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7.3 HYPOSAT - A new routine to locate seismic events

Introduction

A new program, HYPOSAT, has been developed for the purpose of utilizing the largest possible set of available information for locating events.That means, besides the usually used travel times and eventually azimuth informations, this program also inverts for the observed ray parameters (or apparent velocities) as well as for travel-time differences between phases observed at the same station. To invert the ray parameter gives a weaker indication for the epicentral distance but the ray-parameter residual is a good criterion to identify phases and a large residual can also indicate a large azimuth error. Travel-time differences are usually used only in the case of surface reflections (pP or sP) to estimate the depth of the source or in cases where a single station alone observes P and S and an azimuth. With this program all possible travel-time differences can be used as additional observations. In the case of ideal error free data, these travel-time differences are a linear combination of the onset times and they cannot contribute new information to the inversions. But the situation changes in the case of erroneous and incomplete data (see the examples), which is usual for all location problems. All travel-time differences are dependent on the epicentral distance but not on the source time or systematic timing errors; the influence of source-depth errors and velocity anomalies below the stations is also reduced.

In the case of reflections (e.g. pP, sP, pS, sS, PmP, SmP, PcP, PcS, ScP, PcP, ScS) the travel-time difference to a direct phase is strongly influenced by the source depth. The usage of travel-time differences also decreases the influence of model uncertainties, because the travel-time differences are less sensitive for base line shifts between different models.

Intuitively, utilizing all this information for locating events should give a possibility of obtaining better location estimates (origin time, latitude, longitude, and depth). In the following, the program and its usage will be described in some detail, as well as some examples will be shown on event locations with and without the usage of travel-time differences.

Data input

The data input for this program are the models used to calculate the travel times, station informations and the observed data. The following points explain this in more detail:

a) In this version of the program the routine supports the following Earth models prepared for the tau-spline interpolation software of Buland & Chapman (1983): Jeffreys-Bullen (1940), PREM (Dziewonski & Anderson, 1981), IASP91 (Kennett & Engdahl, 1991), SP6 (Morelli & Dziewonski, 1993), and AK135 (Kennett et al., 1995).

b) Additionally, to locate events in local or regional distances, a model of horizontal layers eventually with discontinuities of first or second order can be defined and used for regional phases (Pg, Pb, Pn, Sg, Sb, Sn), their surface reflections (pPg, pPb, pPn, sSg, sSb, sSn), their multiples (PgPg, PbPb, PnPn, SgSg, SbSb, SnSn), and eventually their reflections from the Conrad or the Mohorovicic discontinuity (PbP, PmP, SbS, SmS).

c) Station coordinates in a NEIC-type list and eventually a file containing local P- and S-velocities below the stations to correct onset times for station elevation and possibly for a known velocity anomaly below this station.

d) File containing data for calculating the ellipticity corrections (Kennett & Gudmundsson, 1996).

e) Observed arrival times of all phases as defined in the IASP91 tables or the local/regional model and their standard deviations. As an option, the travel-time differences between phases arriving at the same station are calculated internally and used during the inversion.

f) Observed azimuth and ray parameter (apparent velocity) values from array or polarization measurements and their standard deviations.

g) If known, an initial solution for the hypocenter can be given, including its uncertainty.

The inversion

To get a relatively well defined starting epicenter, all available azimuth observations are used to calculate a mean solution of all crossing azimuth lines. If this fails, a single S-P travel-time difference and a single azimuth observed at the same station can also be used to define an initial epicenter. If this also is not possible, a starting epicenter is guessed either at the closest station or in the center of the station net.

The initial source time is derived from all S-P travel-time differences after Wadati (1933) or derived from the earliest onset time at the closest station.

Usually the location process of a seismic event is formulated as an iterative inversion of a linearized system of normal equations (Geiger, 1910). In this program this equation system is solved with the Generalized-Matrix-Inversion (GMI) technique (e.g. Menke, 1989) using the Single-Value-Decomposition algorithm (SVD) as published in Press et al. (1992). All partial derivatives - except those given by the tau-spline software (Buland & Chapman, 1983) - are calculated in the program during the inversion process and the Jacobi matrix is recalculated for each iteration. The iteration process stops, if the change between two different solutions falls below a predefined limit. Internal procedures test the quality and stability of a solution.

The given standard deviations of the observed data (independently given for every onset, azimuth, and ray parameter observation) are used respectively to weight the corresponding equation in the equation system. The parameters to be modeled (i.e. the source parameters) are weighted initially with the given (or calculated) uncertainties and later with the standard deviations of the modeled parameters, now used as 'a priori' information for the next iteration. This will keep relatively well defined model parameters mostly unchanged in the next iteration. E.g. if the epicenter is well defined by the data, the remaining observed residuals are used mainly to resolve source time and depth. In this version of the program the final standard deviations of the modeled parameters are given as the uncertainties of the estimated source. The calculation of 90% confidence error ellipses is planed for the next upgrade of the program.

All calculations are done for the spherical Earth; internally all latitudes are transformed into geocentric latitudes (Gutenberg & Richter, 1933). The input and output are always in geographic latitudes and longitudes; all standard deviations of the inverted coordinates are given in degrees. An output of the resolution, the correlation and the information-density matrix for the last iteration is optional.

The system of equations to be solved has the following form:

$$\begin{bmatrix} 1 & \frac{\partial t_1}{\partial lat} & \frac{\partial t_1}{\partial lon} & \frac{\partial t_1}{\partial z_o}\ldots \\ 1 & \frac{\partial t_i}{\partial lat} & \frac{\partial t_i}{\partial lon} & \frac{\partial t_i}{\partial z_o} \\ 0 & \frac{\partial dt_1}{\partial lat} & \frac{\partial dt_1}{\partial lon} & \frac{\partial dt_1}{\partial z_o}\ldots \\ 0 & \frac{\partial dt_j}{\partial lat} & \frac{\partial dt_j}{\partial lon} & \frac{\partial dt_j}{\partial z_o} \\ 0 & \frac{\partial p_1}{\partial lat} & \frac{\partial p_1}{\partial lon} & \frac{\partial p_1}{\partial z_o}\ldots \\ 0 & \frac{\partial p_k}{\partial lat} & \frac{\partial p_k}{\partial lon} & \frac{\partial p_k}{\partial z_o} \\ 0 & \frac{\partial azi_1}{\partial lat} & \frac{\partial azi_1}{\partial lon} & 0\ldots \\ 0 & \frac{\partial azi_l}{\partial lat} & \frac{\partial azi_l}{\partial lon} & 0 \end{bmatrix} \cdot \begin{bmatrix} \delta t_o \\ \delta lat \\ \delta lon \\ \delta z_o \end{bmatrix} = \begin{bmatrix} \Delta t_1\ldots \\ \Delta t_i \\ \Delta dt_1\ldots \\ \Delta dt_j \\ \Delta p_1\ldots \\ \Delta p_k \\ \Delta azi_1\ldots \\ \Delta azi_l \end{bmatrix}$$

where

$t_{1,i}$ - i travel times and their residuals $\Delta t_{1,i}$

$dt_{1,j}$ - j travel-time differences between two phases observed at the same station and their residuals $\Delta dt_{1,j}$

$p_{1,k}$ - k observed ray parameters (or apparent velocities) observations and their residuals $\Delta p_{1,k}$

$azi_{1,l}$ - l observed azimuth (from station to epicenter) observations and their residuals $\Delta azi_{1,l}$

δt_o - the calculated change in the source time for one iteration

δlat - the calculated change in the latitude for one iteration

δlon - the calculated change in the longitude for one iteration

δz_o - the calculated change in the source depth for one iteration (if not fixed)

Test examples

The following examples should illustrate the advantages of using travel-time differences as an additional parameter in the inversion. In the case of error-free onset observations, the travel-time differences are not independent from the absolute travel times and therefore they do not change the results of the inversions. But in the case of erroneous or insufficient data, the usage of travel-time differences can improve the result.

To demonstrate this, a synthetic example was chosen. The coordinates of the event are listed in the first row of Table 7.3.1. The travel times calculated for model AK135 (Kennett et al., 1995) to the stations ARCES, FINES, and NORES are listed in Table 7.3.2. These data were inverted to reestimate the theoretical source using different approaches. The results of these inversions are listed in Table 7.3.1. The solution and especially the depth estimation of this example is depending on the initial epicenter because of the disadvantageous geometry of source and observing stations.The initial epicenter for all further inversions was set to latitude 54.5° and longitude 21.5°; azimuth or ray parameter values and station corrections were not used for this test. In the first two inversions the original data were inverted once with and, once without the usage of travel-time differences (TTD). The solution in both cases is within some numerical limits the same. The differences between the two solutions and the differences to the theoretical location can be partly explained by the truncation of the input onset times to 1/100 s, partly by the usage of a finishing convergence criterion for defining a solution, and partly by the disadvantageous geometry. In a next step, the absolute onset times at FINES were disturbed by adding 1 s for both phases (Pn and Sn) to simulate a systematic timing error. Because the source depth was not longer resolvable in this case, it was fixed at 10 km (S1). In the next simulation (S2) the theoretical travel times were kept originally at FINES and NORES, but a 3 s delay was added for all onsets at ARCES. This was done to simulate a station at a larger distance with a weak onset leading to late picks for both Pn and Sn. In a last test (S3) all these effects were combined: the onsets at ARCES were 3 s delayed, for FINES Sn was 1 s delayed and Pn comes 1 s too early, and both onsets at NORES come 1 s too early.

In all cases with erroneous data (S1 - S3) the inversion with travel-time differences gives a solution closer to the 'true' source and the corresponding quality parameters (i.e. standard deviations and the rms values) are smaller, as it can be expected for a least squares fit with more data. This example clearly shows that the usage of travel-time differences helps to define the best location.

The 16 August 1997 event in the Kara Sea

Finally, the new program was used to locate the seismic event of 16 August 1997 in the Kara Sea. For this event the readings of the first P and the first S onsets were precisely picked at many stations in Fennoscandia and northern Russia. Table 7.3.3 contains all readings used to locate this event; included are also assumed reading errors for these onsets. One problem to locate seismic events in this region is that the appropriate model for the upper-mantle structure in the Barents Sea is not well known. Therefore this event was located with several global and regional models; all inversions used travel-time differences as additional data. The results for the different inversions are listed in Table 7.3.4. Also given are the locations published by the IDC (REB) and the NEIC (PDE, weekly). Note that the very small rms value for the IDC solution is due to the very small number of defining onset times (5), the other 6 defining data are azimuth and ray-parameter observations at the stations FINES, HFS, and NORES. Common for all solutions is that this event clearly occurred off-shore of Novaya Zemlya in the Kara Sea. But all different solutions including their given confidence regions span a region of about $2000km^2$, which is double of the uncertainty assumed necessary for verifying compliance with the CTBT.

In this study the global models PREM, IASP91 and AK135 and the regional models KCA (King & Calcagnile, 1976), NORSAR (Mykkeltveit & Ringdal, 1981), and FIN (as used in Helsinki for the Nordic Bulletin, e.g. Uski & Pelkonen, 1996) were used to calculate the epicenter either with a fixed depth at 0 km or at 10 km or to calculate the hypocenter of this event. Models KCA and NORSAR were only developed for P velocities, therefore the corresponding S velocities were calculated with a v_P/v_S ratio of $\sqrt{3}$.

Another open question of this event is its depth. PDE fixed the depth at 10 km and the IDC gave a fixed depth of 0 km, which means that both data centers were not able to invert the depth from their data with their model. Except for model KCA, which had been developed mostly for the lower part of the upper mantle, all solutions show smaller uncertainties for a fixed depth of 10 km than for 0 km. Finally the inversion also included the source depth. No stable solution could be found in this case for models IASP91 and KCA. The large depth of 112 km for model FIN is clearly wrong and for model AK135 the depth could only be determined with a wrong longitude. However, the two other solutions (for models PREM and NORSAR) prefer a hypocenter deeper than 10 km. In conclusion, all these results may indicate a depth of this event in the middle crust, although reservations must be made due to the low SNR and the lack of station specific calibration data at many stations.

In all cases, the uncertainties using the NORSAR model are the smallest, i.e. this model describes quite well the regional upper mantle for events in the Novaya Zemlya region observed in Fennoscandia and northern Russia. This confirms earlier work by Ringdal et al. (1997) about the advantages of this regional model.

Remark

The program HYPOSAT is available including all necessary data files, examples, a manual, and the source code. The newest version can always be found on the ftp-server of NORSAR (ftp.norsar.no) under /pub/johannes/hyposat.

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Table 7.3.1: Theoretical and inverted source coordinates either with travel-time differences (TTD) or without. The cases S1 - S3 have more or less biased onsets, for further details see text.

Time	Latitude [°]	Longitude [°]	Depth [km]	Location Error [km]	RMS [s]	Remarks
00:00:00.000	55.0000	22.0000	10.00			theoretical source
23:59:59.988 ±0.015	55.0022 ±0.0026	21.9990 ±0.0011	9.67 ±0.39	0.41	0.002	with TTD
23:59:59.985 ±0.018	55.0027 ±0.0030	21.9989 ±0.0012	9.60 ±0.46	0.51	0.002	without TTD
00:00:00.417 ±0.416	55.0016 ±0.0265	21.9244 ±0.0390	10.0 fixed	4.85	0.363	S1, with TTD
00:00:00.500 ±0.781	55.0069 ±0.0518	21.9171 ±0.0573	10.0 fixed	5.37	0.367	S1, without TTD
00:00:00.684 ±1.518	54.9728 ±0.0967	21.9053 ±0.1424	10.0 fixed	6.78	1.341	S2, with TTD
00:00:00.378 ±2.902	54.9516 ±0.1909	21.9063 ±0.2132	10.0 fixed	8.07	1.348	S2, without TTD
23:59:59.148 ±1.875	54.8996 ±0.1194	21.8362 ±0.1766	10.0 fixed	15.35	1.439	S3, with TTD
23:59:58.785 ±3.542	54.8752 ±0.2328	21.8489 ±0.2608	10.0 fixed	16.95	1.447	S3, without TTD

Table 7.3.2: The theoretically estimated onset times for the inversion tests of Table 7.3.1.

Station	Distance [°]	Phase	Onset Time
NORES	8.003	Pn	00:01:56.15
NORES	8.003	Sn	00:03:26.58
FINES	6.810	Pn	00:01:39.80
FINES	6.810	Sn	00:02:57.27
ARCES	14.676	Pn	00:03:27.28
ARCES	14.676	Sn	00:06:09.74

Table 7.3.3: The observed onsets of the 16 August 1997 Kara Sea event.

Station	Phase	Onset Time	Time Error	Azimuth	Azimuth Error
APA0	Pn	02:13:18.0	2.0		
APA0	Sn	02:15:00.0	2.0		
FINES	Pn	02:14:46.3	1.0		
HFS	P	02:15:42.5	0.5	24.0	15.0
JOF	Pn	02:14:09.9	1.0		
JOF	Sn	02:16:29.1	2.0		
KAF	Pn	02:14:39.4	1.0		
KBS	Pn	02:13:57.5	1.0		
KBS	Sn	02:16:08.1	2.0		
KEF	Pn	02:14:42.8	1.0		
KEV	Pn	02:13:25.2	0.5		
KEV	Sn	02:15:07.9	2.0		
KJN	Pn	02:14:12.7	1.0		
NORES	P	02:15:44.2	0.5	38.0	15.0
NRI	Pn	02:13:31.4	1.0		
NRI	Sn	02:15:19.1	2.0		
NUR	Pn	02:15:02.3	1.0		
PKK	Pn	02:15:07.1	1.0		
SDF	Pn	02:13:45.2	1.0		
SDF	Sn	02:15:44.7	2.0		
SPITS	Pn	02:13:44.3	0.5	106.0	15.0
SPITS	Sn	02:15:44.8	2.0	100.0	15.0
SUF	Pn	02:14:34.3	1.0		
VAF	Pn	02:14:41.4	1.0		

Table 7.3.4: Calculated hypocenters for the 16 August, 1997 Kara Sea event. Listed are the results of the international bulletins PDE (weekly) and REB and the solutions of this study for several models and source depth tests. The given uncertainties for the IDC and NEIC are 90% confidence limits and for the HYPOSAT solutions standard deviations. Additionally given is the number of defining data (#) and the rms-values for the used onset times.

Model	Origin Time	Latitude	Longitude	Depth [km]	#	RMS [s]
Data center solutions						
IDC (REB)	02:10:59.9 ±0.72 s	72.648° ±10.0 km	57.352° ±5.7 km	0.00 fixed	11	0.20
NEIC (PDEw)	02:10:59.77 ±1.03 s	72.835° ±17.0 km	57.225° ±10.3 km	10.00 fixed	7	1.4
Source fixed at 0.0 km						
PREM	02:11:01.695 ±1.304 s	72.4730 ±0.1102°	56.9182 ±0.3443°	0.00 fixed	33	5.844
IASP91	02:10:59.338 ±1.371 s	72.5256 ±0.1172°	56.9143 ±0.3662°	0.00 fixed	33	6.305
AK135	02:10:59.247 ±1.239 s	72.5181 ±0.1060°	56.9676 ±0.3308°	0.00 fixed	33	5.682
FIN	02:11:03.139 ±0.982 s	72.5176 ±0.0873°	57.2926 ±0.2724°	0.00 fixed	33	3.181
KCA	02:10:59.968 ±0.360 s	72.4594 ±0.0317°	57.4922 ±0.0940°	0.00 fixed	30	1.327
NORSAR	02:11:00.404±0.309 s	72.4439 ±0.0274°	57.4362 ±0.0835°	0.00 fixed	31	1.164
Source fixed at 10.0 km						
PREM	02:11:02.894 ±1.202 s	72.4691 ±0.1017°	56.9573 ±0.3173°	10.00 fixed	33	5.397
IASP91	02:11:00.561 ±1.300 s	72.5250 ±0.1114°	56.9451 ±0.3477°	10.00 fixed	33	5.967
AK135	02:11:00.481±1.183 s	72.5184 ±0.1014°	56.9931 ±0.3162°	10.00 fixed	33	5.409
FIN	02:11:04.315 ±0.915 s	72.5154 ±0.0814°	57.3269 ±0.2536°	10.00 fixed	33	2.897
KCA	02:11:00.969 ±0.382 s	72.4589 ±0.0337°	57.5118 ±0.1000°	10.00 fixed	30	1.435
NORSAR	02:11:01.536 ±0.276 s	72.4442 ±0.0245°	57.4672 ±0.0748°	10.00 fixed	31	1.075
Free depth						
PREM	02:11:06.182 ±1.280 s	72.4937 ±0.0874°	56.4632 ±0.3180°	25.42 ±17.87	32	3.780
AK135	02:11:10.753 ±2.150 s	72.6046 ±0.0523°	54.7204 ±0.4121°	28.05 ±23.92	30	2.377
FIN	02:11:10.179 ±0.591 s	72.5538 ±0.0493°	57.4424 ±0.1511°	112.02 ± 9.42	33	2.147
NORSAR	02:11:02.152 ±0.630 s	72.4443 ±0.0247°	57.4840 ±0.0767°	15.43 ± 5.19	31	1.080