Chapter 6. Generating Travel-Time Tables with Program TTGEN

[This chapter is an excerpt from the HYPOINVERSE manual (Klein, 1985) with only a few minor modifications.]

➢ *6.1 Use of travel-time table*

The program reads a travel-time table generated independently of the location process, and calculates travel time, travel-time derivatives, and emergence angles at the source by interpolation from the table. Three-point (parabolic) interpolation is used within the table, and linear extrapolation is used beyond the table. The table itself is a condensed grid of travel times as a function of distance and depth, so that travel times for shallow nearby sources may be accurately modeled without wasting space on deep or distant grid points where the travel-time curve changes slowly. A user may generate their own travel-time table empirically, with another program, or use the travel-time generating program TTGEN to prepare a table from a given velocity-depth function. The source code for TTGEN, along with sample input and output files, is included in the TTGEN directory.

➢ *6.2 Velocity models allowed by TTGEN*

Velocity models consist of from 2 to 15 points at which the user specifies velocity and depth. Linear velocity gradients are assumed to connect the points. The last point fixes the velocity and depth of the homogeneous half-space underlying the model. The half-space velocity must be the greatest of any velocities specified to insure that rays can be refracted along the top of the half space.

The use of linear gradients smoothes out the discontinuities in travel-time derivatives which result from homogeneous layer models, and gives a more realistic spread in emergence angles of down-going rays than is possible with modeling rays as refracted from discontinuities.

One buried low-velocity zone is permitted in the model. This means that velocity may not decrease with depth except for one group of adjacent velocity points. Hypocenters that occur within a low-velocity zone may produce a shadow zone at the surface, and rays in this distance range are calculated as if refracted along the layer above the low-velocity zone.

TTGEN can handle models with homogeneous layers, (zero gradients), but velocity discontinuities (infinite gradients) are not allowed. Velocity gradients should assume reasonable values such as 0.0 or between 0.02 and 8.0 km/s/km in the interest of numerical stability.

TTGEN operates by shooting rays out from the source and calculating time, distance, and other parameters where (and if) they emerge at the surface. Layers with steep gradients (such as might be used to model a Moho transition) can produce reverse branches in the travel-time curve, and such layers should be at least 0.3 km thick to insure that enough rays will bottom in the layer to define the travel-time curve properly. Errors can be introduced in the final travel-time table by under sampling a too complicated or irregular velocity model with too few rays.

➢ *6.3 Using TTGEN*

At depth intervals specified by the user, the program shoots rays with increasing ray parameter starting with vertically emergent rays, and calculates distance, travel time, and other parameters for each ray (see outputs of TTGEN section). At each depth, a printed listing of these results is produced, noting any reverse branches or rays lost to a low-velocity wave guide. The program then produces the final travel-time table by interpolating travel times at distance intervals specified by the user. Interpolation is done in the first arrival from among the various branches including refractions from the half space and top of a low-velocity zone.

➢ *6.4 Input to TTGEN*

All model parameters including depth, distance, and ray intervals at which computations are to be performed are specified in a velocity model file. The program uses reduced travel times for the table to save space. One specifies the inverse of the reducing velocity REDV (in s/km) to use in calculation. The reduced travel time is the absolute time minus distance multiplied by REDV. The values of reduced travel time passed to the location program with the table are limited to the range 0 to 32 s, and the user is responsible for choosing a suitable reducing velocity to stay within these limits. Using a reducing velocity equal to the half space velocity is a good choice.

The user specifies the amount by which the independent parameter Q is incremented to calculate the distance and time for rays of various ray parameter and emergence angle. The ray parameter P and the emergence angle PHI are functions of Q as follows:

$$PHI = 2\,\mathrm{TAN}^{-1}\left[\frac{Q}{Z_H + \frac{1}{2}}\right]$$

$$P = \frac{\mathrm{SIN}(PHI)}{V_H}$$

where:
Z_H and V_H are depth and velocity at the hypocenter, respectively.

Q is a better independent parameter than either P or PHI since it gives a greater density of rays for deeper penetrations. This also gives the distant travel-time points a distance spacing comparable to nearby points. The parameter Q is incremented as follows. It takes on the value 0.0 and NQ1 values at increments of DQ1, then NQ2 values at increments of DQ2. The largest value of Q is thus NQ1 * DQ1 + NQ2 * DQ2, and the greatest number of rays (maximum value of NQ1 + NQ2) is 200. Ray calculation stops when down-going rays begin to penetrate the half space, and travel times appropriate to a refracted ray are used beyond this point. Values of DQ1= .08, NQ1 = 100, DQ2 = 0.4, and NQ2 = 100 are a good first try, and generally insure that the entire travel-time curve can be adequately defined by less than 200 rays.

The grid points in distance and depth at which travel times are calculated for output to the final table are determined by eight parameters similar in concept to the Q parameters described above. Travel times are calculated at depths of 0.0 and NZ1 values at increments of DZ1, then NZ2 values at increments of DZ2. This permits a fine-grid spacing for shallow depths and a coarse spacing at greater depths where the travel-time curve will be smoother. Similarly, travel times are calculated at distances of 0.0, DD1, 2DD1, up to ND1 * DD1, and then at ND2 values in increments of DD2. Presently the maximum value of NZ1 + NZ2 is 27, and ND1 + ND2 may be as large as 41.

➢ *6.5 Velocity model input format (TTGEN prompts for name of this file)*

<table>
<tr><th>Record #</th><th>Columns</th><th>Format</th><th>Example</th><th colspan="2">Explanation</th></tr>
<tr><td>1</td><td>1-8</td><td>4A2</td><td>TTPR</td><td colspan="2">Name of file with information on run that may be printed.</td></tr>
<tr><td>1</td><td>9-16</td><td>4A2</td><td>TAB</td><td colspan="2">Name of file that will contain the new travel-time table. This is also used to create filenames of the form TABxxx where xxx = DEPTH. One such file is generated for each depth in travel-time table. Each file is designed for plotting a travel-time curve, and contains distance (km), travel time (s) and reduced travel time (s).</td></tr>
<tr><td>1</td><td>17-26</td><td>F10.2</td><td>0.12</td><td colspan="2">REDV, one over the reducing velocity used to condense the travel-time plots and tables.</td></tr>
<tr><td>1</td><td>27-36</td><td>F10.2</td><td>1.78</td><td colspan="2">Vp/Vs velocity ratio. (If negative, use this table for P and the next table for S)</td></tr>
<tr><td>*2</td><td>1-5</td><td>F5.2</td><td>08</td><td>DQ1</td><td rowspan="4">Parameters for incrementing the independent parameter Q governing ray spacing (see Text).</td></tr>
<tr><td>*2</td><td>6-10</td><td>I5</td><td>100</td><td>NQ1</td></tr>
<tr><td>*2</td><td>11-15</td><td>F5.2</td><td>04</td><td>DQ2</td></tr>
<tr><td>*2</td><td>16-20</td><td>I5</td><td>100</td><td>NQ2</td></tr>
</table>

*3	1-5	F5.2	4.	DZ1	Parameters for incrementing the grid spacing in depth (see text).
*3	6-10	I5	12	NZ1	
*3	11-15	F5.2	10	DZ2	
*3	16-20	I5	15	NZ2	
*4	1-5	F5.2	4.	DD1	Parameters for incrementing the grid spacing in distance (see text).
*4	6-10	I5	26	ND1	
*4	11-15	F5.2	15.	DD2	
*4	16-20	I5	15	ND2	
5	1-20	10A2	Alaska	Title to appear within travel-time table.	
*6	1-5	F5.2	5.6	Velocity of first point in model (km/s).	
*6	6-10	F5.2	0.0	Depth of first point (km). This format is repeated for each velocity-depth point of the model, one line per point, up to a total of 15 points. The first depth must be set to 0.0 km. The last point given sets the velocity and depth of the half space.	
*7	1-5	F5.2	5.9	Velocity of second point in model (km/s).	
*7	6-10	F5.2	4.0	Depth to second point of mode.	
Continue with remaining points of the velocity model.					

* All but records 1 and 5 are read in free format in this implementation.

➢ *6.6 Outputs of TTGEN*

The condensed travel-time table contains all the information necessary to identify itself and be used by HYPOELLIPSE. The printed output of TTGEN contains one tabulation for each depth grid-point. One line is printed for each ray calculation until the deepening rays reach the half space. The tabulated data is as follows:

J	Ray index used to reference rays defining the endpoints of a shadow zone or reversed branches.
Q	User-defined parameterizing variable. Equal increments of Q are designed to give a greater density of deeper rays where they are needed to define the travel-time curve.
EM.ANG	Emergence angle of ray at the source, measured in degrees from zenith.
P	Ray parameter in s/km.
DIST	Distance in km at which ray reaches the surface. If DIST = -1, then the ray is trapped in a wave-guide and does not reach the surface.
TIME	Travel time in s.
REDUCED	Reduced travel time in s, given by TTIME - DIST * REDV, where REDV is one over the reducing velocity.
L.BOT	Layer in which down-going rays bottom.
Z.BOT	Depth at which down-going rays bottom.
V.BOT	Velocity at which down-going rays bottom.
DDIF	Distance difference between this and the preceding ray. DDIF is negative on reverse branches.
BR	Branch number. It is incremented by 1 each time a new forward branch is encountered.
AMP	Relative amplitude of the ray at the surface assuming an isotropic source and geometrical spreading. It is just the ratio of the area of a ring on a unit sphere surrounding the source to the corresponding area at which rays emerge at the earth's surface.
AMP*R2	Amplitude times distance squared. Used to estimate the difference between actual and ideal inverse-square spreading.
REMK	Remark such as RB (reversed branch) or WG (ray in wave guide)