2 43.8N;130.7E h=564km Mw=7.3 (NEIC)
90.1 MB
D=68.5°-75.5°
Phases: P, pP, PP, pPP, S, sS, ScS, SS, SSS

Vertical (Z)- and transverse (T)- component records with SRO-LP-simulation. This deep earthquake produced strong body waves with simple waveforms, including clear depth phases and strong, transversely polarized S waves. Surface waves are absent. The clear records of very late core phases PKPPKP, SKPPKP, and SKPPKPPKP in WWSSN-SP filtered records have not been depicted in this animation.

File 7: wendt_peru_qt
N- Peru
02.05.1995 OT=06:06:05.7 3.8S;76.9W h=97km mb=6.5 (NEIC)
27.8 MB
D=90°–93°
Phases: P, PKKPbc, PKPPKPdf (P'P'df), PKPPKPPKPbc (3P'bc)

Shown are four short record windows, each one minute long, for P and pP as well as the multiple core phases PKKPbc, PKPPKPdf, and PKPPKPPKPbc with their respective depth phases. These late and very late core phases have travel-times of about 30, 38, and 59 min, respectively. Despite their long travel paths through the Earth, these late core phases still have an astonishingly good signal-to-noise ratio at most stations. They may easily be misinterpreted at individual stations as P-wave onsets from other independent events. Note the negative slowness of the phases PKKP and P'P'.

File 8: wendt_newbritain_qt
New Britain region
10.05.1999 OT=20:33:02.1 5.2S;150.9E h=138km mb=6.5 (NEIC)
25.6 MB
D=122°-126°
Phases: Pdiff, PKPdf, PP, PPP, PS, PPS, SS, SSS, LQ, LR, 4PKPbc

The rarely observed phase 4PKPbc with a travel time of about 79 min is recorded with good SNR in the WWSSN-SP filtered traces (sampling rate of 20Hz). The projection of its path on the surface is (2×360 - 124) deg = 596 deg. The long-period diffracted P-wave arrival Pdif (old name Pdiff) is well developed and arrives about 3.5 min ahead of PKPdf in the SRO-LP filtered Z-component record (see record window in the lower left corner; sampling rate 1 Hz). The SRO-LP filtered Z-component (top left window) and T-component records (middle left window) show several mantle phases, a sharp onset of Love waves (LQ) in T and the onset of the Rayleigh wave LR in Z. The latter shows clear normal dispersion with rather long-period waves (T ≈1 min) and large amplitudes at the beginning whereas shorter periods have much smaller amplitudes due to the intermediate source depth of this earthquake.

File 9: **wendt_fiji_qt**
Fiji Islands region
18.12.2000 OT=01:19:18.6 21.3S;179.2W h=600km mb=6.4 (NEIC)
35.9 MB
D=147°-152°
Phases: PKPdf, PKPbc, PKPab, PP, PPP, PPS, SS, sSS, sSSS, PKKKKKP (P5KP)

Shown are SRO-LP filtered vertical (Z)- and transverse (T)- component records (upper and middle record window) as well as zoomed record windows in the lower left and middle with WWSSN-SP filtered Z-component records of the beginning (PKP-wave group) and the very late part of the seismogram with the rare phase.
Note the good match of the actual and theoretically expected travel-time onsets according to the IASP91 Earth model for mantle phases in the upper and middle record window. In contrast, this model does not predict well the onsets of the core phases which arrive about 5 to 15 seconds later than expected by this model.

File 10: **wendt_nz_qt**
East of North Island, New Zealand
21.08.2001 OT=06:52:06.7 37.0S;179.8W h=33km mb=6.5 (NEIC)
52.0 MB
D=160°-167°
Phases: PKPdf, PKPab, PP, PP2, PcPPKP, PPP2, SS, SSSS

The SRO-LP-filtered seismograms of this very distant event show remarkably strong PP2 and PPP2 onsets, which arrived at the stations from the opposite backazimuth over the long ray paths (360°–D). On the inserted map of Central Europe, which also shows the position of the stations of the GRSN, the passing of these wave fronts can be watched: The phases PKP, PP, PPP, SS and SSSS approach from the NE whereas the phases PcPPKP, PP2 and PPP2 approach from the SW. Also note that the wave fronts of the first arriving waves with rather small (steep) incidence angles have a very high apparent horizontal speed of wave propagation whereas the wave fronts of the later phases with large (shallow) incidence angles travel much slower through the network of seismic stations. Also note the well developed and very long surface-wave train from this shallow (crustal) earthquake. The surface waves arrive for this very distant earthquake more than one hour after the PKP first arrival.

References

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