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HYPOSAT – An Enhanced Routine to Locate Seismic Events

JOHANNES SCHWEITZER[1]

Abstract—A program package, called HYPOSAT, has been under development that attempts to use the maximum information possible to estimate the hypocenter of a seismic source. The standard input parameters can be used: arrival times of first and later onsets with backazimuths and ray parameters (or apparent velocities). In addition, travel-time differences between different phases observed at the same station can be optionally used. The observed standard deviations are used to weight all input parameters and the inversion is done with a generalized matrix inversion code.

A starting solution with *a priori* uncertainties can be calculated as the intersection of all backazimuth observations. If S observations are also available, a preliminary origin time is estimated using Wadati's approach to estimate a source time.

Global earth models and user-defined horizontally layered local or regional models can be used alone or together to locate seismic events. To gain the best result from all input data, observations of all seismic phases as defined in the IASPEI91 tables can be inverted. Station corrections and corrections for phases with reflection points at the earth's surface can be applied by using local velocity structures.

Key word: Hypocenter inversion.

Introduction

Since the early days of seismology, seismologists have tried to locate the source of observed seismic waves in space and time. The precision of the estimated locations has always depended strongly on our knowledge of the distribution of seismic velocities inside the earth. That is, seismic event locations are only true locations within the framework of the applied velocity model, and all estimated uncertainties must be considered in relation to other hypocenter solutions using the same model.

Although many modern location routines are based on nonlinear inversion techniques, the approach of GEIGER (1910, 1912) is still the most frequently applied algorithm today. He solved the nonlinear problem of hypocenter determination with a step-wise linearized least-squares algorithm. Limitations in computing capabilities were the reason for concentrating on the inversion of first P onsets for the next 50 years after Geiger. As computer facilities became more readily available, it became possible to include larger data sets and to develop new ideas. Location programs like

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[1] NORSAR, P. O. Box 51, N-2027 KJELLER, Norway. E-mail: johannes@norsar.no

HYPO71 (Lee and Lahr, 1972), HYPOINVERSE (Klein, 1978), and HYPOCENTER (Lienert *et al.*, 1986) came into use worldwide for local and regional events. Another important step was the development of the seismic array concept which created the possibility of measuring more accurately the slowness vector of an observed seismic phase, and algorithms to locate events with this parameter became available (e.g., Lilwall and Douglas, 1968; Gjøystdal *et al.*, 1973). Bratt and Bache (1988) combined the array location procedures with the classical travel-time inversion in the program TTAZLOC. However, this program was based on ideas already published at the beginning of the 20th century, when Abt (1907) observed the propagation of seismic phases over a net of seismic stations by assuming a plane-wave propagation. He located earthquakes by taking the backazimuth from the observed slowness vector and calculated the epicentral distance from the travel-time difference between the different onsets. A newer version of TTAZLOC, called LOCSAT, is now in use at the prototype International Data Center (pIDC) being developed to monitor the Comprehensive Nuclear-Test-Ban Treaty (CTBT). Lienert and Havskov (1995) published a new version of HYPOCENTER, which was also able to invert for later phases, backazimuth, slowness observations, and explicitly given travel-time differences between different phases observed at one station.

However, in 1996 at the Ruhr-University Bochum, I started to develop my own program, called HYPOSAT, for the purpose of utilizing the largest possible set of available information for locating events. This program has similarities with other location programs but also newer ideas or newly combined features which will be explained in this contribution. The algorithm can invert travel times of all P- and S-type onsets, for which travel-time information is available, backazimuth observations, ray parameters (or apparent velocities), and if desired travel-time differences between phases observed at the same station. Using the ray parameter in an inversion gives a relatively weak indication of the epicentral distance, however the ray parameter is a good criterion to identify (especially later) phases, and a large ray-parameter residual for an otherwise defined phase may also indicate problems with corresponding backazimuth estimation.

The Concept of HYPOSAT

The Starting Solution

For every hypocenter determination it is necessary to define the data used and the kind of corrections applied to increase the quality of the determination. For this purpose, a location program is needed, which is open for all input parameters and for various corrections.

Event location procedures are defined as iterative processes. The first step in determining a hypocenter is the definition of a starting solution for the iterations. If no preliminary hypocenter information is available, the starting solution must be derived from the input data. Because the installation of seismic arrays and the polarization analysis of signals at 3C stations has increased in recent years, measuring the backazimuth of a seismic onset is an increasingly common feature. These backazimuth observations are very useful for determining a starting solution. Taking all backazimuth observations from the different phases at the different stations, a first estimate of the epicenter can be derived by calculating the mean point of all intersections of the backazimuth directions. From the scatter of all these intersections and the uncertainties of the single backazimuth observations, an uncertainty for this starting epicenter can also be derived. If insufficient data are available, other methods must be used for such a determination, e.g., single array locations.

The next parameter of a starting solution is the source time. If P-type and S-type onsets are both reported, a simple method to obtain a source time is Wadati's approach (WADATI, 1933). Searching for S-P, Sn-Pn, Sb-Pb, and Sg-Pg travel-time differences at all stations, and sorting these travel-time differences for phase types, one can easily calculate a source time using Wadati's formula for each phase type separately. The source time of the starting solution and its standard deviation can now be calculated as the mean value of all source times after weighting with the uncertainties of the single phase readings.

The depth of an event should be either *a priori* fixed, inverted from the beginning or the inversion should be able to start with a fixed depth which will be freed for the final iterations, after a stop criterion has been reached.

Theoretical Travel Times

A location routine should capably handle observed data from all epicentral distances. Therefore different velocity models are needed: for teleseismic observations the standard radially symmetric earth models should be available. In the program, the models JEFFREYS-BULLEN (1940), PREM (DZIEWONSKI and ANDERSON, 1981), IASPEI91 (KENNETT and ENGDAHL, 1991), SP6 (MORELLI and DZIEWONSKI, 1993), and AK135 (KENNETT *et al.*, 1995) are implemented. To calculate the travel time and all derivatives with respect to distance and source depth, these models were prepared to be used by the tau-spline interpolation software of BULAND and CHAPMAN (1983).

However, these global models are usually not the right choice at local or regional distances. Here different models should be usable together with the global one. Therefore regional models of horizontal layers can be defined for which travel time and all derivatives can be calculated. In addition to the phase list of the tau-spline software, it should also be possible to calculate reflections from the Conrad and/or the Mohorovicic discontinuity. The implemented algorithm for regional models includes the corrections needed to transform a horizontally layered model into layers of the spherical earth (MÜLLER, 1977). If desired, a local or regional velocity model should be derivable from published crustal models. The possibility of deriving by bilinear interpolation, velocity models of source regions from the published model CRUST 5.1 (MOONEY *et al.*, 1998) was implemented.

Corrections

Velocity models contain neither the effect of topographic differences between seismic stations nor the differences in the local seismic velocities below the seismic stations. Adding station-dependent local P- and S-velocities, the observed onset times should be corrected for these effects with respect to phase type and incidence angle of the actual phase.

Following the ideas of Engdahl *et al.* (1998) a location routine should be able to correct surface reflections (e.g., pP, sP, sS, PP, P'P', ...) for the local velocity structure at the reflection points. The corrections should be calculated by using the actual ray parameter (i.e., incidence angle) of the reflection and estimating the travel time and distance effect for the velocity model at the reflection point, both in the global model and the local model. The difference between these two estimates then gives the corresponding correction. The model CRUST5.1 was also implemented here to interpolate for crustal velocities and elevations (or sea depth) at the actual reflection points.

Because all velocity models are derived for the earth as a sphere and not as an ellipsoid, this must be corrected. The program uses ellipticity corrections to calculate theoretical travel times. Therefore, all internal calculations must be done in geocentric instead of geographic latitudes (GUTENBERG and RICHTER, 1933), and the travel times must be corrected for the ellipticity of the earth. Ellipticity corrections either provided by KENNETT and GUDMUNDSSON (1996) or listed in the IASPEI91 tables are used.

Observations

As observations, the onset times of all seismic phases as defined in the IASPEI91 tables or by the local/regional model should be available for the inversion. Usually, seismic events are well defined by inverting for the first P onsets and some S observations. However, the possibility of inverting for all later phases is important in all cases in which only a small amount of observed data is available. The same is valid for slowness observations: to invert for backazimuth and ray parameter is far more important for events observed only at some stations than for well observed ones. The usage of slowness observations may become even more important when slowness corrections will be available for more seismic arrays and 3C stations (e.g., SCHWEITZER, 2001). In addition, the standard deviations of all observations should be given so that all input parameters can be adequately weighted.

As an option, the travel-time differences between phases arriving at the same station should be internally calculable and usable during the inversion. In the case of ideal, error-free data, these travel-time differences are a linear combination of the directly measured onset times and they cannot contribute new information to the inversion. However the situation changes in the case of erroneous and incomplete data (see the examples), which is the general case in 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, ScS) the travel-time difference between these phases and a direct phase is strongly influenced by the source depth and less dependent on the epicentral distance. The usage of travel-time differences can decrease the influence of model uncertainties, because the travel-time differences are less sensitive to base-line shifts between different models. However, because the systematic errors and the quality of the travel-time difference measurements are unknown, the best method for calculating standard deviations of travel-time differences is to derive them from the standard deviations of the single phases.

Intuitively, utilizing all this information for locating events should present a possibility of obtaining better location estimates (origin time, latitude, longitude, and depth).

The Inversion

Most frequently, the location process of a seismic event is formulated as an iterative inversion of a linearized system of normal equations (Geiger, 1910, 1912). In this program this equation system is solved with the Generalized-Matrix Inversion (GMI) technique (e.g., Menke, 1978) using the Single-Value Decomposition algorithm (SVD) as published in Press *et al.* (1992). This inversion technique was chosen because subsequently further information can also be retrieved pertaining to the quality of the inversion, i.e., the information density matrix can aid removal of unimportant input data, the resolution matrix explains the quality of the inverted parameter, and the covariance matrix can be used to analyze the trade-off between the modeled parameter. In addition, it is easy to weight the equation system with the *a priori* uncertainties of the hypocenter parameters to be modeled.

In the location routine presented here, all partial derivatives are calculated during the inversion process and the Jacobi matrix is recalculated and reconstructed for each iteration. The standard deviations of the observed data (independently given for every onset, backazimuth, and ray-parameter observation) are used respectively to weight the corresponding equation in the equation system. The given (or calculated) uncertainties of the parameters to be modeled (i.e., the source parameters) are initially used to weight the inversion. For a new iteration the equation system is always reweighted with the standard deviations of the modeled parameters as calculated during the former iteration, now used as *a priori* information. This will keep relatively well-defined model parameters mostly unchanged in the next iteration. For example, if the epicenter is well defined by the data, the remaining observed residuals are then used mainly to resolve source time and depth. The final standard deviations of the modeled parameters are given as the uncertainties of the estimated solution.

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

$$\begin{bmatrix} 1 & \frac{\partial t_i}{\partial \mathrm{lat}} & \frac{\partial t_i}{\partial \mathrm{lon}} & \frac{\partial t_i}{\partial z_o} \\ 0 & \frac{\partial dt_j}{\partial \mathrm{lat}} & \frac{\partial dt_j}{\partial \mathrm{lon}} & \frac{\partial dt_j}{\partial z_o} \\ 0 & \frac{\partial p_k}{\partial \mathrm{lat}} & \frac{\partial p_k}{\partial \mathrm{lon}} & \frac{\partial p_k}{\partial z_o} \\ 0 & \frac{\partial azi_l}{\partial \mathrm{lat}} & \frac{\partial azi_l}{\partial \mathrm{lon}} & 0 \end{bmatrix} \cdot \begin{bmatrix} \delta t_o \\ \delta \mathrm{lat} \\ \delta \mathrm{lon} \\ \delta z_o \end{bmatrix} = \begin{bmatrix} \Delta t_i \\ \Delta dt_j \\ \Delta p_k \\ \Delta azi_l \end{bmatrix} \tag{1}$$

where

t_i – rows with travel times and their residuals Δt_i

dt_j – rows with travel-time differences between two phases observed at the same station and their residuals Δdt_j

p_k – rows with observed ray parameter (or apparent velocity) observations and their residuals Δp_k

azi_l – rows with observed backazimuth (from station to epicenter) observations and their residuals Δazi_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)

One known problem of inverting for hypocenter solutions is the occurrence of oscillations between a set of hypocenter solutions. In this case, the iteration process is automatically interrupted by calculating the mean values for all hypocenter parameters as new starting solutions for the next iteration, and this helps to resolve the global minimum of all solutions. If only the depth is oscillating (together with the source time), the depth will be automatically fixed at the mean value of all solutions or at the earth's surface.

Test Examples

A Synthetic Test

The following examples are meant to illustrate the advantages of using travel-time differences as additional parameters in the inversion. In the case of error-free onset observations, the travel-time differences are linear combinations of the absolute travel times and therefore they do not change the inversion results. 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 1. The travel times calculated for model AK135 (Kennett *et al.*, 1995) to the stations ARCES, FINES, and NORES are listed in Table 2, and Figure 1 shows a map with the seismic stations and the hypothetical event. These data were inverted to reestimate the theoretical source using different approaches. The results of these inversions are also listed in Table 1. The solution and especially the depth estimation of this example depends 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°; backazimuth or ray parameter values 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 numerical limits, the same. The differences between the two solutions and the differences from 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 the 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 no longer resolvable in this case, it was fixed at 10 km (S1). In the next simulation (S2) the theoretical travel times were unaltered 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 the last theoretical test (S3) a combination of such effects was introduced: the onsets at ARCES were 3 s delayed, for FINES Sn was 1 s delayed and Pn was made to come 1 s too early, and both onsets at NORES were 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.

A Case Study: The November 11, 1999 Explosion in the Dead Sea

Finally, the new program HYPOSAT was used to locate an explosion in the Dead Sea. On November 11, 1999 the Geophysical Institute of Israel (GII) blasted a charge of 5 ton TNT in a water depth of ca. 70 m in the Dead Sea as a calibration shot for the CTBT (see Table 4). GII published the exact coordinates of this explosion and it was observed by some of the seismic stations contributing data to the pIDC. Table 3 lists all parameters of the onsets associated by the pIDC to this event and used in

Table 1

Theoretical (first line) and inverted source coordinates with and without travel-time differences (TTD). 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 2

The theoretically calculated onset times for the inversion tests of Table 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

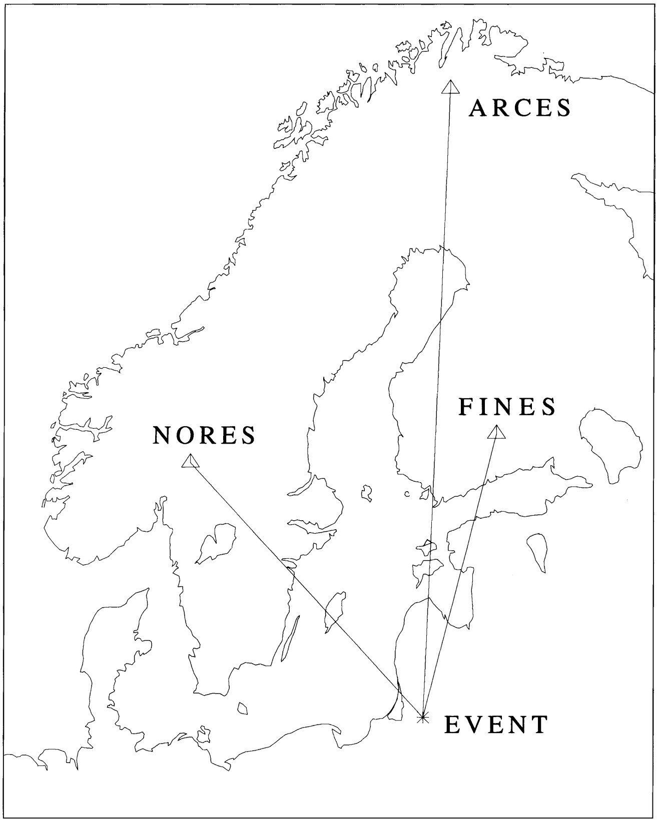

Figure 1
Map showing the locations of the seismic arrays (triangles) and the theoretical test event (star) to demonstrate the advantage of including travel-time differences in the inversion process (for details see text).

their location as published in their bulletin (REB): the pIDC location is quite precise with only a small location error of 2.45 km. These pIDC data were used as input for HYPOSAT and the event was relocated with several options. In all relocations with

HYPOSAT, the IASPEI91 model was used as the theoretical model. Without any further information about the local structure below the different stations, all elevation effects were corrected with the same velocities (V_p = 5 km/s, V_s = 2.89 km/s), which are slightly lower than the uppermost velocities in IASPEI91. However, no other model modifications were applied.

Using all intersections of the listed backazimuth observations (43 combinations could be used), a starting epicenter (latitude 37.7 ± 13.7°, longitude 34.9 ± 4.8°) could be estimated. Comparing this epicenter with the true one, the discrepancy for the latitude of about 690 km too far to the north is obvious, although the error in the longitude of approximately 50 km is relatively small. However, the known location is inside the estimated uncertainties of this starting solution. The Wadati analysis of the S-P onset times gave a preliminary source time of 15:00:07.665 ± 1.404 s which is about 8 s too late with respect to the true origin time. Consequently, this starting solution is not the best choice with respect to the two regional stations, however with respect to the teleseismic observations this epicenter is a usable solution as a first guess.

After trial inversions it became clear that ray parameter and backazimuth data contribute very little to the final inversion because of their large uncertainties (Table 3). Therefore they were not used further. Also the inversion for the source depth showed that this parameter has a very low resolution in this case and was therefore fixed at 0 km.

To demonstrate with real data the different effects in using travel-time differences as an additional condition, the following relocations were tried: "HYPOSAT 1" is the result using all observed travel times but no travel-time differences. If one looks at the absolute location error of 3.04 km (see Table 4), the location routine works quite well. "HYPOSAT 2" uses travel-time differences but not the absolute travel times of the corresponding phases. That is, the two regional stations contributed in this case only with their travel-time differences. Not surprisingly, the location error is now larger (5.32 km). In "HYPOSAT 3" the travel-time differences were used and in addition the absolute travel times of the corresponding P onsets to fix the absolute timing. The error of 2.76 km is now smaller with respect to the first tests. "HYPOSAT 4" displays the opposite configuration: the usage of the absolute travel times of the S onsets and the travel-time differences. In this case the error becomes larger again. In a final test ("HYPOSAT 5") all absolute travel times and all possible travel-time differences were used. The differences in the location errors are relatively small, but again, the result including both the absolute travel times and travel-time differences exhibits the smallest absolute location error of only 2.39 km. This demonstrates the advantage of including travel-time differences as additional data in the inversion process to find the best solutions.

Table 3

Observed onsets of the November 11, 1999 Dead Sea explosion as measured at the pIDC including their standard deviations (STD). The phase identification in parentheses is from HYPOSAT and the distances are the theoretical ones.

Station	Phase	Distance [deg]	Onset Time ± STD	Azimuth [deg] ± STD	slowness [s/deg] ± STD
MRNI	Pg(Pn)	1.475	15:00:28.34 ± 0.120	348.52 ± 11.5	15.68 ± 3.15
MRNI	Lg(Sg)	1.475	15:00:48.491 ± 0.424	300.14 ± 07.4	19.93 ± 2.57
EIL	Pn	1.905	15:00:34.626 ± 0.120	25.86 ± 09.4	12.56 ± 2.07
EIL	Lg(Sn)	1.905	15:01:00.901 ± 1.002	20.39 ± 09.2	14.20 ± 2.28
MLR	Pn	15.777	15:03:45.880 ± 1.070	23.65 ± 15.6	11.22 ± 3.06
GERES	P	23.839	15:05:16.325 ± 0.838	127.41 ± 23.8	11.06 ± 4.12
ARU	P	29.656	15:06:06.085 ± 1.049	202.23 ± 37.8	10.67 ± 6.91
BGCA	P	30.699	15:06:18.063 ± 1.070	355.36 ± 17.5	13.49 ± 4.11
ESDC	S	32.807	15:06:35.350 ± 0.765	98.58 ± 08.6	7.29 ± 1.09
PDYAR	P	56.913	15:09:48.200 ± 0.966	267.82 ± 20.0	8.48 ± 2.94

Table 4

Hypocenters for the November 11, 1999 Dead Sea explosion. Listed are the hypocenter as announced by the Geophysical Institute of Israel (GII), the epicenter published by the pIDC (REB), and the results of several relocations using the HYPOSAT routine (for details see text). The given uncertainties are, for the pIDC solution, the 90% confidence limits, and for the HYPOSAT solutions, the standard deviations of the calculated source parameters. Additionally given is the number of defining data (#), the RMS values for the absolute arrival times used, and the absolute horizontal location error. The number of definings contains both the number of absolute travel times and the number of travel-time differences used for the inversion. For details of the different HYPOSAT solutions, see text. The source depth was fixed for all inversions at 0. km.

Model	Origin Time	Latitude [deg]	Longitude [deg]	#	RMS [s]	Error [km]
GII	15:00:00.795	31.5336	35.4413	–	–	–
pIDC (REB)	15:00:00.78 ± 1.21	31.5199 ± 17.0 km	35.4616 ± 10.3 km	10	0.89	2.45
HYPOSAT 1	15:00:00.595 ± 0.760	31.5520 ± 0.0091	35.4651 ± 0.0926	10	0.883	3.04
HYPOSAT 2	15:00:01.034 ± 0.555	31.5744 ± 0.0253	35.4709 ± 0.1072	8	1.067	5.32
HYPOSAT 3	15:00:00.615 ± 0.181	31.5508 ± 0.0096	35.4623 ± 0.0918	10	0.962	2.76
HYPOSAT 4	15:00:00.893 ± 0.427	31.5733 ± 0.0136	35.4678 ± 0.0911	10	0.958	5.07
HYPOSAT 5	15:00:00.633 ± 0.161	31.5550 ± 0.0081	35.4440 ± 0.0828	12	0.903	2.39

Remarks

HYPOSAT employs the new version of the regionalization in seismic units (YOUNG *et al.*, 1996). The program will be further developed and is open to new ideas and improvements, and its use is therefore encouraged. For instance, the method of uniform reduction to handle long-tailed residual distributions (JEFFREYS, 1932) as an alternative weighting method of the observations, the usage of travel-time differences to test the plausibility of phase identifications, and the calculation of confidence ellipsoids for the determined hypocenter are planned for the next implementation of the program. The program HYPOSAT is available including all necessary data files, examples, a manual, and the source code. The newest version can be found on the ftp server of NORSAR (ftp.norsar.no) under/pub/outgoing/johannes/hyposat.

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