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 new 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 phases. The code has been developed at the Institute for Meteorology and Geophysics, University of Frankfurt, Germany, the Institute of Geophysics, Ruhr-University Bochum, Germany, and, most recently, in this new (English) version at NORSAR.

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}. With this input the program calculates the group velocity as defined by:

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

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 but the 'receivers' are 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 center 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 Multiples between any two layers (*e.g.*, PPmP, a diving P wave from 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.

The newest versions of the programs (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*** for free download from NORSAR's anonymous ftp-address *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 need. The meaning and format of the input is described in the following sections.

Installation of **LAUFZE**:

1) Make a sub-directory for **LAUFZE,** copy the compressed tar-file containing the ***laufze-software package*** from the *ftp.norsar.no site*, 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*.

3) Executing **LAUFZE**:
Change to the subdirectory *examples/*.
Here you will find an example for an input file.

LAUFZE runs with one input file. To check your installation, try the following:

run:
../bin/laufze

The program needs one input file in ASCII format. You will be asked for the name of the input file and you here 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 two files, one containing the P-velocity model and ray definitions for P phases and one file containing the S-velocity model and ray definitions for S phases. 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-da***t, 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, 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**, **PEREFF**, **LA1**, **LA2**, **NLA.**

   PER is the dominant signal period T_{sig} [s].
   PERREF is the reference period T_{ref} [s].
   If these two period values are 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 travels through the depth range **Z**(**LA1**) <= **Z**(I) < **Z**(**LA2**) **NLA** times more 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 has 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 source is in this depth of the model.

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

= **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).

In all other cases **AZ** must be blank.

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 transformed 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 depth points of the model; **IB** values of 10 – 20 usually give 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, 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 multiples for each order steep-angle reflection.
MULTR = 1 will, for example, result in PmP2 or ScS2 and MULT = 2 will give, *e.g.*, ScS3.

4 The File *laufze-out*

With the above 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 6.0



 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

                                                       FLATT EARTH
      Z        V(Z)      Q(Z)  U(Z,Q,PER) AZ(Z)  [ 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 = EXP(-2*PI*f_{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 as given as **IB**) and forms one 'branch' of the travel-time curve. These rays are always written as one block in the listing. 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 the bottoming in the outer core rays were deleted!]

```
   154.616  1186.983     8.731     0.001     0.996     2.090  5121.000
```

[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 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.*, below 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.*, below 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.*, below 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.*, below 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 does the program **LAUFZE,** 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. Therefore, the input for **LAUFPS** consists of two files: one containing the P-velocity model and one containing the S-velocity model. Both files must have the same format as the input files to run **LAUFZE**, e.g., one file is then called ***laufp-dat*** and one is called ***laufs-dat***. Both files must sample the velocity models (*i.e.*, the P and the S models) identically and the source must be at 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 description of the input-file for **LAUFZE**):

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

   PER is the dominating signal period T_{sig} [s].
   PERREF is the reference period T_{ref} [s].
   If these two period values are 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**(**LA1**) <= **Z**(I) < **Z**(**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 <= **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 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, 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 <= **MULT**), *e.g.*, the travel-time curve of PPS will need to set **IKMG** = 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 <= **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***) with some of the mentioned settings. In addition to these input files, the program **LAUFPS** needs one file containing steering parameters for each travel-time curve to define further conversions. This file (here *e.g.*, called ***laufps-in***) must contain the following information in the described format:

a) In the first line the parameter **KONSO**R 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 after setting **KONSOR** = 0 and listed in ***laufps-out*** with a own phase header, one has to add one line with the parameters **KON**, **KON1**, **NDISK1**, **KON2**, **NDISK2** in FORMAT (5I5).

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

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

NDISK2 gives the number of the discontinuity 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 I have added no example of an output file here. For an example of a ***laufps-out*** file applying the here listed ***laufps-in*** file, please see the files in the directory *examples/*.