

Program **VELEST USER'S GUIDE** - Short Introduction

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This short introduction corresponds to the VELEST Version 3.1 (10.4.95) by:

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## **1. Purpose and history of VELEST**

Program VELEST is a FORTRAN77 routine that has been designed to derive 1-D velocity models for earthquake location procedures and as initial reference models for seismic tomography (Kissling 1988; Kissling et al. 1994). Originally written in 1976 by W.L. Ellsworth and S. Roecker for seismic tomography studies (under program name HYPO2D, see Ellsworth 1977; Roecker, 1978) VELEST has been modified by R. Nowack (who also gave it its current name), C. Thurber, and R. Comer who implemented (among other things) the layered-model raytracer (Thurber 1981). In 1984 E. Kissling and W. L. Ellsworth after modifications of the flow structure and implementation of several new options used it to calculate a 'Minimum 1-D model' (i.e., a well-suited 1-D velocity model for earthquake location and for 3-D seismic tomography) for Long Valley area, California (Kissling et al., 1984). Since then VELEST has been applied to local earthquake and controlled-source data from several areas in California, Alaska, Wyoming, Utah, and the Alps (Kissling 1988; Kradolfer 1989; Kissling and Lahr 1991; Maurer 1993). U. Kradolfer implemented the option to use VELEST as single-event-location routine and H. Maurer reintroduced the option to use both P- and S-wave data, separately or combined. Thanks to the cleaning efforts of U. Kradolfer and of H. Maurer the code no longer suffers from quick-and-risky programming by too many authors. The current version of VELEST has been tested to correctly run under both UNIX (HP and SUN) and VMS (DEC) operating systems with (optimized) standard FORTRAN77 compilers.

If you need a reference please use Kissling et al. (1994) (see reference list) or the appropriate of the ones mentioned above. In order to avoid misunderstandings it is recommended that you also mention the version of the program.

## **2. Simultaneous Inversion and Coupled Hypocenter-Velocity Model Problem**

This USER'S GUIDE to VELEST is intended to provide a brief introduction on how to run and use the program to simultaneously locate earthquakes and to calculate 1-D (layered) velocity models with station corrections. As an introduction to the coupled hypocenter-velocity model problem the reader is referred to Crosson (1976), Ellsworth (1977), and Thurber (1981). The concept of a 'Minimum 1-D model' is described in detail by Kissling (1988) and Kissling et al. (1995), who also provide several examples of applications of such 1-D velocity models for both improved earthquake locations and as initial reference models for 3-D seismic tomography. Kissling et al. (1994) -after describing the effects of initial reference models on 3-D tomographic results- in an appendix provide a brief overview over the procedure to be followed to calculate a 'Minimum 1-D model' with VELEST. The following USER'S GUIDE is written under the assumption that the reader is vaguely familiar with the problems and solutions described in the above mentioned publications (see reference list). Here only a brief overview will be given.

Program VELEST (iteratively, i.e., "non-linearly") solves

- \* in 'simultaneous mode': the coupled hypocenter-velocity model problem for local earthquakes, quarry blasts, and shots; for fixed velocity model and station corrections  
VELEST in simultaneous mode performs the Joint-Hypocenter-Determination (JHD).
- \* in 'single-event-mode': the location problem for local earthquakes, blasts, and shots.

The model consists of a (layered) 1-D velocity model and station corrections. In both modes the forward problem is solved by ray tracing from source to receiver, computing the direct, refracted, and (optionally) the reflected rays passing through the 1-D model. In both modes the inverse problem is solved by full inversion of the damped least squares matrix  $[A_t A + L]$  ( $A$ = Jacobi matrix,  $A_t$ =transposed Jacobi matrix;  $L$ =damping matrix). Because the inverse problem is non-linear, the solution is obtained iteratively, where one iteration consists of solving both the complete forward problem and the complete inverse problem once (see Fig. 1). In 'single-event-mode' an additional singular value decomposition of the symmetric matrix  $A_t A$  (in this case a  $4 \times 4$  matrix only) is performed in order to calculate the eigenvalues.

Due to the intrinsic ambiguity of the inverse problem the final solutions obtained by VELEST are but a small part -and often the least significant part- of all the output of this program. VELEST has been designed to allow great flexibility in the approach and, therefore, a large number of options and control parameters must be set and properly adjusted in the process. Though default values may be obtained from the examples provided with the source code, the calculation of a Minimum 1-D model requires multiple runs with VELEST to select and test control parameters appropriate to the data set and to the problem. If you are in a hurry or if you are used to the idea that proper computer programs always provide a unique solution that is either

obviously inappropriate or precise and correct, please accept the warning: To calculate a Minimum 1-D model a single or even a few VELEST runs are useless, as they normally do not provide any information on the model space (see chapt. 4)!

The principal procedure for simultaneous mode (and with minor modifications also for single\_event\_mode) is summarized in the flowchart given in Fig. 1. The main (print) output of VELEST reflects this procedure and provides detailed information about many intermediate calculation steps even within one single iteration step. It is mainly from these intermediate results that the appropriate control parameters are obtained through many runs of VELEST.

Please do not use resolution calculation in simultaneous mode. There is a bug in this part that will be fixed in version VELEST 3.2 by end of 1995.

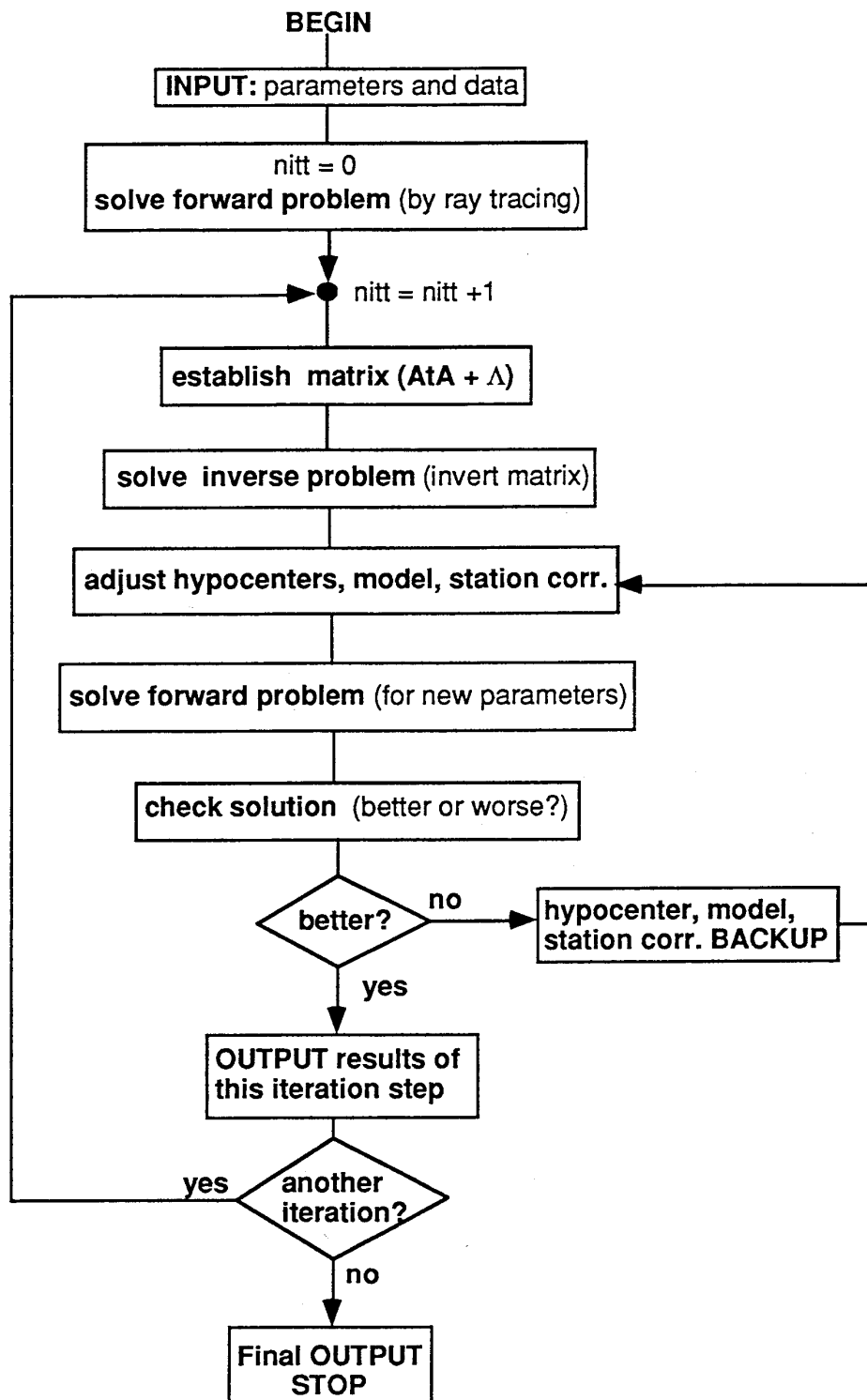


Fig. 1 Overview of procedure VELEST

### **3. Installation of FORTRAN program VELEST:**

VELEST version 3.1 may be obtained for UNIX (SUN and HP) machines and for VAX/VMS (DEC) systems. Please check that you get the appropriate source code among the files

- VELESTUNIXSUN.F
- VELESTUNIXHP.F
- VELESTVMS.F .

In each case you also need the file VEL\_COM.F that contains the common block variables. The difference between the UNIX and VMS version are the I/O - file attachments ("open" - calls) only. Thus, in the UNIX versions you will find aside of each active line for opening call an additional line beginning with "cvms" with the open calls in the VMS-system and vice versa in the VMS version are lines beginning with "cunix" and the open calls for UNIX. The only system-dependent calls are found in the two subroutines DATETIME and CPUTIMER; so if the program should be moved onto another machine, only these two small subroutines located at end of the source code have to be changed. Alternatively, delete all calls to these two routines which are not essential for the main calculations (they just provide run-time information).

VELEST is currently set up to invert data in simultaneous mode from a maximum of 658 earthquakes (iepmax=658) and max. 50 shots or quarry blasts (inshotsmax=50) with max. 500 observations per event (maxobsperevent =500). Current setting also allow a max. number of 500 stations in the station list (istmax=500), max. 2 velocity models (itotmodels=2) with max. 100 layers per velocity model (inltot=100).

If you decide to need other dimensions please only adjust the parameters at the beginning of the file VEL\_COM.F and compile the source with an (optimized) F77 compiler.

In addition to the source you should also get a set of files providing examples of input and output data for simultaneous mode. To each example there belong 5 types of files:

- |         |   |                                |
|---------|---|--------------------------------|
| Input:  | - | *.cmn (control parameters)     |
|         | - | *.sta (station list)           |
|         | - | *.mod (initial velocity model) |
|         | - | *.cnv (local earthquake data)  |
| Output: | - | *.out (main print output)      |

### **4. Calculation of Minimum 1-D model (simultaneous mode)**

Solutions to the coupled hypocenter-velocity model problem consist of the **hypocenters, the velocity model, and station corrections**. Each such solution may be rated by comparing its corresponding (calculated) travel times with the measured (observed) travel times. These travel time differences are called the misfit (or residuals) of the solution and we may measure the total misfit by using any Norm. Most often the

RMS (root-mean-squared)-misfit of the solution is used. Consider any possible combination of hypocenters, velocity model, and station corrections be rated by its RMS misfit for a well-posed problem that would only have one solution with minimal RMS. Such a situation could be represented by Figure 2a. In the case of the coupled problem with local earthquake data, however, such a diagram displaying the RMS misfit for various solutions most probably looks more like Figure 2b, where several local RMS minima occur. In such situations the solution obtained by any iterative algorithm strongly depends on the initial model and initial hypocenter locations.

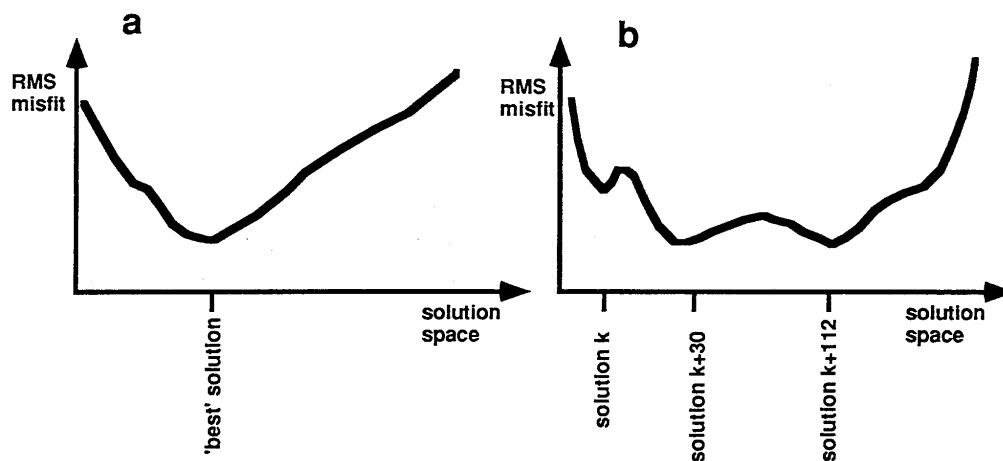


Figure 2. Quality estimate of solutions to the coupled problem. a: Simple case with unique "best fit" solution. b: Normal case with several local minima of RMS misfit.

Unfortunately, we do not a priori know this function (Fig. 2b) and, therefore, we must search for different solutions with minimal misfit (RMS) by varying initial models and hypocenter locations within reasonable but large bounds. Thus, the calculation of a Minimum 1-D model amounts to a TRIAL-AND-ERROR process (for different initial models) with internal non-linear (iterative) INVERSION procedure, performed by VELEST.

Since VELEST does not automatically adjust layer thickness (as opposed to layer velocities), the appropriate layering of the model must be found by a trial-and-error process. Thus the calculation of a Minimum 1-D model normally starts with

### FINDING AN APPROPRIATE MODEL LAYERING.

Introduce layers according to refraction models and according to main phases visible in data when displayed similar to Fig. 3. Put the trial layer thickness at 2km for shallow crustal levels and increase layer thickness with increasing depth to about 4 to 5 km at Moho depth. Allow several 5km-thick layers in the depth range where you expect the crust-mantle boundary.

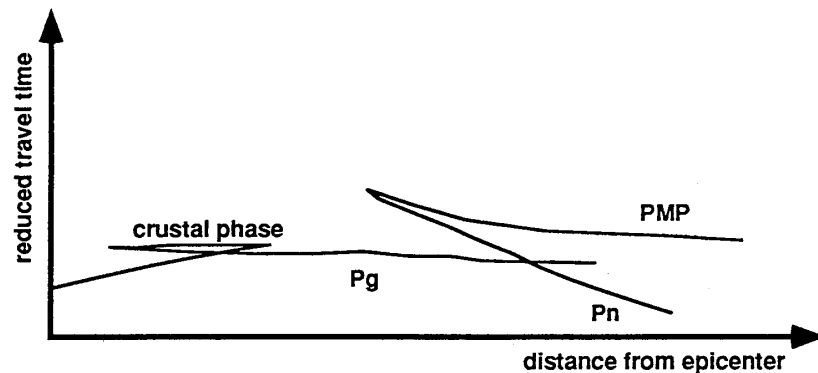


Figure 3. Phase correlation by refraction seismology type record section for stations grouped in sectors seen from epicenter.

### SETTING APPROPRIATE DAMPING and CONTROL PARAMETERS

Begin without low velocity layers ( $LOWVELOCITY=0$ ) since they have strong effects on the ray paths and, thus, they increase the non-linearity of the problem. Set  $VTHET=1.0$ ,  $STATHET=0.1$ , and the hypocentral damping parameters to 0.01. Set  $INVERTRATIO$  to 1 and allow between 5 and 9 iterations. Normally, do not use shots or quarry blast data. Save this data for later testing (see below). The option to include (with special treatment) shot data has been implemented for specific VELEST use only.

### INITIAL VALUES and FIRST INVERSIONS

**INITIAL VELOCITIES:** The average velocity for the crust should remain within reasonable bounds provided by information from controlled-source seismology but otherwise try a large variety of initial velocity models. Set velocity damping parameters ( $vdamp$ ) in Model File (\*.mod) all equal to 1.0.

**INITIAL HYPOCENTERS:** Use the locations of best routine location procedure. If your trial velocity model is largely different from the one used to obtain initial hypocenter locations you might want to try two VELEST runs, one with  $INVERTRATIO=1$  and one with  $INVERTRATIO=2$ . In order to allow easy comparison do not vary any other parameter. If you feel like your hypocenters shift too much in the first iteration steps you might want to hold your initial model fixed ( $VTHET=999.$ ) and let the hypocenters and station corrections approach a local minimum. You may then use these final hypocenter locations and station corrections as initial parameters for the next run of VELEST where you let the model float again. Note: Whenever you use final values as initial values for another VELEST run you are biasing your solution in a specific way, which is sometimes a good thing, since you want the solution to approach one of the minima.

**INITIAL STATION CORRECTIONS:** Set all of them to zero.

## PROBING THE SOLUTION SPACE

Try to first get a feeling for the solution space (Fig. 2b) corresponding to your specific problem (stability and diversity of potential solutions) and for the robustness of your data. Possible mathematical solutions to the coupled model-hypocenter problem span a much wider range than the physically reasonable solutions. Example: In one case a velocity model with one layer having a velocity of nearly zero showed an excellent fit to the data. By not allowing low-velocity layers in this first round of VELEST runs most such solutions may be avoided. One does, however, like to get a feeling for the range of the physically reasonable solutions and, therefore, one must try extreme initial velocity models as well. Normally, we have a fairly good idea about the probable average crustal velocity and about the Moho depth. Try several initial velocity models that fulfill these -even vague- constraints and that correspond with petrophysical arguments. Velocities near the surface may be as low as 2 km/s and as high as 6.5 km/s. Average velocities of lower crustal material may vary between 6 km/s and 7.8 km/s.

To probe the dependence of the solution on the initial model one should try at least three different initial velocity models for any model geometry (layer thickness): one with extremely low crustal velocities, one with extremely high and one with intermediate crustal velocities.

After many VELEST runs with different initial model parameters (layer thickness and velocities), hypocentral parameters, and various control parameters you will get a feeling of how parts of the RMS misfit function (Fig. 2b) for your problem-data set look like. You will also see if the problem is reasonably well determined by the data. You may then decide on the best model layering based on the results of the previous VELEST runs and based on the depth distribution of the earthquakes. Choose a simple model by combining layers where velocities are very similar, unless you want to mimic a gradient.

Note: Topmost layers are mostly subvertically and bottom layers are mostly subhorizontally penetrated. Therefore, the resolution in these layers is generally lower than in the central layers that contain the hypocenters.

## APPROACHING A MINIMUM

If one finds a local minimum RMS region one would hope that the velocity model part of the solution is similar to the situation in Fig. 4, where the final velocity models (B1 and B2) within the well-resolved depth range are almost identical for different initial models (A1 and A2). If the near-surface velocities and the Moho depth are well-known one could increase the damping for these layers in the model file (\*.mod).

Note: Fix the Moho depth by increased damping of the sub-Moho velocities only, do not overdamp both layer velocities below and above the Moho.



Once a local minimum in the RMS-function (Fig. 2b) has been found one may want to check for low velocity layers (LVL's). For reason of apriori information or else one might want to allow LVL's only at certain depth ranges or one might want to fix some layer velocities obtained by earlier VELEST runs. The additional damping parameter for each layer provided by the input velocity model file allows to have variable layer velocity damping.

Note: Do not fix (overdamp) near-surface layer velocities and also overdamp station delays unless a Minimum 1-D model with corresponding station delays has been reached.

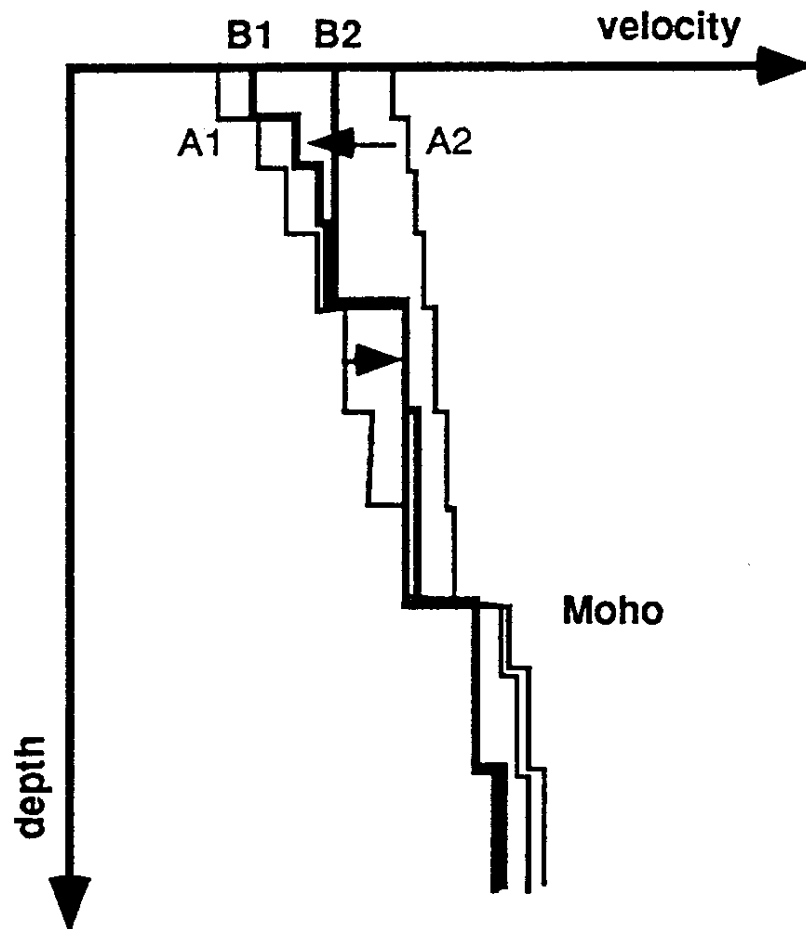


Figure 4. Final velocity models (B1 and B2) resulting from two identical inversion procedures of same data with two different initial velocity models (A1 and A2).

In many cases it is advantageous to calculate two runs with fewer iterations each than one VELEST run with double the number of iterations since in the first case one may select among the output files (velocity model, station delays, earthquake locations) data for use as input in the second run.

## TESTING A MINIMUM 1D MODEL

There are numerous tests that may be performed and some might already have been performed during the previous VELEST runs. Here I just list a few possibilities.

### USING SHOTS and QUARRY BLASTS

Because these sources normally lay at or near the Earth's surface raypaths for shots and blasts travel twice (at either end) through the near-surface structure. Thus shots and blasts are much harder to locate by a well-distributed seismic array (Kissling 1988). We take advantage of this and of the known source parameters by using shot and blast data to estimate absolute location errors (Kissling 1988, Kradolfer 1989). When performing this test, however, shot data should NOT be treated differently from earthquake data in routine location procedure where the Minimum 1D model with the station corrections is fixed (INVERTRATIO=ITTMAX+1) or at least heavily damped (VTHET=STATHET=999.)

Note: Normally, shot and quarry blast data should NOT be used to derive a Minimum 1D model other than providing information for the model layering (from refraction type experiments) for two reasons. First, (as noted above) the errors resulting from near-surface heterogeneity are larger for shots than for earthquakes. Second, the test described above is only valid if the tested model is independent of the test data. Shots recorded along a seismic refraction line are excellent to densely sample the wave field in a specific direction and to derive a model of the underlying structure. The station distribution of such an experiment, however, rate among the worst possible ways to deploy a seismic station array for earthquake location. Obviously, data from such different experiments should not be mixed and treated in a similar way by a trial-and-error process that involves many inversions. Rather, these data should both be used in different ways that exploit their strengths, as suggested above.

### COMPARING INITIAL and FINAL HYPOCENTERS

When dealing with a large (>200) data set of well-locatable earthquakes ( $\text{gap} < 180$ ;  $\text{nobs} > 10$ ) one might want to check for a bias in the velocity model and station corrections as a result of systematic (though possibly small) shift of the hypocenters. Use the Minimum 1D model with station corrections as initial model parameters and apply damping of  $\text{VTHET}=1.$ ,  $\text{STATHET}=0.1$ ,  $\text{XYTHET}=\text{ZTHET}=\text{OTHET}=0.01$  with  $\text{ITTMAX}=9$  and  $\text{INVERTRATIO}=2$ . To obtain initial hypocenters you write a short routine that shifts all hypocenters randomly (!) by 5 km or 10 km (avoid "air quakes") from the locations obtained with the Minimum 1D model. If the Minimum 1D model with stations corrections denotes a very robust minimum, the results of this test should be a small or negligible variation in the Minimum 1D model and station corrections while the hypocenters should be more or less relocated back to their original (correct) positions. Hypocenters that remain in the wrong locations need to be checked individually. If the final model and/or station corrections obtained in this test deviate significantly from the Minimum 1D model, the solution space has not been sampled completely and the search for another (or better) Minimum 1D model must continue.

## COMPARING MINIMUM 1-D MODEL and STATION DELAYS with CRUSTAL STRUCTURE

In the Minimum 1D model, the layer velocities will approximately equal the average velocity of the 3D structure within the same depth range that has been sampled by the data. Note that it is not the spatial average of all the area under study. Rather, the velocities of the 1D model approach the average of the 3D structure in each layer weighted by the total ray length. The station delays are the average values for the azimuthally and radially varying time delays at these stations relative to the near-surface velocities of the Minimum 1D model. In teleseismic studies, the main data signal to be interpreted and inverted is the distribution of travel times delays at seismic stations with respect to the azimuth of the incoming wave fronts. With local earthquake data the azimuthal and radial dependences are never as uniform for all stations as for the teleseismic data if the hypocenters are well distributed over the area.

## 5. Overview of Input/Output files

## 5.1 INPUT-FILES

Content: default name

VELEST-control-file	VELEST.CMN
Model-file	INITIAL.MOD
Station-file (coords,elev,etc.)	LIST.STA
Earthquake data (hypocenters and travel times)	PHASEDATA.CNV
or (in SED-format)	PHASEDATA.SED
or (in archive-format)	DATA.ARCVEL
data (optional)	SHOTS.CNV
(for single_event_mode:)	
Region names (Swiss & Flinn-Engdahl)	EGIONSNAMEN.DAT
Region coordinates (Swiss & Flinn-Engdahl)	REGIONSKOORD.DAT
Seismo-file (for Magnitude-calculation; optional)	SEISMO.PARAM

## 5.2 OUTPUT-FILES

Content: default name

main print-output	VELEST.OUT
final hypocenters and travel times (may be used as input for another iteration)	VELOUT.CNV
new station list with new sta. corrections (may be used as input for another iteration)	VELOUT.STA
(in single_event_mode:)	
'HYPO71'-compatible output of the locations (print-output in single_event_mode)	VELOUT.ARCVEL

Optional Output:

file011 - summary cards of final hypocenters (for plotting)	VELOUT.SMP
file013 - raypoints of all the rays	VELOUT.RAY
file021 - partial derivatives of all the rays	VELOUT.DRV
file075 - coordinates and ALE of all located events	VELOUT.ALE
file076 - coordinates and DSPR of all located events	VELOUT.DSPR
file077 - coordinates and residual of reflected ray	VELOUT.RFL
file078 - coordinates and residual of refracted ray	VELOUT.RFR
file079 - residual and according distance	VELOUT.RES

## 6. Overview of content of INPUT files

### 6.1 Explanation of Control Parameters (file VELEST.CMN)

This input file contains the control-parameters only, model- and station-parameters are read in from separate files (their names are specified in the control-file). All parameters are read in free format.

OLAT, OLON, ROTATE:

Latitude and Longitude (in degrees) or center of cartesian coordinate system and of short distance conversion. ROTATE denotes the angle of clockwise rotated y-axis from North.

ICOORDSYSTEM: Default value: 0

- = 0 for short distance conversion to cartesian coordinate system all over the Earth with positive values representing Longitude West
- = 1 for short distance conversion to cartesian coordinate system all over the Earth with positive values representing Longitude East (CAUTION: this option has not yet been fully tested!)
- =2 for Swiss coordinate system Latitudes and Longitudes are used throughout the program (and its input/output) in decimal-degrees. In all



ITRIAL, ZTRIAL: Default values: 0 , 0.0

Controlling the trial hypocenter in the single\_event\_mode.

itrial =0 use hypocenter coordinates provided by summary card.

=1 trial hypocenter equals station coordinates of earliest observation and ztrial for depth.

ISED: Default value: 0

Controlling the input format of the earthquake data.

=0 in converted (\*.CNV) archive format

=1 VELEST archive type format

=2 SED format (SED= Swiss Seismological Service)

If program VELEST should read in other than one of the above formats, the user may add an additional subroutine, which reads the desired format. Any subroutine of this kind should always read the phase data of one entire event. The call of the routine may look as follows:

```
call INPUTxyz(iunit,nobsread,sta,iyr(i),imo(i),iday(i),ihr(i),imin(i),sec,rmk1,
rmk2, cphase,ipwt,amx,prx,xlat,alon,emag(i),depth,e(1,i),i1,ifixsolution,
i3,eventtype)
```

NEQ: number of earthquakes

NSHOT: number of shots or blasts

ISINGLE: Default value: 0

Switch controlling mode of VELEST.

=0 simultaneous mode

=1 single\_event\_mode

IRESOLCALC: Default value: 0

Resolution matrix calculation in single\_event\_mode.

DMAX: Default value: 200.0

Maximal epicentral distance for use of phase. Observations at stations at greater distances are neglected.

ITOPO: Default value: 0

This switch is useful for precise location of shallow earthquakes in areas of very rough topography. In order to use this option the USER must supply the topographic data and must properly adjust the INPUT routine to read the topo array.

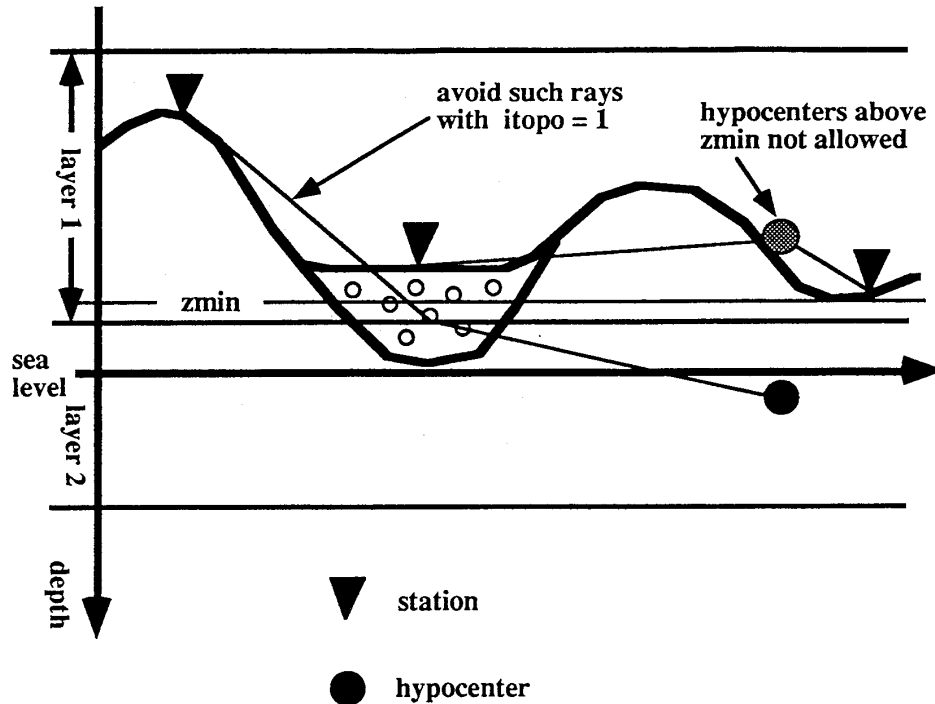


Figure 6. Purpose of switches *zmin* and *itopo*. *Zmin* denotes the highest possible level for hypocenters to avoid "airquakes".

**ITOP:**

- = 0 no topographic array is used
- = 1 *zmin* is set automatically to the topographic height at this point (surface), so the source can float upward as far as the true Earth surface.
- = 2 each raypoint is checked whether it is below the surface or not. Attention: setting *itopo* to 2 makes program VELEST very slow (by a factor 10).
- = 3 (and *icoordsystem*=2): For epicentral distances < 10 km the first and last ray-segment are each splitted into four subsegments. Each of the additional 2 x 3 raypoints is checked, whether it is below the surface or not. Any ray-point in the air is pushed below the surface. The new travel time is calculated and the total travel time of the ray corrected. See subr. BENDRAY for further details.

**ZMIN:** Default value: 0.0

Minimal depth for hypocenters. Used to avoid 'air quakes'.

**VELADJ:** Default value: 0.2

Maximal adjustment of layer velocity in each iteration step.

**ZADJ:** Default value: 5.0

Maximal adjustment of hypocentral depth in each iteration step.

LOWVELOCLAY: Default value: 0

- =0 no low-velocity layers will result from velocity-inversion
- =1 low-velocity-channels may result

If reflected waves are used, no low-velocity-layers are allowed; if in such a case the introduction of a low-velocity-layer is attempted during one iteration, the velocity of this layer is set equal to the velocity of the layer just above it and a remark is written to the main print output file.

NSP: Default value: 1

- =1 P phases only
- =2 P and S phases
- =3 P-S relative travel time

SWTFAC: Default value: 0.5

General weighting factor for S wave data relative to P wave data of same observation weight.

VPVS: Default value: 1.730

VpVs ratio.

NMOD: Default value: 1

Number of velocity models.



#### DAMPING PARAMETERS:

Default values for simultaneous mode:

OTHET=0.01 XYTHET=0.01 ZTHET=0.01 VTHET=1.0

STATHET=0.1

OTHET = damping of origin-time

XYTHET = damping of horizontal hypocentral coordinates

ZTHET = damping of hypocentral depth

STATHET = damping of station-corrections

VTHET = damping of velocity-model

NSINV: Default value: 1

=0 Do NOT invert for station corrections

=1 invert for station corrections

NSHCOR and NSHFIX are for specific use of VELEST only. Use default values.

NSHCOR: Default value: 0

=0 no shot correction applied

=1 apply shot corrections

NSHFIX: Default value: 0

=0 Do NOT fix shots

=1 fix shots

NSHCOR and NSHFIX are for specific use of VELEST only. Use default values.

IUSEELEV: Default value: 1

=0 station-elevations are NOT used (assumed all equal zero = sea level). See Figure 6 !!

IUSESTACORR: Default value: 1

=0 station-corrections from input-file are ignored

ITURBO: Default value: 1

=1 OUTPUT files 2,7,11,12,77,78,79 are NOT created.

=0 above (large!) OUTPUT files are created

ICNVOUT: Default value: 1

Option to create \*.CNV file with final hypocenters.

ISTAOUT: Default value: 1

Option to create \*.out.STA file for station list with final station corrections.

ISMPOUT: Default value: 0

Option to create \*.SMP file with summary cards of final hypocenters.

If switches IRAYOUT, IDRVOUT, IALEOUT, IDSPOUT, IRFLOUT, IRFROUT, IRESOUT are set to 1 the corresponding output files are written. Default: 0

DELMIN: Default value: 0.01  
Criterion to stop iteration in single-event-mode.

ITTMAX: Default value: 5 to 9  
=0 no iteration is performed, but all statistics are calculated and printed!  
=N N iterations with each consisting of a forward and a full inverse solution are performed

INVERTRATIO: Default value: 1  
In simultaneous mode VELEST may either invert for all hypocenters and model (with station corrections) parameters [type A] or invert only for all hypocenters [type B]. If INVERTRATIO is set to 2, then every second iteration is an inversion type A. If it is set to 1, then every iteration is of type A.  
Example for ITTMAX=5 and INVERTRATIO=3:  
The consecutive iterations would then be of type BBABB.

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Example of Control File:

```
***** CONTROL-FILE FOR PROGRAM V E L E S T (28-SEPT1993) ***** ***
*** ( all lines starting with * are ignored! )
*** ( where no filename is specified,
*** leave the line BLANK. Do NOT delete!)
***
*** next line contains a title (printed on output):
N. Gabilans Run #6, no station elev, Nov 1994
***
*** olat      olon  icoordsystem  zshift  itrial  ztrial  ised
    36.5000   121.2500      0      0.000   0   0.00   0
***
*** neqs  nshot   rotate
    257   00     0.0
***
*** isingle  iresolcalc
      0      1
***
*** dmax  itopo  zmin  veladj  zadj  lowveloclay
    200.0   0    0.05   0.20   5.00   0
***
*** nsp  swtfac  vpv  nmod
      1   0.00  0.000   1
***
*** othet  xythet  zthet  vthet  stathet
      0.01  0.01   0.01   01.   0.01
***
*** nsinv  nshcor  nshfix  iuseelev  iusestacorr
      1      0      0      0      1
***
```

```

*** iturbo  icnvout  istaout  ismpout
      1      1      2      0
***
*** irayout  idrvout  ialeout  idspout  irflout  irfrout  iresout
      0      0      0      0      0      0      0
***
*** delmin  ittmax  invertratio
      0.010  03      1
***
*** Modelfile:
bv.mod
***
*** Stationfile:
bv.sta
***
*** Seismofile:
***
*** File with region names:
***
*** File with region coordinates:
***
*** File #1 with topo data:
***
*** File #2 with topo data:
***
*** DATA INPUT files:
***
*** File with Earthquake data:
bv.cnv
***
*** File with Shot data:
***
*** OUTPUT files:
***
*** Main print output file:
VELMOD06bv.OUT
***
*** File with single event locations:
***
*** File with final hypocenters in *.cnv format:
VELMOD06bv.CNV
***
*** File with new station corrections:
mod06bvsta.OUT
***
*** File with summary cards (e.g. for plotting):
***
*** File with raypoints:
***
*** File with derivatives:
***
*** File with ALEs:
***
*** File with Dirichlet spreads:
***
*** File with reflection points:
***
*** File with refraction points:

```

\*\*\*

\*\*\* File with residuals:

\*\*\*\*\* END OF THE CONTROL-FILE FOR PROGRAM V E L E S T \*\*\*\*\*

## 6.2 Content of station list (file \*.STA)

The station list contains the name, the station coordinates (latitude, longitude, elevation), and other station parameters necessary for travel time studies. These additional parameters are the P- and the S-wave station delays, a number defining the velocity models (P and S) corresponding with this station (if at all one wants to use different models for different groups of stations), and the ICC number.

Example of station list:

```
(a4,f7.4,a1,1x,f8.4,a1,1x,i4,1x,i1,1x,i3,1x,f5.2,2x,f5.2,3x,i1)
name  coordinates      elevation      pdelay sdelay imod
BAVM  36.6458N 121.0298W 0230 1 003 0.00 0.00 1
BBGM  36.5783N 121.0385W 0312 1 004 0.00 0.00 1
BEHM  36.6647N 121.1742W 0223 1 008 0.00 0.00 1
BEMM  36.6613N 121.0960W 0302 1 009 0.00 0.00 1
                                in icc
```

ICC: The ICC number corresponds to the unknown station delay parameter assigned to this station. If each station has a different number, then all station delays are calculated independently. Any two (or more) stations that carry the same ICC number will obtain a common station delay. This might be useful for stations with different names that are virtually in the same location or very close to each other. The station with the highest ICC number is the reference station. This station will maintain its initial delay (normally set to zero). Only the P-wave station correction is fixed for the reference station, the S-wave correction is free floating.

How to select a reference station?

The reference station should be a high-quality station near the center of the station network with a long recording record and with at least 50% of the total possible readings. Knowledge about the near-surface velocity structure beneath the reference station may help to qualitatively interpret the station delays.

ATTENTION: For reasons of setup of the ray tracer, all stations **MUST** lie within layer 1 and **MUST NOT** be at same depth as top of layer 2. Thus, if you do not use station elevations put top of layer 2 to +0.05 km in the model file.

## 6.3 Content of velocity model file ( \*.MOD)

The model file consists of a title line and for each model of one line with the number of layers (layer boundaries) and for each layer one line with the velocity (in km/s), the upper interface of the velocity layer (in km), vdamp, reflchr, titl. REFLCHR denotes the reflected phase type, currently only used for single\_event\_mode.

Example of model file:

GABILANS1D-model (mod.06 CT070194) Ref. station BCGM

```
10    vel,depth,vdamp  (f5.2,5x,f7.2,2x,f7.3,3x,a1)
4.80  -3.0    001.00 P-VELOCITY MODEL
5.00  0.05    001.00
5.20  1.0     001.00
5.40  3.0     001.00
5.60  5.0     001.00
5.90  7.0     001.00
6.10  10.0    001.00
6.50  15.0    001.00
6.80  20.0    001.00
8.05  28.0    001.00
10    vel,depth,vdamp  (f5.2,5x,f7.2,2x,f7.3,3x,a1)
2.80  -3.0    001.00 S-VELOCITY MODEL
3.00  0.05    001.00
3.20  1.0     001.00
3.40  3.0     001.00
3.60  5.0     001.00
3.90  7.0     001.00
4.10  10.0    001.00
4.50  15.0    001.00
4.80  20.0    001.00
4.05  28.0    001.00
```

Separate damping factors (vdamp) may be applied to each velocity layer. vdamp is a real number between 0 and 999.99. The effective damping factor for each velocity layer is calculated as follows:  $\text{damp\_eff} = \text{damping (VTHET, given in file VELEST.CMN)} * \text{vdamp}$ . Thus, if  $\text{vdamp} = 1$  --> Ordinary damping as specified in VELEST.CMN,  $\text{vdamp} = 0$  --> No damping is applied to this velocity layer,  $\text{vdamp} = 999$  --> The velocity layer is almost fixed to the starting value (overdamped).

#### 6.4 Content of local earthquake file ( \*.CNV)

The input-data in \*.CNV - format contains a summary-card of the format:

```
(3i2.2,1x,2i2.2,1x,f5.2,1x,f7.4,a1,1x,f8.4,a1,f7.2,f7.2,i2...)
iyear,month,iday,ihr,min,sec,xlat,cns,xlon,cew,depth,emag,ifx...
      (where cns is 'N' or 'S' and cew is 'E' or 'W')
```

This summary card is followed by an unspecified number of lines each with six phase data. The end of the event is marked by a blank line. For each phase the station name, the phase type, the observation weight, and the observation time (in sec) relative to the origin time must be specified.

Example of earthquake data file in \*.CNV format:

```

90 1 1 1349 0.36 36.6745N 121.3038W 6.08 2.10 1
BLRMP0 1.51 BCGMP0 1.59 BSCMP0 1.62 BHRMP0 2.42 BJOMP0 1.71 BEHMP0 3.22
BSLMP0 3.33 BVYMP0 2.59 BVLMP0 3.08 HJSMP1 3.88 BJCMP0 2.91 BEMMP2 4.19
HFPMP2 3.32 BSRMP0 3.43 HQRMP1 4.55 HLTMP1 5.39 BPIMP0 4.27 BAVMP0 5.36

90 1 2 310 7.67 36.6922N 121.3207W 4.32 3.20 0
BCGMP0 1.11 BLRMP0 1.58 BHRMP0 2.23 BSCMP0 1.85 BJOMP0 2.37 BSLMP0 2.88

```

Switch IFX: Default value=0

For each event the switch IFX (i2, after magn.) may be set. If IFX=1, then adjustment of this hypocenter in y-direction (to rotate y-axis see parameter ROTATE in control file \*.CMN) is inhibited.

In the same event only one phase of the same type (P or S) is accepted for the same station! VELEST may also use S-P travel time differences. They must be written into a phase file of INPUTSED format (ISED=2). The phase description is "S-P". The phase identifier is a "-" rather than P or S. Reflected waves are computed only if the arrival-time is specified as one of a reflected wave (see below); in this case, the ray is forced to be a reflected one and no other raypaths are computed (because a reflected wave hardly is the first arrival...!).

## 7. Overview over main print OUTPUT file

The head of this file recapitulates the content of the control input file (\*.cmn) for this run and summarizes the most important parameters of the short distance conversion. Subsequently, the content of the input model file, the station file, and the input phase data are listed. This is followed by the so-called 'iteration 0' - a one-step forward (location only) solution for each event to obtain the initial observation residuals and RMS residuals. Each iteration starts with a summary of the control parameters and the effective number of unknowns.

number of unknowns = 4\*ieq + #station + #blasts + #layers

The number of unknowns might vary between iterations if INVERTRATIO is any number other than 1. Before the resulting RMS values and other statistical estimators are given a check is performed if the data variance has decreased. If new iteration leads to a worse solution than the previous one, model and hypocenter are 'backuped'.

For each event the hypocenter adjustments are listed and at the end the average and the average absolute adjustment are calculated to allow an overview over the step length. The average velocity calculations may provide a summary of the model for comparison with known average crustal velocities. Since the first layer contains all stations (at possibly variable elevation) and in some cases this layer may be very thin and of very low velocity, a second list with average velocities to different depth is provided beginning with only layer two. The information for each iteration ends with the list of the new station delays and the adjustments to the old station delays.

## **8. Explanation of SINGLE-EVENT-MODE**

Modified to use first station (+.001 deg lat/lon) as trial hypocenter (optionally) instead of the one on the first line of each event in the \*.CNV input-file. To do so, set ITRIAL to 1 and ZTRIAL to the desired value, else set ITRIAL to zero. In case of the hypocenter-parameters, the depth must not be reset by 1/2 of the step-vector ( b(j) ), but rather by 1/2 of the effective z-change. In case of a 'depth-constraint', the depth used to be put down to much during the backup-procedure. Now the effective depth-change is stored in variable EFFDELTAZ(ievent). Instead of calculating a EFFDELTAZ in subr. adjustmodel, the depth is in all cases constrained directly on the adjustment-vector-element. So in subr. backup the hypocentral depth is 'backed up' in the same way as are all the other hypocentral parameters. As a consequence of doing so, the calculated step-length reflects now the ACTUAL (applied) step-length. Therefore further iterations are avoided, if the epicenter is already o.k. but the inversion-process continues trying to put the hypocenter above ZMIN . Now the step-length gets indeed small if no more adjustments are allowed and the iteration process stops as desired in such a case!

outputfile (unit=2) with STATISL-compatible output is generated

(STATISL is a statistic-analysis-program for locations of local earthquake-data). Resolution- and covariance-matrices are calculated and printed in output-file. Dirichlet-spread of resolution-matrix is determined and added to the output (file 16 & screen). During first 2 iterations, depth-adjustment is set to 0.0. The same is done if igap of the event is > 250 degrees. If depth-adjustment > zadj (set in input-file) then depth-adjustment is constrained ! Covariance matrix is now calculated as the UNIT covariance matrix, so the resulting SIGMAs (for OT, X, Y, Z) need to be multiplied by the effective (assumed) SQRT(data variance) SIGMAdata (e.g. 0.1) ! Before, cov was multiplied by davar1, which occurred to be very small sometimes (in case, the model-parameters fitted the model well) and therefore unrealistic small values for COV were obtained. For Swiss-data the local magnitude is calculated (see subr. MAGNITUDE and others). MI is calculated only in single-event-mode In single-event-mode the regionname is determined according the coordinates of the final solution. Usually the Flinn-Engdahl names are used; if possible, the names of the 1:25'000 maps of Switzerland are used.

In single-event-mode only readings with obs-weight < 4 are used for the solution and only those are used for AVRES, RMS, DATVAR and so on. Therefore the normalization of the weights is not based on knobs directly, but rather on (knobs-nobswithw0), where nobswithw0 is the number of observations with w(nobs,ievent)=0.0 [these observations have either an observation-weight of 4 or they were rejected during the iteration process (see subr. rejectobs)]. However, these readings are taken for calculation of residuals and magnitude. File 2 contains first a STATISL-compatible output and second this output is equivalent to the one from HYPO71 (Version at the Swiss Seismological Service, ETH-Zurich). Two additional parameters are printed out: The ALE (Average logarithmic eigenvalue of GtG) and the D-SPR (Dirichlet ccu spread). Reject observation if NITT > 2 .and. RES(nobs) > 2.0 sec. If a rejected arrival gets a residual smaller than 1 sec, then its weight is 'revived'



and again used in further calculation. If any of the hypocentral parameters is fixed, both the ALE and the Dirichlet-spread are calculated for the SOLVED parameters only! In file02 [HYPO71-compatible and STATISL-compatible output] a notification made if any of the hypocentral parameter is fixed: the word DEPTH or the words LAT, LON and DETH respectively, appear as \*DEPTH\*, \*LAT\* and \*LON\* if they are fixed. One single card of a phase-list consists usually not only of the P-phase, but also of the S-phase and sometimes amplitude&period-data. In the case, that only an S-arrival is read from the seismogram, many location- programs need a 'dummy-P-arrival-time' and the operator then usually sets the fantasy-P-arrival to an observation-weight of 4! Program VELEST allows, to add only a S-arrival (plus eventually amplitude- and period-data) and NO P-arrival-time. In this case the field, where usually the P-observation-weight stands, the number 5 must be typed in the phaselist. If done so, all the data on the phaselist-line are used with the exception of the P-time. Of course, in the output-file (file02) there isn't printed any information about any P of this station, but the full information of the S-ray is printed out. If the input-line contains only P-data and its observation-weight is set to 5, the observation isn't used at all. The user of VELEST is recommended (in case the subroutine which inputs the phase-data - here INPUTSED - is substituted by another one) to be sure that in case the field with the P-arrival-second is empty, this 'phase' is either skipped or set to a weight of 5 ! If a trial-hypocenter for event-location is to be found, the first station in the data which is on the station-list and has an observation-weight less than 5 is taken as starting point. Now all subsequent arrivals are checked whether they arrive earlier and have an obs.-weight less than 5 and are on the station-list. The station with the first arrival in time which satisfies these conditions is taken as trial epicenter. Note: In case that anything goes wrong during this search and the first station is recognized to be blank, the first station in the station-list is taken as trial epicenter (well, this should almost never be the case, but one never knows...).

Single-event-mode: If depth is fixed and fix-depth is less/equal zero, depth is always set to ZMIN (=zmin allowed). ZMIN is read from the input-command-file and altered (during iteration-process) to the real surface-height (depending on current horizontal coordinates) if option ITOPO is set. The calculation of the data resolution matrix in the single event mode was applied. The diagonal elements (importance) are applied to the output of the statisl file. The importance is a measurement of the 'importance' of a station residual. Large residuals with a high importance are very suspicious!!! (See PhD thesis H. Maurer 1993, for further information.) The dataresolution (hat) matrix is set up as follows: The matrix G (data kernel) is recreated in vel\_main.f. Then the damped normal equations are set up. Next, the normal equations are solved using the matrix inversion routine matrinvs (declared in matrinvs.f). Finally the hat matrix is calculated and the diagonal elements are extracted. The importance values are written into the statisl output file (last parameter of each 'phase line').

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## **Initial reference models in seismic tomography**

Abstract, Appendix and References

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### **Abstract**

The inverse problem of 3D local earthquake tomography is formulated as a linear approximation to a non-linear function. Thus, the solutions obtained and the reliability estimates depend on the initial reference model. Inappropriate models may result in artifacts of significant amplitude. Here, we advocate the application of the same inversion formalism to determine hypocenters and 1D velocity model parameters, including station corrections, as the first step in the 3D modelling process. We call the resulting velocity model the minimum 1D model. For test purposes, a synthetic data set based on the velocity structure of the San Andreas fault zone in central California was constructed. Two sets of 3D tomographic P-velocity results were calculated with identical traveltimes data and identical inversion parameters. One used an initial 1D model selected from a priori knowledge of average crustal velocities, and the other used the minimum 1D model. Where the data well-resolve the structure, the 3D image obtained with the minimum 1D model is much closer to the true model than the one obtained with the a priori reference model. In zones of poor resolution, there are fewer artifacts in the 3D image based on the minimum 1D model. Although major characteristics of the 3D velocity structure are present in both images, proper interpretation of the results obtained with the a priori 1D model is seriously compromised by artifacts that distort the image and that go undetected by either resolution or covariance diagnostics. (Seismic tomography, initial reference models.)

### **Appendix:**

#### **"Recipe" to calculate a minimum 1D model**

The following guide-lines for the calculation of a minimum 1D model have been developed through the application of equation (3) in many areas of both simple and complex crustal structure around the world [Reasenber and Ellsworth, 1982; Kissling and Lahr, 1991; Maurer, 1993]. These guidelines do not guarantee convergence to an optimal solution. Rather, specific characteristics of the data set, and of the velocity structure may demand modifications of the procedure. The results also depend on the effectiveness of the data selection process [Kissling, 1988].

Most of our modelling has been done with the program VELEST [Ellsworth, 1977; Roecker, 1981; and Kradolfer, 1989]. The programs of Crosson [1976] and Pavlis and Booker [1980] have also enjoyed considerable success for this purpose [Steppe and Crosson, 1978]. Scott [1992] has recently conducted a thorough investigation of the problem.

## **1. Establishing the a priori 1D model(s)**

Obtain all available a priori (prior to the 1D or 3D inversion) information regarding the stratification of the area under study (velocities, layer thicknesses, etc.). In general, use refraction seismic models, simplified where necessary to constant velocity layers. If no controlled-source seismology models are available, use phase correlations and cross over distances [e.g., Deichmann, 1987] from well-recorded earthquakes and/or infer the layered structure from geologic information. Define the media by several layers of increasing velocity with depth. Thicknesses of the layers in the upper crust should be about 2 km and in the lower crust about 4 to 5 km. Estimate layer velocities according to a priori information or a general crustal model. In case of incomplete or inconsistent information, or, if the area under consideration confines two or more distinctly different tectonic provinces, establish several 1D models. Choose a reference station with a continuous or nearly-continuous record of events. It must be a reliable station, preferably located toward the center of the network, and should not show extreme site effects. The model(s) and the reference station are called the a priori 1D model(s). If several significantly different a priori 1D models are established the following steps 2 through 5 are repeated for each 1D model separately.

## **2. Establishing the geometry and the velocity intervals of potential 1D model(s)**

Select about 500 of the best events in the data (i.e., those with the most high-quality P-arrivals) that cover the entire area under consideration. Relocate them with routine VELEST using a damping coefficient of 0.01 for the hypocentral parameters and the station delays, and 0.1 for the velocity parameters. Invert for hypocenters every iteration and for station delays and velocity parameters every second iteration. Repeat this procedure several times with new (updated) velocities in the reference 1D model, with perhaps the new station delays, and with new hypocenter locations. Repeat the procedure also for reduced number of layers where possible by combining adjacent layers with similar velocities. Unless clearly indicated by the data, in most cases it is preferable to avoid low velocity layers, as they normally introduce instabilities.

Our experience suggests that shot or blast data should not be included in the 1D-model inversion. Rather, such data should be used to set the near surface velocities, and to test the performance of the resulting minimum 1D model when used for locating hypocenters. This counterintuitive suggestion may be understood by considering that raypaths with both endpoints near the surface sample, on average, a much more heterogeneous part of the Earth than do raypaths from events in the seismogenic crust.

The goal of this trial and error approach is to establish reasonable geometry of the crustal model and corresponding intervals for the velocity parameters and station delays. In addition, this approach provides valuable knowledge about the quality of the data. Proceed to the next step when, a) the earthquake locations, station delays, and velocity values do not vary significantly in subsequent runs; b) the total RMS-value of all events shows a significant reduction with respect to the first routine earthquake locations; and c) the calculated 1D velocity model and the set of station corrections make some geological sense (e.g., stations with negative traveltime residuals should lie in local high velocity areas with respect to the reference station, etc.) and do not

violate a priori information. If all these requirements are satisfied, the result may be called the "updated a priori 1D model with corresponding station residuals".

### **3. Relocation and final selection of events**

Relocate all events using the updated a priori 1D model with station residuals with a routine location procedure (HYPO71 [Lee and Lahr 1975]; HYPOINVERSE [Klein 1978]; HYPOELLIPSE [Lahr 1980]) or with VELEST in the single event mode (fixing the station and velocity parameters). Reselect the best (consider gap, number of observations, distance to next station) 500 or so events that should be well distributed over the volume under investigation. If more than one such subset of about 500 events can be extracted, proceed for each subset separately with step 4 but try to obtain similar results.

### **4. Calculation of minimum 1D model for one subset**

In general terms repeat step 2 with the updated a priori 1D model and station residuals and with a damping of 0.01 for the hypocentral, 0.1 for the station, and 1.0 for the velocity parameters. The goal of this step is to calculate the 1D model (velocity parameters and station residuals), that minimizes the total estimated location errors for a fixed geometry. Test the stability of the result by systematically and randomly shifting hypocenters and by underdamping the velocity parameters. If you are pleased with the performance of the solution fix the updated velocity parameters by overdamping and calculate the station residuals. The resulting velocity model with corresponding station residuals is called "minimum 1D model".

### **5. Calculation of minimum 1D model for several subsets**

If several subsets of 500 events were extracted, test the dependence of your minimum 1D model on specific data. Find the 1D model and station residuals that will best fit the results from all subsets, mix data from different subsets, and repeat step 4. If the results are unsatisfactory, evaluate the best 1D model by the procedure described in step 6.

### **6. Evaluation of different minimum 1D models for same area**

If several significantly different a priori 1D models were established and steps 2 through 5 were successfully completed for each of them, you may base your choice of one minimum 1D model on the result of the following performance test: Select all traveltime data from quarry blasts or shots (i.e., from sources of known location) and relocate these events for the different minimum 1D models without fixing the depth during the location process. If the near surface velocities for several station locations are known, compare the station residuals with the differences between the average layer velocity and the local velocities. Finally, select the minimum 1D model that best resembles the a priori information.

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