

Topic	LAUFZE / LAUFPS
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User Manual for LAUFZE and LAUFPS

1 Introduction

The program **LAUFZE** calculates travel-time curves for a P- or an S-velocity model. This is a newer version of a routine, which was originally developed in the 1970s at the Institute of Geophysics in Karlsruhe, Germany, by the late Prof. Gerhard Müller and Dr. Christoph Gelbke. Since then, the author has extended the code to include many new features and options, in particular for calculating different types of teleseismic and of multiply reflected or refracted phases. These changes were made at the Institute for Meteorology and Geophysics, University of Frankfurt, Germany, the Institute of Geophysics, Ruhr-University Bochum, Germany, and, most recently, at NOR SAR.

The travel-time curves can be calculated for horizontally layered or spherically symmetric models with or without reduced time scale. The velocity model is defined by input as a function of the depth z , the dominant signal period T_{sig} , and the depth-dependent quality factor Q given for a reference period T_{ref} . Then, with this as input information, the program calculates and then uses the *group velocity* for the different model depths as defined by:

$$u(z, T, Q) = v(z) \cdot \left(1 + \frac{1}{\pi \cdot Q(z)} \cdot \left(\ln\left(\frac{T_{ref}}{T_{sig}}\right) + 1\right)\right)$$

If no Q -structure is given, the program uses as default value $Q(z) = 10^6$. However, Q is always assumed to be frequency independent.

The source can be placed in any depth as well as the ‘receivers’. However, the ‘receivers’ are by default assumed to be at the Earth’s surface. In the case of a spherical Earth model the Earth radius used for the Earth-flattening transformation is 6371 km. However, the Earth’s centre cannot be reached! The velocities for depths, at which they are not explicitly given, are linearly interpolated.

The whole program is based on the ray approximation of seismic waves, which means that the different kinds of seismic phases must be separately defined by the input parameters. Travel-time curves for the following phase types can be calculated:

- I Direct waves from the source to the Earth’s surface (only in the case that the source is not at the surface).
- II Diving waves from the source radiated down in the Earth.

- III Reflections from any layer below the source, back to the Earth's surface (*e.g.*, PcP, ScP, PmP).
- IV Reflections of diving waves at any layer back down into the Earth (*e.g.*, PP, SS, PKKP, SKKS).
- V Multiple [reflections](#) between any two layers (*e.g.*, PPmP, a diving P wave from [the](#) source to the Earth's surface, reflected from there back into the Earth, and finally reflected at the Mohorovičić (Moho) discontinuity back to the surface).
- VI For the phases III – V, any number of multiple reflections can be calculated (*e.g.*, P3, P5KP, SmS3).
- VII If the source is not at the surface, for all phases of II – VI the corresponding surface reflections can be calculated (*e.g.*, pP, sScS, pP3KP).
- VIII The multiple reflection(s) as defined under V will automatically be calculated for all above defined phases. That means, *e.g.*, not only for the direct P phase a Moho reverberation PPmP will be calculated but also *e.g.*, for pPKP we will get a pPKPPmP phase.
- IX For the direct to the surface radiated wave (see I) reflections can be calculated from any layer between source and the Earth's surface down back into the Earth (*e.g.*, p450P, or smS, but also pP).

All parameters for steering the program must be given in a formatted ASCII file. The program asks for the name of the input file.

All results of the program are written in a ASCII file called *laufze-out*. This file can then easily be edited and the listed travel-time curves can then be plotted with any plotting routine or used as ASCII input for other programs.

LAUFPS is a program like **LAUFZE** but it calculates travel times not only for one model (P or S) but also for both models together in one step, including converted phases. However, this program cannot be used to place 'receivers' below the Earth's surface. All settings for **RECE** (see below) are ignored!

The newest versions of the programs **laufze** **laufps** (including source code, this manual, data files containing examples for input and output files) are located in two compressed tar-files; either in *laufze.version.tar.Z* or in *laufze.version.tar.gz*. They can be downloaded for free either directly from the program list in the NMSOP-2 cover page folder *Download Programs & Files* or from NORSAR's anonymous ftp-server *ftp.norsar.no* under the directory */pub/outgoing/johannes/lauf*. If using your web-browser, the address is: <ftp://ftp.norsar.no/pub/outgoing/johannes/lauf>. Questions related to program updates and maintenance should be directed to the author.

2 Getting Started

This section describes how the example for **LAUFZE** can be started and executed. The simplest way to use the program for own travel-time calculations is to use the following examples and to modify the input data and parameters for your needs. The meaning and format of the contents of the input file are described in the following sections.

Installation of **LAUFZE**:

1) Make a sub-directory for **LAUFZE**, download the compressed tar-file containing the *laufze-software package*, decompress it, and run:

```
tar -xvf laufze.version.tar
```

You will then have a directory containing the following files and subdirectories:

```
bin/ bin_l/ examples/ man/ README src/
```

The file *README* contains a complete list of all files included in the *laufze-software package* and a short explanation of these files.

2) If needed, recompile the software in the *src/* subdirectory by running:

```
make -f Makefile.laufze
```

and/or

```
make -f Makefile.laufps
```

The software was tested under UNIX as well under LINUX and should therefore run on both platforms without any compatibility problems. In the case of a LINUX system please use the corresponding *Makefiles* with the extension *_linux_g77* or *_linux_gfortran*, depending on your installed FORTRAN compiler.

3) Executing **LAUFZE**:

Change to the subdirectory *examples/*.

Here you will find an example for an input file.

To check your **LAUFZE** installation, try the following:

```
../bin/laufze
```

The program needs one input file in ASCII format. You will be asked for the name of the input file and here you answer with *laufze-in*. This file contains all parameters to steer the travel-time calculations and the layered velocity model. All results of the program are written in a file called *laufze-out*. The output file you get should be identical to the file *laufze-out.test* distributed with the *laufze-software package*. Contents and structure of these files will be explained in the following sections.

The program **LAUFPS** uses the same input file format as **LAUFZE** but it needs three files, one containing the P-velocity model and ray definitions for the requested P phases, one file containing the S-velocity model and ray definitions for the requested S phases and one file containing additional parameters to steer the requested converted phases for both P-to-S and S-to-P types of phase conversions. After starting the program with

```
../bin/laufps
```

you will be asked for names of the files containing the P- and S-velocity models and the file

to steer the behaviour of all P-to-SV and/or SV-to-P conversions (e.g., *laufp-dat*, *laufs-dat*, and *laufps-in*). If you use the files as delivered with the *laufze-software package*, the LAUFPS output file *laufps-out* should be identical to the file *laufps-out.test*.

3 The File *laufze-in*

The file *laufze-in* must contain the velocity model for P (or S) waves and all information about the seismic phases for which travel times shall be calculated. The program asks for the name of the file containing this information in the format below described. The user can of course use any file name.

----- example for a *laufze-in* file -----

```

For a source in 100 km, Jeffreys-Bullen Model
  0.000 180.000 0.00 0 0
  0.000 0.000 0 0 0
  0.0 6.11 STRU 0.000 ! for pP
  33.0 6.11
  33.0 7.76
  100. 7.95 SOUR
  200. 8.26
  300. 8.58
  413. 8.97
  600. 10.25
  800. 11.00
  1000. 11.42
  1200. 11.71
  1400. 11.99
  1600. 12.26
  1800. 12.53
  2000. 12.79
  2200. 13.03
  2400. 13.27
  2600. 13.50
  2800. 13.64
  2898. 13.64 REFL ! for PcP
  2898. 8.10
  3000. 8.22
  3200. 8.47
  3400. 8.76
  3600. 9.04
  3800. 9.28
  4000. 9.51
  4200. 9.70
  4400. 9.88
  4600. 10.06
  4800. 10.25
  4982. 10.44
  5121. 10.44 REFL ! for PKiKP
  5121. 11.16
  5700. 11.26

                                     ! blank line, no more layers
  1 1 20
    1 1 ! for PP
    1 2 ! for P3
    21 1 ! for PKKP

```

```

21          2          ! for P3KP
                ! blank line: no more such mult. phases
1          ! for PcPPcP + PKiKPPKiKP
                ! blank line: no more such mult. phases
----- end of the example-----

```

The contents of the *laufze-in* file is as follows:

1. 1 line of maximum 80 characters with any explaining text as **TITLE**.
2. 1 line in FORMAT (3F10.3,3I5) containing the parameters: **RMIN**, **RMAX**, **VR**, **IELAS**, **NF11**.

RMIN is the beginning of the distance range from which onset times are calculated. Either measured in [deg] or in [km], see the definition of **VR**.

RMAX as **RMIN** but the end of the distance range used to print out the travel-time branches.

VR is the velocity or slowness to reduce the travel times.
If **VR** > 0, **RMIN** and **RMAX** are measured in [km] and **VR** is a reduction velocity [km/s].
If **VR** <= 0, **RMIN** and **RMAX** are measured in [deg] and **VR** is a reduction slowness [s/deg].

IELAS if this flag is set to 1, $Q(z)$ is set to 10^6 in all depths (pure elastic case).

NF11 if this flag is set to 1, no direct up-going rays from a source below the surface are calculated.
3. 1 line in FORMAT (2F10.3,3I5) containing the parameters: **PER**, **PERREF**, **LA1**, **LA2**, **NLA**.

PER is the dominant signal period T_{sig} [s].
If **PER** is set to 0 s, the default value of 1 s is used.

PERREF is the reference period T_{ref} [s].
If **PERREF** is set to 0 s, the default value of 1 s is used.

LA1 is the number of the upper layer for the described reverberations (see V of the program options in the **Introduction**).

LA2 as **LA1**, now the number of the lower layer.

NLA gives the number of reverberations.
The multiple phase travels **NLA** times more often through the depth range $Z(\text{LA1}) \leq Z(I) < Z(\text{LA2})$ than the regular phase. If **LA1** = **LA2** or **NLA** = 0, no reverberations are calculated.
4. Now follows the model. The model is defined by one line for each depth with velocity information. All lines must fit in the FORMAT (2F10.3,A4,6x,F10.3) and contain the parameters **Z**, **V**, **AZ**, **QU**. The model can contain a maximum of 1000 layers. First

order discontinuities for one of the given parameters have to be defined by 2 lines in the same depth **Z**.

Z depth in [km] below the Earth's surface. The surface has the depth $Z(1) = 0$.

V seismic velocity in the depth **Z**.

AZ four characters long key words, with which one can define special actions in this depth:

= **SOUR** means that the seismic source is located in this depth of the model.

= **RECE** means that the 'receivers' are in this depth (to be set only if not at the surface, by default receivers are assumed to be at the surface).

= **SORE** means a combination of both **SOUR** and **RECE** in the same depth.

= **SURF** means that the seismic source is located in this depth and that for all (!) phases their corresponding surface reflections are additionally calculated (*e.g.*, pP, sScS, ...).

= **SURE** means a combination of both **SURF** and **RECE** in the same depth.

= **STRU** means that an up-going direct ray is reflected in this depth back down into the Earth (see IX of the program options in the **Introduction**).

If **STRU** is set at the surface, the classical surface reflection is calculated (*i.e.*, only pP or sS but not *e.g.*, pPP or sScS).

= **REFL** means that steep-angle reflections from this depth are calculated (see III of the program options in the **Introduction**).

AZ must be blank in all other cases.

QU is the quality factor for seismic waves in this depth; if $QU = 0$, the program sets it by default to $QU = 1\ 000\ 000$.

An empty line finishes the model input.

5. 1 line in FORMAT (3I5) with the three parameters **IS**, **IA**, **IB**.

IS = 0 the input model is assumed to be flat, *i.e.*, it consists of a set of horizontally flat layers.

= 1 the input model is spherical and has to be modified by the Earth-flattening transformation.

IA = I ; only the parts of the travel-time curves, which have their turning points below the I'th layer, are calculated. If **IA** = 1, all travel-time branches of all phases are calculated.

IB gives the number of rays, which will have their turning points between two given depth points of the model; an **IB** value of 10 – 20 usually gives a good approximation of the travel-time branch.

6. In the following line(s), the reflections of diving rays at any layer back down into the Earth can be defined (see IV of the program options in the **Introduction**). For each (!) such reflection 1 line in FORMAT (2I10) is needed with the parameters **IKMG** and **MULT**. If no (further) reflections of this type are to be calculated, one has to give a blank line.

IKMG is the number of the layer at which the ray is reflected; *e.g.*, for PP one has to set **IKMG** = 1.

MULT gives the number of reflections at this reflector (*e.g.*, for PP, SS, or PKKP one has to set **MULT** = 1, and for P3, S3, or S3KS one has to use **MULT** =2).

7. Finally, multiple reflections for the steep-angle reflections as defined with **AZ** = **REFL** can be ordered with the following line(s) in **FORMAT** (I10) containing the parameter **MULTR**. No (further) multiples of this type have to be indicated by another blank line.

MULTR gives the number of additional multiples for each steep-angle reflection. **MULTR** = 1 will, for example, result in PmP2 (= PmPPmP) or ScS2 (= ScSScS) and **MULT** = 2 will give, *e.g.*, ScS3.

4 The File *laufze-out*

With the above listed example for a *laufze-in* file, you will obtain the output-file *laufze-out*. Please note that the output file has been truncated by numerous lines to reduce the number of pages in this manual. The ASCII listing of the travel times can easily be extracted and the user can plot them with any plotting program after some simple editing work. The original output file has 3117 lines and is included in the *laufze-software package*. Explanations are included in [....]:

-----example for a *laufze-out* file -----

Travel times from LAUFZE 6.2

For a source in 100 km, Jeffreys-Bullen Model

Distance range
 RMIN = 0.000 deg
 RMAX = 180.000 deg

Ray parameter to reduce travel times P = 0.000 s/deg

The travel times are calculated for a group velocity
 at a reference period of 1.000 s

Model input (depth, velocity)
 + modified velocity-depth function after application
 of the Earth-flattening transformation

Z	V(Z)	Q(Z)	U(Z,Q,PER)	AZ(Z)	FLATT EARTH	
					[Z-FL	U-FL]
0.000	6.110	1000000.0	6.110	STRU	0.000	6.110
33.000	6.110	1000000.0	6.110		33.086	6.142
33.000	7.760	1000000.0	7.760		33.086	7.800
100.000	7.950	1000000.0	7.950	SOUR	100.793	8.077

200.000	8.260	1000000.0	8.260		203.207	8.528
300.000	8.580	1000000.0	8.580		307.293	9.004
413.000	8.970	1000000.0	8.970		426.995	9.592
600.000	10.250	1000000.0	10.250		630.162	11.316
800.000	11.000	1000000.0	11.000		854.873	12.580
1000.000	11.420	1000000.0	11.420		1087.799	13.546
1200.000	11.710	1000000.0	11.710		1329.566	14.427
1400.000	11.990	1000000.0	11.990		1580.871	15.367
1600.000	12.260	1000000.0	12.260		1842.496	16.372
1800.000	12.530	1000000.0	12.530		2115.328	17.464
2000.000	12.790	1000000.0	12.790		2400.367	18.642
2200.000	13.030	1000000.0	13.030		2698.760	19.903
2400.000	13.270	1000000.0	13.270		3011.817	21.290
2600.000	13.500	1000000.0	13.500		3341.056	22.808
2800.000	13.640	1000000.0	13.640		3688.241	24.335
2898.000	13.640	1000000.0	13.640	REFL	3865.526	25.022
2898.000	8.100	1000000.0	8.100		3865.526	14.859
3000.000	8.220	1000000.0	8.220		4055.441	15.535
3200.000	8.470	1000000.0	8.470		4445.107	17.017
3400.000	8.760	1000000.0	8.760		4860.167	18.785
3600.000	9.040	1000000.0	9.040		5304.164	20.785
3800.000	9.280	1000000.0	9.280		5781.437	22.996
4000.000	9.510	1000000.0	9.510		6297.381	25.554
4200.000	9.700	1000000.0	9.700		6858.818	28.466
4400.000	9.880	1000000.0	9.880		7474.555	31.936
4600.000	10.060	1000000.0	10.060		8156.231	36.190
4800.000	10.250	1000000.0	10.250		8919.681	41.568
4982.000	10.440	1000000.0	10.440		9704.131	47.886
5121.000	10.440	1000000.0	10.440	REFL	10375.893	53.211
5121.000	11.160	1000000.0	11.160		10375.893	56.880
5700.000	11.260	1000000.0	11.260		14339.481	106.911

Travel-time branch 1 and all the following ones were calculated, each travel-time branch consists of 20 rays

P H A S E :

[If **NF11** is set to 1, this wave will not be calculated]
 Directly upgoing wave

[DELTA is the distance measured in [km] or in [deg], see input parameter **VR**, TT is the (eventually reduced) travel time, AIN is the radiation angle at the source, T^* is the travel time divided by the mean quality factor TT/Q , ATT is the amplitude attenuation due to T^* , i.e., $ATT = EXP(-2*PI*f_{ref}*T^*)$, and P is the ray parameter measured in [s/deg]]

DELTA	TT	AIN	T*	ATT	P
0.000	13.931	180.000	0.000	1.000	0.000
0.033	13.940	177.722	0.000	1.000	0.547
0.066	13.967	175.443	0.000	1.000	1.094
0.099	14.012	173.165	0.000	1.000	1.639
0.132	14.075	170.886	0.000	1.000	2.181
0.166	14.158	168.608	0.000	1.000	2.719
0.200	14.260	166.329	0.000	1.000	3.254

0.234	14.381	164.051	0.000	1.000	3.783
0.269	14.524	161.772	0.000	1.000	4.306
0.305	14.688	159.494	0.000	1.000	4.823
0.342	14.874	157.215	0.000	1.000	5.332
0.380	15.085	154.937	0.000	1.000	5.832
0.419	15.321	152.658	0.000	1.000	6.323
0.459	15.584	150.380	0.000	1.000	6.804
0.500	15.877	148.101	0.000	1.000	7.275
0.543	16.201	145.823	0.000	1.000	7.734
0.588	16.559	143.544	0.000	1.000	8.181
0.635	16.954	141.266	0.000	1.000	8.614
0.685	17.389	138.987	0.000	1.000	9.034
0.737	17.870	136.709	0.000	1.000	9.440
0.792	18.401	134.430	0.000	1.000	9.831
0.850	18.988	132.152	0.000	1.000	10.207
0.913	19.638	129.873	0.000	1.000	10.566
0.980	20.359	127.595	0.000	1.000	10.908
1.053	21.162	125.316	0.000	1.000	11.234
1.131	22.059	123.038	0.000	1.000	11.541
1.218	23.067	120.759	0.000	1.000	11.830
1.313	24.204	118.481	0.000	1.000	12.101
1.418	25.494	116.203	0.000	1.000	12.353
1.536	26.969	113.924	0.000	1.000	12.584
1.670	28.667	111.646	0.000	1.000	12.796
1.823	30.640	109.367	0.000	1.000	12.988
2.000	32.953	107.089	0.000	1.000	13.159
2.207	35.688	104.810	0.000	1.000	13.310
2.451	38.953	102.532	0.000	1.000	13.439
2.742	42.881	100.253	0.000	1.000	13.547
3.091	47.631	97.975	0.000	1.000	13.634
3.512	53.386	95.696	0.000	1.000	13.699
4.018	60.330	93.418	0.000	1.000	13.743
4.621	68.624	91.139	0.000	1.000	13.765

P H A S E :

Diving wave

[DELTA is the distance measured in [km] or in [deg], see input parameter **VR**, TT is the (eventually reduced) travel time, AIN is the radiation angle at the source, T* is the travel time divided by the mean quality factor TT/Q, ATT is the amplitude attenuation due to T*, i.e., $ATT = \text{EXP}(-2 * \text{PI} * f_{\text{ref}} * T^*)$, P is the ray parameter measured in [s/deg], and for diving waves also the depth [km] of the ray's turning point is given.]

DELTA	TT	AIN	T*	ATT	P	ZS
4.961	73.311	90.000	0.000	1.000	13.767	100.000
6.323	92.033	85.613	0.000	1.000	13.727	105.303
6.995	101.248	83.803	0.000	1.000	13.687	110.602
7.549	108.820	82.420	0.000	1.000	13.647	115.897
8.040	115.504	81.258	0.000	1.000	13.607	121.186
8.488	121.598	80.238	0.000	1.000	13.568	126.472
8.906	127.257	79.319	0.000	1.000	13.529	131.753
9.299	132.574	78.477	0.000	1.000	13.490	137.029
9.673	137.613	77.696	0.000	1.000	13.451	142.301
10.031	142.418	76.966	0.000	1.000	13.413	147.569
10.375	147.021	76.277	0.000	1.000	13.374	152.832

10.706	151.448	75.624	0.000	1.000	13.336	158.091
11.027	155.720	75.003	0.000	1.000	13.298	163.345
11.338	159.853	74.409	0.000	0.999	13.261	168.595
11.641	163.860	73.840	0.000	0.999	13.223	173.840
11.936	167.752	73.292	0.000	0.999	13.186	179.081
12.223	171.539	72.765	0.000	0.999	13.149	184.317
12.504	175.230	72.255	0.000	0.999	13.112	189.549
12.779	178.832	71.762	0.000	0.999	13.076	194.777
13.049	182.351	71.284	0.000	0.999	13.039	200.000

[Each layer of the model gives one block of rays (number of rays given as parameter **IB**) and forms one 'branch' of the travel-time curve. These rays are always written as one block in the listing. If one plans to plot the travel-time curves, one should plot each block as separate branch of the travel-time curve. Here all blocks with rays bottoming in the mantle were omitted!]

[The next possible rays are the phases bottoming in the Earth's core: here PKPab, PKPbc]

178.309	1310.499	18.832	0.001	0.996	4.444	3959.714
173.109	1287.400	18.810	0.001	0.996	4.439	3961.852

[All rays bottoming in the outer core were deleted!]

154.616	1186.983	8.731	0.001	0.996	2.090	5121.000
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[The inner core boundary (ICB) is a first order discontinuity with a positive velocity jump. The following rays 'bottoming' in the boundary build the over-critical part of the travel-time curve of PKiKP, the over-critical reflection from the ICB!]

154.616	1186.983	8.731	0.001	0.996	2.090	5121.000
144.603	1166.084	8.699	0.001	0.996	2.082	5121.000
140.610	1157.784	8.667	0.001	0.996	2.075	5121.000
137.605	1151.561	8.636	0.001	0.996	2.067	5121.000
135.111	1146.414	8.605	0.001	0.996	2.060	5121.000
132.943	1141.955	8.574	0.001	0.996	2.052	5121.000
131.006	1137.987	8.543	0.001	0.996	2.045	5121.000
129.244	1134.390	8.513	0.001	0.996	2.038	5121.000
127.621	1131.087	8.482	0.001	0.996	2.031	5121.000
126.111	1128.026	8.452	0.001	0.996	2.024	5121.000
124.695	1125.167	8.423	0.001	0.996	2.017	5121.000
123.361	1122.481	8.393	0.001	0.996	2.009	5121.000
122.096	1119.944	8.364	0.001	0.996	2.002	5121.000
120.893	1117.538	8.334	0.001	0.996	1.996	5121.000
119.744	1115.249	8.305	0.001	0.997	1.989	5121.000
118.644	1113.065	8.277	0.001	0.997	1.982	5121.000
117.587	1110.975	8.248	0.001	0.997	1.975	5121.000
116.571	1108.971	8.220	0.001	0.997	1.968	5121.000
115.590	1107.044	8.191	0.001	0.997	1.962	5121.000
114.643	1105.190	8.163	0.001	0.997	1.955	5121.000

[Now followed the deleted PKPdf branch.]

Surface reflection of the direct wave

[See the parameters **STRU** and/or **SURF** in the input file. The ray output for pP, pPKP, and pPKiKP (over-critical part) was deleted.]

P H A S E :

Diving wave 1-times reflected at the Earth's surface

[See the parameters **IKMG** and **MULT** in the input file. The ray output for PP, P'P', and PKiKP2 (over-critical part) was deleted.]

P H A S E :

Diving wave 2-times reflected at the Earth's surface

[See the parameters **IKMG** and **MULT** in the input file. The ray output for P3, P'3, and PKiKP3 (over-critical part) was deleted.]

P H A S E :

Diving wave 1-times reflected down at layer 21

[See the parameters **IKMG** and **MULT** in the input file; layer 21 is here the core-mantle boundary. The ray output for PKKP and PKiKKiKP (over-critical part) was deleted.]

P H A S E :

Diving wave 2-times reflected down at layer 21

[See the parameters **IKMG** and **MULT** in the input file; layer 21 is here the core-mantle boundary (CMB). The ray output for P3KP and P3KiKP (over-critical part) was deleted.]

P H A S E :

Steep-angle reflection from 2898.000 km

[See the parameter **AZ = REFL** in the input file. Steep-angle reflection (*i.e.*, before the critical point) from the CMB; the ray output for PcP was deleted.]

P H A S E :

Steep-angle reflection from 5121.000 km

[See the parameter **AZ = REFL** in the input file. Steep-angle reflection (*i.e.*, before the critical point) from the ICB; the ray output for PKiKP was deleted.]

P H A S E :

Multiple reflection (1-times) for the
Steep-angle reflection from 2898.000 km

[See the parameters **AZ = REFL** and **MULTR** in the input file. Multiple steep-angle reflection (*i.e.*, before the critical point) from the CMB; the ray output for PcP2 was deleted.]

P H A S E :

Multiple reflection (1-times) for the
Steep-angle reflection from 5121.000 km

[See the parameters **AZ = REFL** and **MULTR** in the input file. Multiple steep-angle reflection (*i.e.*, before the critical point) from the ICB; the ray output for PKiKP2 was deleted.]

-----end of example for a *laufze-out* file -----

5 The Program LAUFPS and the File *laufps-in*

The program **LAUFPS** calculates travel-time curves for a given velocity model, as the program **LAUFZE** does, and was developed on the base of **LAUFZE**. In addition to **LAUFZE**, **LAUFPS** calculates P- and S-phase travel-time curves in one step and it can also calculate travel-time curves for converted phases. The input for **LAUFPS** consists of one steering and two model files:

One the model files contains the P-velocity model and one contains the S-velocity model. Both model files must have the same format as a **LAUFZE** input file, e.g., one file is then called *laufp-dat* and one *laufs-dat*. Both model files must sample the velocity models (*i.e.*, the P and the S model) at identical depths and the source must also be in the same depth. However, these input files can be extended at three points to inform the program in the case of multiple phases, how often these reverberations are eventually travelling through the model as converted phase. These additions are the following ones (I refer to the number of the format descriptions of the input-file for **LAUFZE**):

- 1 line in FORMAT (2F10.3,4I5) containing the parameters: **PER**, **PERREF**, **LA1**, **LA2**, **NLA**, **NLA2**.

PER is the dominant signal period T_{sig} [s].

If **PER** is set to 0 s, the default value of 1 s is used.

PERREF is the reference period T_{ref} [s].

If **PERREF** is set to 0 s, the default value of 1 s is used.

LA1 is the number of the upper layer for the described reverberations (see V of the program options in the **Introduction**).

LA2 as **LA1**, now the number of the lower layer.

NLA gives the number of reverberations.

The multiples travel through the depth range $Z(\text{LA1}) \leq Z(I) < Z(\text{LA2})$

NLA times more than the regular phase. If **LA1 = LA2** or **NLA = 0**, no reverberations are calculated.

NLA2 gives how many of the **NLA** reverberations are travelling as converted phase (**NLA2** must be $\leq \text{NLA}$).

6. In the following line(s) the reflections of diving rays at any layer back down into the Earth can be defined (see IV of the program options in the **Introduction**). For each (!) such reflection 1 line in FORMAT (3I10) is needed with the parameters **IKMG**, **MULT**, and **MULT2**. If no (further) reflections of this type shall be calculated one has to add a blank line.

IKMG is the number of the layer at which the ray is reflected; *e.g.*, for the surface reflection PP one has to set **IKMG** = 1.

MULT gives the number of reflections at this reflector (*e.g.*, for PP, SS, or PKKP one has to set **MULT** = 1, for P3, S3, or S3KS one has to use **MULT** = 2).

MULT2 gives how many of the **MULT** reverberations are travelling as a converted phase (**MULT2** must be \leq **MULT**), *e.g.*, the travel-time curve of PPS will need to set **IGMG** = 1, **MULT** = 2, and **MULT2** = 1.

8. Finally, multiple reflections for the steep-angle reflections as defined with **AZ** = **REFL**, can be ordered with the following line(s) in FORMAT (2I10) containing the parameter **MULTR** and **MULTR2**. No (further) multiples of this type have to be indicated by another blank line.

MULTR give the number of multiples for each order steep-angle reflection. **MULTR** = 1 will *e.g.*, result in PmP2 or ScS2 and **MULT** = 2 will give *e.g.*, ScS3.

MULTR2 gives how many of the **MULTR** reverberations are travelling as converted phase (**MULTR2** must be \leq **MULTR**), *e.g.*, the travel-time curve of PcPScS will need to set **MULTR** = 2, and **MULTR2** = 1.

The directory *examples/* contains files with one P- (*laufp-dat*) and one S-velocity model (*laufs-dat*) applying some of the mentioned settings.

In addition to these two model related files, the program **LAUFPS** needs one file containing steering parameters for each travel-time curve to define further phase conversions. It is recommended to run the program in a first step with setting the parameter **KONSAR** to 0 and then editing the steering file again. This steering file (here *e.g.*, called *laufps-in*) must contain the following information in the described format:

- a) In the first line the parameter **KONSOR** in FORMAT (I5). **KONSOR** steers the general behaviour of **LAUFPS**:

= 0 ; no conversions are calculated (not even the ones defined above!).

= 1 ; only conversions from P to SV type phases are calculated.

= 2 ; only conversions from SV to P type phases are calculated.

= 3 ; all types of conversions are calculated.

- b) For each (!) phase, as calculated in a first test run after setting **KONSOR** = 0 and then listed in *laufps-out* with an own phase header, one has to add one line with the parameters **KON**, **KON1**, **NDISK1**, **KON2**, **NDISK2** in FORMAT (5I5). For the test run, one can just add a large number of empty lines.

KON = 0 ; no conversion for this phase.

- = 1 ; this is a P phase and we get a P to SV conversion.
- = 2 ; this is an S phase and we get a SV to P conversion.
- = 9 ; the next entry is for the same phase but another conversion type.

KON1 = 1 ; the first conversion happens on the ray path down.
 = 2 ; the first conversion happens on the ray path up.

NDISK1 gives the discontinuity number for the first conversion: see the listing in the table in the *laufps-out* file.

KON2 = 1 ; a possible second conversion happens on the ray path down.
 = 2 ; a possible second conversion happens on the ray path up.

NDISK2 gives the discontinuity number for the second conversion.

```

-----example for a laufps-in file -----
00003
  0   0   0   0   0   0   Pdirect -->
  0   0   0   0   0   0   Sdirect -->
  1   2   3   0   0   0   P/PKP  -->  PKS
  1   2   2   0   0   0   P/PKP  -->  P/PKP at Moho to SV
  0                                     pP   -->
  0                                     PP   -->
  0                                     PPS  -->
  0                                     S/SKS -->
  0                                     sS   -->
  0                                     SS   -->
  2   2   3                               S3KP -->
  1   2   3                               PcP  -->  PcS
  0                                     PcPScS -->
  2   2   3                               ScS  -->  ScP
-----end of example for a laufps-in file -----

```

The output from program **LAUFPS** can become very complex and long. However, the principle listing looks very like the output for **LAUFZE** and no example of an output file had been added here. For an example of a *laufps-out* file please apply the here listed *laufps-in* file and see also the files in the directory *examples/*.