HYPOSAT 6.2 and HYPOMOD 2.2 – The User Manual

Johannes Schweitzer

ORCID: 0000-0002-5986-1492

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1 INTRODUCTION

HYPOSAT is a program developed to locate single seismic sources and **HYPOMOD** is a program to calculate residuals of observed data for a given seismic source location. Both programs utilize observed onset time, backazimuth (*i.e.*, station-to-event azimuth, BAZ) and ray-parameter observations. Additionally, all possible travel-time differences between different onsets at individual stations can be included in the location process (*e.g.*, the onset-time difference between the phases PcP and P ($t_{PcP} – t_P$) gives additional constraint for the source depth). If amplitude and period measurements are available for P or S onsets or for surface waves, individual station and network magnitudes can also be estimated. The files ***HYPOSAT_HISTORY.md*** and ***HYPOMOD_HISTORY.md***, which are part of the program documentation, contain listings of the program versions and main changes from version to version.

For clarity, all file names in this Manual are written in bold ***italics***. This document and all **HYPOSAT / HYPOMOD** output are consequently using the phrases 'location uncertainty', 'model uncertainty' and 'data uncertainty' instead of 'location error', 'model error' and 'data error' and it is clearly distinguished between the terms 'backazimuth' and 'azimuth', where backazimuth (BAZ) is used for defining the direction from the station to the epicenter measured from North clockwise over East in [°].

Seismic phases considered in both programs are those included in IASPEI 1991-type travel-time tables. The program follows the seismic phase name convention as recommended by IASPEI on its General Assembly in Sapporo, in July 2003 (Storchak *et al.*, 2002; 2003; 2006; 2009; 2011; Bormann *et al.*, 2013; Schweitzer *et al.*, 2021a). A software package (*libtau*-software) for travel-time-table calculations for spherical Earth models is distributed with the IASPEI 1991 tables. It is based on the tau-spline algorithm (Bulland & Chapman, 1983) and was implemented and modified here so that all precalculated data files become platform independent ASCII files. In addition to the original software version, diffracted PKPbc and double surface reflections of body waves (*e.g.*, PPP or S'S'S'), depth phases for surface reflections (pPP & sSS, pP'P' *etc.*), depth phases of core reflections (pPcP, sScS), single surface reflections of core phases (PcPPcP & ScSScS) as well as S3KS were included in the travel-time-table calculations. Reflections from the Conrad discontinuity – in the following abbreviated as 'the Conrad' – (PbP, SbS) and the Mohorovičić discontinuity – in the following abbreviated as 'the Moho' – (PmP, SmS), are included if local/regional seismic velocity models are used.

For most of the phases or their proxies, ellipticity corrections are automatically calculated with the adapted software of Kennett & Gudmundsson (1996). Instead of the original Kennett & Gudmundsson coefficients, the program uses the updated and corrected set of coefficients from Russell *et al.* (2022). However, note that for double surface reflections (*e.g.*, PgPgPg, SnSnSn, PPP, SSS, P'P'P' *etc.*), ellipticity corrections cannot be applied at this moment.

Since **HYPOSAT 6 / HYPOMOD 2** (see Schweitzer, 2018) the global crustal model Crust 5.1 (Mooney *et al.*, 1998) with 5° x 5° resolution has been replaced by the global crustal model CRUST 1.0 (Laske *et al.*, 2013) with 1° x 1° resolution. With **HYPOSAT 6.1 / HYPOMOD 2.1**, the usage of CRUST 1.0 is extended: when requested, the program can now correct reflections at the Earth's surface not only for topography but also for the water-depth of oceans and larger lakes (as far as defined in CRUST 1.0); for further details see Schweitzer (2025). With this change, pwP-type phases are now included, but the program will also correct all types of P- or S-phase reflections at the surface and may change the phase name accordingly. As an extension to the IASPEI phase-name convention (Storchak *et al.*, 2002; 2003; 2006; 2009; 2011; Bormann *et al.*, 2013; Schweitzer *et al.*, 2021a), **HYPOSAT** / **HYPOMOD** allow not only pP changing to pwP but also *e.g.*, PP to PwP or P'P' to P'wP').

HYPOSAT runs in an iterative mode, in which each iteration step is based on the solution of an equation system with the Generalized Matrix Inversion (GMI) (see *e.g.*, Bolt (1970) and Niewiadomski (1989) or the textbooks of Aki & Richards (1980) or Menke (1989)). All partial derivatives for the matrix inversion are recalculated before each iteration. After each iteration, the program evaluates the inversion results and either continues with another iteration step or stops all processing and generates an output with the location results. The user can steer this processing with different options for the usage of the input data and theoretical travel-time models and additional parameters for the inversion itself (see Chapter 3). More details about the program features can also be found in Schweitzer (1997; 2001; 2002; 2006; 2018; 2025), Schweitzer & Kennett (2007) and Schweitzer *et al.* (2021b).

To invert for a seismic event location, the program reads a set of ASCII-formatted input files. Two files are user defined input files. One file contains the observed data for the event to be localized (***hyposat-in***) and the other file contains a list of parameters to steer this inversion process (***hyposat-parameter***). The location results will be written in the file ***hyposat-out***. The contents and structure of these files will be explained in the following three Chapters of this Manual. The program **HYPOMOD** (see for further details Chapter 5) uses the same input files as **HYPOSAT** but writes its results in the file ***hypomod-out***.

In addition, there are a number of files containing static input data for the travel-time-table calculations in global spherical Earth models (*e.g.,* ***iasp91_A.tbl*** and ***iasp91_A.hed***), the ellipticity corrections (***elcordir.tbl***), all data defining the global crustal model CRUST 1.0 (***crust1.vp***, ***crust1.vs***, ***crust1.bnds***) of Laske *et al.* (2013), crustal models of the global models (***std_crusts.dat***), attenuation corrections for magnitude estimations (***MB_G-R.DAT***, ***MB_V-C.DAT***, ***MB_M-R.DAT***, ***MLCORR.TABLE***, ***MLCORR.TBALE.wa***, ***MLCORR.TABLE.nicolas***), ISC default-depth definitions (***isc_def_depth.dat***, ***grn_def_depth.ak135.dat***), the file with the geographic coordinates of the stations ***stations.dat*** and a list of European seismo-tectonic units (***REG_L3.DAT***, see *e.g.*, Lindholm et al., 2000). These static files must be either located in the run-directory or in a shared directory defined by the environment variable **HYPOSAT_DATA**. For some files, alternative directories can be set in ***hyposat-parameter***; for further details see Chapter 3.

The newest version of **HYPOSAT** and **HYPOMOD** (including source code, this Manual, the PDF version of Schweitzer (1997), data files containing travel-time models and station parameters, and several examples) are available from GitHub for free download. The software is written in Fortran, C or C++ and was developed and tested with the GNU Compiler Collection (GCC) on LINUX PCs and Intel® compilers in a WINDOWS 10 and Windows 11 environment. For instructions on installing **HYPOSAT** and **HYPOMOD** on your computer, please consult the documentation on GitHub (https://github.com/NorwegianSeismicArray/Hyposat).

All older software-package versions are obsolete, as well as testing the implementation in a SUN (Solaris) environment, and are no longer supported. Be also aware, that the previous option to download the software package from NORSAR's anonymous FTP address *ftp.norsar.no* is no longer supported from version **HYPOSAT 6.1 / HYPOMOD 2.1** on.

Questions related to program updates and maintenance should be directed to the author.

2 THE *hyposat-in* FILE

HYPOSAT needs as input a file with all the observed data for a specific event: This file has by default the name ***hyposat-in***, but another name can be defined in the parameter file ***hyposat-parameter***. Be aware that the format of this file has slightly changed in **HYPOSAT 6**. If you have older formatted files, this must be indicated in the ***hyposat-parameter*** file (see Chapter 2). The data input file must have the following format:

1st line: any title for event identification of maximum 80 characters (used also in the output-file ***hyposat-out***).

2nd – to (n+1)th line for n observed onsets. These lines **must** (!) be compatible with the following format (Fortran: 'a' is ASCII string, 'i' is integer number, 'f' is floating-point number, 'x' is a separating blank space):

(a5,1x,a8,1x,i4,4(1x,i2),1x,f6.3,1x,f5.3,1x,f6.2,3(1x,f5.2),1x,a7,1x,f6.3,1x,f12.2,1x,f7.2,1x,a8,1x,f5.2)

station id (a5), phase name (a8), year (i4), month (i2), day (i2), hour (i2), minute (i2), second (f6.3), standard deviation (STD) of the onset time (f5.3), backazimuth (BAZ) (f6.2), standard deviation of the BAZ observation (f5.2), either slowness or ray parameter [s/deg(ree) or s/°] or apparent velocity [km/s] (f5.2) (see the parameter setting with **SLOWNESS [S/DEG]** in the file ***hyposat-parameter*** in § 3.5.5) and standard deviation of the slowness or the apparent velocity observation in [s/°] or [km/s] (f5.2).

If the type of the P or S onset is unknown, you can use the phase names **P1** or **S1** to indicate that this is the 1st P-type or the 1st S-type onset at this station. Then, the program chooses the right phase name depending on the epicentral distance of the observation and the employed travel-time table.

Following the IASPEI standard, phases named **tx (TX)** , **rx (RX)** , **x (X)** , **Px (PX)** or **Sx (SX)** are assumed to be unknown phase onsets. Then, onset time and slowness will not be included in the inversion. After the inversion, the program will search for the best fitting seismic phase and list it as used phase name.

For each phase name not defined by the applied travel-time model(s), the program searches for the best fitting phase. However, onset time and slowness or ray parameter of such a phase are not used in the inversion, but the BAZ information may be used if the parameter **USE ALL BAZ INFORMATION** is set in ***hyposat-parameter*** (see § 3.5.4).

If an onset time, a BAZ, or a slowness value is given without its standard deviation, the following default values are used: onset time 2 s; BAZ 30° (40° for LQ and LR); slowness or ray parameter 5 s/° (any apparent velocity in [km/s] input will be internally converted to [s/°]). If BAZ or slowness values are not available, these places can stay blank, or they must be set to '-999.' or '-1.'.

Then follows a seven-character long combination of steering flags (a7). These seven steering flags (**1234567**) control the usage of the different onset parameters during the inversion and have the following meanings and options:

Position **1** the time reading of this onset can be used (‘**T**’ or ‘**t**’) or not used (‘**_**’) for the inversion. The travel-time difference between S- and P-type onsets (t_S - t_P) can be used for calculating an initial solution for the source time with the Wadati method (Wadati, 1932; 1933) and/or the epicentral distance from the corresponding station. For this, Position **1** must have been set to ‘T’ or ‘t’ for both onsets.

Position **2** the BAZ reading of this onset can be used (‘**A**’ or ‘**a**’) or not used (‘**_**’) for the inversion.

Position **3** the slowness reading of this onset can be used (‘**S**’ or ‘**s**’) or not used (‘**_**’) for the inversion.

Position **4** the time reading of this onset can be used (‘**D**’ or ‘**d**’) or not used (‘**_**’) to calculate travel-time differences as input data for the inversion.

Position **5** the onset time reading of this onset will be corrected (‘**R**’ or ‘**r**’) or not corrected (‘_’) for the crustal structure below a reflection point at the Earth’s surface by calculating the travel-time difference for the ray path through the crust in the used global model (as set with **GLOBAL MODEL** in ***hyposat-parameter***) and in CRUST 1.0.

Position **6** the amplitude and period readings of this onset can be used (‘**M**’ or ‘**m**’) or not used (‘_’) for magnitude calculations. (Remark: the ***hyposat-in*** files in older format do not have this flag).

Position **7** if set to ‘**2**’, ‘**3**’, or ‘**4**’, other global, spherical Earth models (as set with **GLOBAL MODEL 2**, **GLOBAL MODEL 3**, or **GLOBAL MODEL 4** in file ***hyposat-parameter***) will be used to calculate the theoretical onset time, the slowness or ray parameter, and their partial derivatives for this onset. With any other character at this place, the standard global Earth model (see **GLOBAL MODEL** in file ***hyposat-parameter***) will be used.

If keeping the positions **1** – **7** blank (‘   ‘) the flag combination **TASDRM_** will be automatically used as default value.

Then, one can add the following optional input data: the period of the observed onset (f6.3), the amplitude of the signal in [nm] (f12.2), the signal-to-noise ratio (SNR) (f7.2), an eight-character long arrival-id (a8) and finally the 2nd standard deviation for the onset time reading (see also **DOUBLE SIDED TIME UNCERTAINTY** in ***hyposat-parameter***) (f5.2).

The input of the values for amplitude, period, SNR, arrival-id and 2nd standard deviation are optional. The amplitude / period information is only used if both values are larger than 0.0. The SNR is not used in the program but listed in the output files.

All lines starting with ‘STOP’, a star ‘*****’ or a blank space ‘ ‘ as well as identical lines following each other are ignored and not used.

When using the correct format, an input file may look like the example below:

------------- example of a ***hyposat-in*** file ---

```
NORTHERN MOLUCCA SEA, 1996 29 June, converted from pIDC’s Reviewed Event Bulletin (REB)
* The row above is the title line
*
*23456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789
*aaaa aaaaaaaa iiii ii ii ii ii ff.fff f.fff fff.ff ff.ff ff.ff ff.ff aaaaaaa ff.fff fffffffff.ff ffff.ff aaaaaaaa ff.ff
WRA   P        1996 06 29 00 41 44.700 0.300 331.50 20.00 11.10  1.00 TASD_M_  0.300         4.50   97.80 abcdef01  0.10
WRA   S        1996 06 29 00 45 48.7   0.600 338.0  20.0  17.0   2.00 TASD_M_  0.900         2.00    8.10 abcdef02  0.20
QIS   P1       1996 06 29 00 42 12.8   0.300 -999.   0.0  -999.  0.00 T__D___                       35.50 abcdef03  0.10
QIS   PcP      1996 06 29 00 45 44.8   0.300                          T__D___                             abcdef04  0.10
ASAR  P        1996 06 29 00 42 16.9   0.300 346.3  20.0   7.1   1.00 TASD_M_  0.500         3.40   35.10 abcdef05  0.10
ASAR  PcP      1996 06 29 00 45 45.2   0.300 345.1  20.0   2.3   1.00 TASD_M_  0.500         2.20   11.50 abcdef06  0.10
ASAR  S        1996 06 29 00 46 45.3   0.600 347.6  20.0  20.3   2.00 TASD_M_  0.800         3.90    6.10 abcdef07  0.20
WARB  P        1996 06 29 00 42 31.2   0.300 339.4  30.0   8.2   2.00 TASD_M_  0.700         6.50    8.20 abcdef08  0.10
WARB  PcP      1996 06 29 00 45 49.4   0.300 -999.   0.0  -999.  0.00 T__D___                             abcdef09  0.10
MEEK  P        1996 06 29 00 42 42.7   0.300 -999.   0.0  -999.  0.00 T______                        6.80 abcdef10  0.10
CMAR  P        1996 06 29 00 43 09.0   0.300 109.7  30.0   7.8   2.00 TAS__M_  0.400         0.60    4.30 abcdef11  0.10
CMAR  LR       1996 06 29 00 57 48.7  50.000 110.0  30.0  39.5   2.00 _A___M_ 19.360       188.80         abcdef12 25.00
FORT  P        1996 06 29 00 43 11.3   0.300                          T______                       10.80 abcdef13  0.10
WOOL  P        1996 06 29 00 43 15.6   0.300   7.9  30.0   9.9   2.00 TAS__M_  0.600         4.10    8.80 abcdef14  0.10
SHK   P        1996 06 29 00 43 25.4   0.300 -999.   0.0  -999.  0.00 T______                             abcdef15  0.10
STKA  P        1996 06 29 00 43 46.8   0.300 323.2  20.0   9.0   1.00 TASD_M_  0.600         7.20    8.30 abcdef16  0.10
STKA  PcP      1996 06 29 00 46 12.0   0.300 -999.   0.0  -999.  0.00 T__D___                             abcdef17  0.10
KSAR  P        1996 06 29 00 43 46.7   0.300 177.3  20.0  10.1   2.00 TAS__M_  0.700         1.70    7.20 abcdef18  0.10
KSAR  LR       1996 06 29 01 04 25.0  50.000 160.0  20.0  46.0   2.00 _A___M_ 19.860        40.10         abcdef19 25.00
MJAR  P        1996 06 29 00 43 51.9   0.300 357.1  20.0  18.8   1.00 TAS__M_  0.550         2.00         abcdef20  0.10
PDY   P        1996 06 29 00 46 47.0   0.300 111.2  30.0   6.6   2.00 TAS__M_  0.450         4.30   23.80 abcdef21  0.10
ZAL   P        1996 06 29 00 47 09.0   0.300 -999.   0.0  -999.  0.00 T______                             abcdef22  0.10
ABKT  P        1996 06 29 00 48 09.5   0.300 -999.   0.0  -999.  0.00 T______                             abcdef23  0.10
*
*NRI   P        1996 06 29 00 48 08.7   0.300 195.9  30.0    3.9  2.00 TAS__M_  0.750         3.00   11.20 abcdef24  0.10
* Note, the following phase has an unknown phase name! Therefore, its onset time or slowness cannot be used
* for the inversion. However, the backazimuth observation may be usable.
*
NRI   x        1996 06 29 00 48 08.7   0.300 195.9  30.0   3.9   2.00 _A___M_  0.750         3.00    11.2 abcdef24  0.10
MAW   P        1996 06 29 00 49 01.1   0.300 -999.   0.0  -999.  0.00 T______                             abcdef25  0.10
KVAR  P        1996 06 29 00 49 17.2   0.300 -999.   0.0  -999.  0.00 T______                             abcdef26  0.10
NPO   P        1996 06 29 00 49 31.0   0.300 -999.   0.0  -999.  0.00 T______                             abcdef27  0.10
ARCES P        1996 06 29 00 49 51.7   0.300  94.5  20.0   4.1   1.00 TAS__M_  0.550         0.80   10.50 abcdef28  0.10
SPITS P        1996 06 29 00 49 55.9   0.300 116.6  30.0   3.5   2.00 TAS__M_  0.900         3.60   10.40 abcdef29  0.10
FINES P        1996 06 29 00 50 00.0   0.300 111.2  20.0   5.9   1.00 TAS__M_  0.550         0.60    6.60 abcdef30  0.10
HFS   P        1996 06 29 00 50 28.7   0.300 311.3  30.0   1.5   2.00 TAS__M_  0.750         1.10    3.70 abcdef31  0.10
TXAR  PKPdf    1996 06 29 00 55 42.7   0.300 -999.   0.0  -999.  0.00 T______                             abcdef32  0.10
SCHQ  PKPdf    1996 06 29 00 55 41.2   0.300 -999.   0.0  -999.  0.00 T______                             abcdef33  0.10
DBIC  PKPdf    1996 06 29 00 55 57.1   0.300 -999.   0.0  -999.  0.00 T______                             abcdef34  0.10
PLCA  PKPdf    1996 06 29 00 56 09.1   0.300 311.9  30.0   6.4   2.00 TAS__M_  0.900         0.90    4.40 abcdef35  0.10
LPAZ  PKPdf    1996 06 29 00 56 44.7   0.300 -999.   0.0  -999.  0.00 T______                             abcdef36  0.10
```

--------------- end of the ***hyposat-in*** file example --

3 THE hyposat-parameter FILE

The file ***hyposat-parameter*** contains the inversion-steering parameters and is read by both programs **HYPOSAT** and **HYPOMOD** (see Chapter 5). The file must be located either in the directory where the program is executed or in the directory defined by the environment variable **HYPOSAT_PARA**. For instructions on how to define environment parameters please consult the program-package-installation documentation on GitHub. If the parameter file has another name than ***hyposat-parameter***, this name, including its whole directory path name, must be defined by the environment variable **HYPOSAT_PARA**. This file is read only once at the beginning of a location run.

Several of the parameters are only applicable in special cases. They contribute to the customization possibilities of the program for different applications and the user should check carefully what is really needed for their actual case and what can just be ignored or not set. See the examples in the directory ***./examples/*** and the file ***hyposat-parameter_all*** in the directory ***./man/*** with all possible parameters listed together with their default settings.

HYPOSAT and **HYPOMOD** can read data either from files formatted in their native format or in the International Seismic Format (ISF 1.0) as defined by the Commission of Seismological Observation and Interpretation of IASPEI version ISF 1.0. This format is compatible with the format used by the International Monitoring System (IMS) of the Comprehensive Test-Ban-Treaty Organization (CTBTO) for its bulletins. **HYPOSAT** can also write the inversion results in ISF 1.0 and in JSON formatted output files. For the i/o of ISF formatted files an ISC-software package was adapted for the usage in **HYPOSAT**. Some parameter settings in the ***hyposat-parameter*** file are only related to i/o of ISF formatted files (see § 3.8).

The syntax in the ***hyposat-parameter*** file has changed during the development of the different **HYPOSAT** versions. For compatibility reasons, the old syntax versions are still working and will be supported – at least for a while. All parameter settings in old syntax and their new equivalent entries are listed at the end of Chapter 3.

In the following, all parameters and their possible settings are explained in detail. Parameter settings and relevant parts of their definitions are denoted in this document in **bold** and **capital characters**. As reference, the syntax for each parameter setting is given in red with the default parameter setting. For running **HYPOSAT** with specific parameter settings, you can just copy the relevant lines from these examples and modify them as needed. See also the file ***hyposat-parameter_all***.

3.1 GENERAL FORMATTING RULES

Each parameter is defined in an extra line, starting with the **mandatory parameter name**, followed by a **required colon** (‘:’) After the **mandatory colon** follows one **mandatory blank space** (‘ ‘) and then the parameter setting itself.

Leading blank spaces (‘ ‘) in a line as well as all characters between the **parameter name** and the **required colon** will be ignored. *E.g.*, for better readability, a blank space (‘ ‘) was added before the **required colon** for all examples of parameter settings in this document.

Be aware that since **HYPOSAT 6.2**, this **mandatory colon** has no longer to be located at the fixed position at character 36 in the line, but it **must** follow after the parameter name. However, all old ***hyposat-parameter*** files will still work as before.

Any blank line or lines with a star (*) as 1st character are ignored.

Whenever a line does not comply with these rules, a warning message will be written when running the program and the setting in the line will be ignored.

The order in which the parameters are set is arbitrary. Each line can be repeated several times within the file with another setting. In this case, the last set value is applied for the location process. The total number of lines in the file is limited to 2000 lines.

All default values are set when starting the program. For file names, the full directory path name can be given with a maximum length of 512 characters.

3.2 SEISMIC VELOCITY MODELS – TRAVEL-TIME TABLES

3.2.1 Global Models

The parameter **GLOBAL MODEL** (or **GLOBAL MODEL 1**) defines the reference spherical velocity model used to calculate all travel-time related theoretical data. The **HYPOSAT 6.2** package contains data files for the following global models:

ak135_A	AK135 model (Kennett *et al.*, 1995)
ek137_A	EK137 model (Kennett, 2020)
iasp91_A	IASPEI 1991 model (Kennett, 1991; Kennett & Engdahl, 1991)
iasp91a_A	IASPEI 1991**,** with a corrected core model (Kennett, pers. communication)
jb_A	Jeffreys-Bullen model (Jeffreys & Bullen, 1940 and later)
prem_A	PREM model (Dziewonski & Anderson, 1981)
sp6_A	SP6 model (Morelli & Dziewonski, 1993)

Some additional, regional spherical Earth models with different crusts and uppermost mantle layers are also included in the **HYPOSAT** software package. From a depth of 220 km on, they are identical to the AK135 model:

barey_A	BAREY, regional model for the European Arctic (Schweitzer & Kennett, 2007)
barez_A	BAREZ, regional model for the European Arctic (Schweitzer & Kennett, 2007)
barents16_A	BARENTS16, regional model for the western Barents Sea (Pirli & Schweitzer, 2017)
bergen_A	University of Bergen's velocity model for Norway (Havskov & Bungum, 1987)
fescan_A	NORSAR's Fennoscandia model (Mykkeltveit & Ringdal, 1981)

The directory, where these data files are located, must be specified with the environment variable **HYPOSAT_DATA** before starting the program. The travel-time tables are calculated with the *libtau*-software package (Buland & Chapman, 1983), and originally distributed as IASPEI91-software, here with the extensions described in the **Introduction**. To become computer architecture and operation system independent, all global travel-time models for the *libtau*-software were recalculated for the **HYPOSAT** package, stored in ASCII format and got the suffix '_A' in their table names. The default global model is 'ak135_A'

GLOBAL MODEL : ak135_A

or alternatively:

GLOBAL MODEL 1 : ak135_A

One can give the name of any other 2nd global model to be used for specific ray paths as indicated in the data input file ***hyposat-in***. Up to three additional spherical Earth models can be used for specific travel paths.

GLOBAL MODEL 2 : ak135_A

One can give the name of any other 3rd global model to be used for specific ray paths as indicated in the data input file ***hyposat-in***.

GLOBAL MODEL 3 : ak135_A

One can give the name of any other 4th global model to be used for specific ray paths as indicated in the data input file ***hyposat-in***.

GLOBAL MODEL 4 : ak135_A

The seismic velocities in the crust must be known for the chosen dominant global model (set with the parameter **GLOBAL MODEL**), so that **HYPOSAT** can apply crustal travel-time corrections. The crustal structures of all prepared *libtau*-type models are collected in a file called ***std_crusts.dat*** and marked with a unique code. This file must reside in the same directory as defined by the environment variable **HYPOSAT_DATA**. ***std_crusts.dat*** is included in the directory ***./data/***. If you use another global model than AK135 as defined by **GLOBAL MODEL** (or **GLOBAL MODEL 1**), the program will automatically adjust this parameter. However, you can overwrite this setting and force the program to use a specific standard crust by setting the following parameter. The following different codes are possible:

E1 Jeffreys-Bullen (global standard model)
E2 PREM (global standard model)
E3 IASPEI 1991 (global standard model)
E4 IASPEI 1991a (global standard model, with corrected core)
E5 SP6 (global standard model)
E6 AK135 (global standard model)
E7 FESCAN (regional standard model)
E8 BAREY (regional standard model)
E9 BAREZ (regional standard model)
EA BARENTS16 (regional standard model)
EB BERGEN (regional standard model)
EC EK137 (global standard model)

By default, the standard code is 'E6' (for AK135).

GLOBAL CRUSTAL MODEL CODE : E6

If using as input a ***hyposat-in*** formatted file (see Chapter 2), the usage of alternative spherical Earth models can be specified for specific observations. In the case of using an ISF-formatted input file this is not possible. In this case, one can define an epicentral distance in [°], from which **GLOBAL MODEL 2** should be used to calculate the theoretical onset times. However, be aware that the model usage may differ for some observations from iteration to iteration because of a change in the epicentral distance.

The default value is '999.', which means no usage of a 2nd velocity model in the case of an ISF formatted input file.

ISF_2ND MODEL DISTANCE : 999.

3.2.2 Local or Regional Velocity Models

HYPOSAT can combine global velocity models with an epicentral-distance-dependent **LOCAL OR REGIONAL MODEL**. The local/regional travel-time models are either used around the source and/or to calculate travel-time corrections for reflection points of phases at the Earth's surface or for crustal differences between the dominant global model and the actual structure at the stations (velocities & elevation). The input is a file containing the model parameters. The velocity model must contain the following information:

- In the 1st line maxdis = maximum distance in [°] for which this model shall be used.
- It is followed by lines with depth in [km], the P velocity (Vp) in [km/s], and the S velocity Vs in [km/s]. The model may contain layers with a constant velocity or with velocity gradients.
- First order discontinuities must be specified with two lines for the same depth.
- Additionally, the Conrad and the Moho must be marked as shown in the following example. Please note that the mark for the Conrad and the Moho must be in the 1st line defining the first order discontinuity. Without these discontinuity definitions, the program will name all calculated crustal and regional phases Pg (or Sg, respectively).

CRUST 1.0 defines the Moho but not the Conrad. Here **HYPOSAT** is setting the Conrad at the depth where the P-velocity Vp ≥ 6.3 [km/s].

All direct phases from sources below a depth of 210 km or with a ray path in a layer below this depth will be named P (or S, respectively) instead of Pn (Sn).

The maximum number of model layers is set to 100.

----------------------example for a file containing a regional velocity---------------------------------------
```
 10.                                  | maxdis in free format
     0.000      5.400     3.100       | depth, Vp, Vs in format (3F10.3)
    10.000      5.800     3.200
    20.000      5.800     3.200CONR | + mark for the 'Conrad'
    20.000      6.500     3.600       |   in format (3F10.3,A4)
```

```
   30.000      6.800     3.900MOHO | + mark for the 'Moho'
   30.000      8.100     4.500     |   in format (3F10.3,A4)
   77.500      8.050     4.400
  120.000      8.100     4.500
```

---------------------end of example---

If the file containing this velocity model is not available in the run-directory or the directory defined by the environment variable **HYPOSAT_DATA**, one must give the full file name including its directory path. Set it to '_' if no local model is used.

LOCAL OR REGIONAL MODEL : _

Travel times will be calculated for the following seismic phases (as far as the ray theoretically exists with respect to distance and source depth):

- Direct and reflected P-phases: Pg, Pb, Pn, P, pPg, pPb, pPn, pP, PbP (*i.e.*, in this program, the upper side reflection from the Conrad), PmP, PgPg, PbPb, PnPn, PP, PgPgPg, PbPbPb, PnPnPn, PPP
- P-to-S converted phases: pSg, pSb, pSn, pS, PbS, PmS
- Direct and reflected S-phases: Sg, Sb, Sn, S, sSg, sSb, sSn, sS, SbS, SmS, SgSg, SbSb, SnSn, SS, SgSgSg, SbSbSb, SnSnSn, SSS
- S-to-P converted phases: sPg, sPb, sPn, sP, SbP, SmP

When using the local/regional model for calculating local/regional travel-time tables and their partial derivatives, one can define the seismic phase types to be considered by a 4-digit number code: The position of a digit defines the phase type and the value of the digit defines the action for this phase:

dxxx the digit (d) in the 1st position is the flag related to surface reflections (*e.g.*, pP or sS).

xdxx the digit (d) in the 2nd position is the flag for surface multiples (*e.g.*, PP, SS, PPP or SSS).

xxdx the digit (d) in the 3rd position is the flag for reflections at the Conrad or the Moho (*e.g.*, PbP or SmS). Note that here the name 'PbP' is used to indicate a reflection from the Conrad, which is not a regular phase name as recommended by IASPEI (Storchak *et al.*, 2002; 2003; 2006; 2009; 2011; Bormann *et al.*, 2013; Schweitzer *et al.*, 2021a).

xxxd the digit (d) in the 4th position is the flag for converted phases (*e.g.*, sP or PmS).

The digit **d** itself can have the following values:

1 = only P-type onsets will be calculated
2 = only S-type onsets will be calculated
3 = both phase types (P and S) will be calculated

E.g., the combination **1320** means the phases pP, PP, PPP, SS, SSS, SbS and SmS will be calculated, but none of the converted phases. The combination **0000** or simply **0** means only the direct P- and S-onsets, but none of the reflected and/or converted phases will be calculated. For any value below **0**, the program will ignore the local/regional model set by **LOCAL OR REGIONAL MODEL**. The default value is set to ‘3333’.

PHASE INDEX FOR LOCAL MODEL : 3333

The following setting is steering the usage of the 1° x 1° crustal model CRUST 1.0 of Laske *et al.* (2013) together with the other local/regional velocity models. The usage can be chosen by an integer number:

- <= **0** = no usage of CRUST 1.0 or any other local/regional model as defined with **LOCAL OR REGIONAL MODEL** (this is also the default value).
- **1** = only the local/regional model is used as defined in **LOCAL OR REGIONAL MODEL**. The model is also used for eventually correcting teleseismic travel times of near source reflections (depth phases) (pP, pwP, sS, sP, *etc.*).
- **2** = CRUST 1.0 is only used for calculating station corrections and for travel-time corrections for model differences at the reflection points of the phases (*e.g.*, pP, sS, PnPn, sS, P’P’ ...). Reflection point corrections **cannot (!)** be calculated for multiple reflections as *e.g.*, pPP, SSS, *etc.*, and if stations or reflection points are located within the maximum distance from the source as defined in **LOCAL OR REGIONAL MODEL**. Then, it is assumed that the **LOCAL OR REGIONAL MODEL** contains already the correct seismic velocities and no further corrections are needed.
- **3** = CRUST 1.0 is only used to calculate travel times to stations with a maximum distance of 1.5° from the source. **LOCAL OR REGIONAL MODEL** is not used.
- **4** = combines options (2) and (3).
- **5** = **LOCAL OR REGIONAL MODEL** is used for near source surface reflections (depth phases) and CRUST 1.0 is used for all other corrections (station and reflection points).
- **6** = CRUST 1.0 is used to calculate reflection-point corrections only, not for station corrections.

CRUST 1.0 : 0

One can indicate to the program that all the stations are within an epicentral distance of less than about 50 km and that a **LOCAL OR REGIONAL MODEL** is given by setting the parameter **VERY LOCAL GEOMETRY** to ‘1’. Then, the ray-tracing algorithm is adjusted for a denser ray coverage to calculate the travel times for the different local/regional phases and no ellipticity corrections for the travel times are applied.

VERY LOCAL GEOMETRY : 0

3.2.3 Group Velocities

HYPOSAT can use observations from different types of surface waves, for which the mean group velocities in [km/s] can be set by the following parameters:

RG GROUP-VELOCITY : 2.5

LG GROUP-VELOCITY : 3.5

LQ GROUP-VELOCITY : 4.4

LR GROUP-VELOCITY : 3.95

Infrasound onsets and T-phases can also be included. Onset times of these phases are not well defined but mean group velocities can be used to identify such onsets.

The mean infrasound group velocity (celerity) and the T-phase mean group velocity can be set in [km/s] by:

IS-PHASE GROUP-VEL : 0.33

T-PHASE GROUP-VEL : 1.45

3.2.4 Model Uncertainties

HYPOSAT can account for model uncertainties by defining mean uncertainties of travel-time tables. The default value is taking no model uncertainties (‘0’).

INCLUDING MODEL UNCERTAINTY : 0

As one implemented option, the uncertainties can be given separately for P- and S-type onsets in [s] but are assumed to be distance independent and then equal for all phases of the same phase type (P or S). These uncertainties will be added to the onset-time uncertainties and thereby influence the weighting of the observations and the final uncertainty of the inversion results. The default values are set to 0. s for both P- and S-type onsets.

MEAN P-WAVE MODEL UNCERTAINTY : 0.

MEAN S-WAVE MODEL UNCERTAINTY : 0.

Another option is to define uncertainties in [s] for some specific phases separately. For now, this is possible for the following regional phases: Pg, Pb, Pn, Sg, Sb, Sn and Lg. The default values are again set to 0. s.

MEAN PG TRAVEL-TIME UNCERTAINTY : 0.

MEAN PB TRAVEL-TIME UNCERTAINTY : 0.

MEAN PN TRAVEL-TIME UNCERTAINTY : 0.

MEAN SG TRAVEL-TIME UNCERTAINTY : 0.

MEAN SB TRAVEL-TIME UNCERTAINTY : 0.

MEAN SN TRAVEL-TIME UNCERTAINTY : 0.

MEAN LG TRAVEL-TIME UNCERTAINTY : 0.

3.3 STATION RELATED PARAMETERS

The program needs one file with the geographic coordinates of the sensor locations (employed station coordinates). Four file formats are supported: PDE (NEIC, see also the file ***data/stations.dat*** in the program package), CSS3.0, an ISC-type listing or a comma separated listing. These file formats are automatically detected. To obtain the location results faster, it is recommended to use a file containing only your network stations. The file must be either located in the run-directory, or the directory defined by the environment variable **HYPOSAT_DATA**, or one has to give the full file name including directory path information. The default file name is '***stations.dat***'.

The four possible format definitions (Fortran) are, with examples:

PDE (NEIC) format:

station id, flag, lat [degrees], lat [minutes], lat [seconds], N/S, lon [degrees], lon [minutes], lon [seconds], E/W, elevation [m], name

(a5,a1,i2,i2,f4.1,a1,i3,i2,f4.1,a1,f7.1,a48)

```
NOA   610223.0N 111253.1E  717.0NORSAR Array
```

CSS3.0 format:

station id, start time, end time, lat [°], lon [°], elevation [km], name

(a5,2x,i8,1x,i8,1x,f9.4,1x,f9.4,1x,a48)

```
NOA      1976275   9999365   61.0397   11.2148    0.7170 NORSAR Array
```

ISC-type listing format:

1st title line

2nd title line

station id, lat [°], lon [°], elevation [m]

(a5,1x,3(1x,f10.0))

```
NOA       61.0397    11.2148      0.7170
```

Comma separated ISC-type listing:

station id, station id, lat [°], lon [°], elevation [m]

```
NOA, NOA, 61.0397, 11.2148, 0.7170
```

STATION FILE : ./stations.dat

In the case that one has two different station-coordinate lists, one can define an alternative station file, which the program will check for station coordinates if it cannot find the station in the file defined by the parameter **STATION FILE**. With this option one can also combine the usage of station lists if they have two different file formats. The default file name is also '***stations.dat***'.

ALTERNATIVE STATION FILE : ./stations.dat

There are several possibilities to correct onset times for station specific effects. For details on how the estimation of such corrections is implemented in **HYPOSAT** see Schweitzer (2025). This parameter is a flag on whether station corrections (elevation, crust) will be applied. By default, station corrections are taken in account '1'.

STATION CORRECTIONS : 1

One can set global crustal velocities in [km/s] for estimating elevation corrections with these parameters. If the parameter **S-VELOCITY TO CORRECT ELEVATION** is not set or set to 0. and the parameter **P-VELOCITY TO CORRECT ELEVATION** is defined earlier in the file, the **S-VELOCITY TO CORRECT ELEVATION** is calculated from the **P-VELOCITY TO CORRECT ELEVATION** value divided by sqrt(3.). All values below 0.001 and above 99. km/s are ignored and the AK135 values are used as default.

E.g., for AK135:

P-VELOCITY TO CORRECT ELEVATION : 99.1

S-VELOCITY TO CORRECT ELEVATION : 99.1

or

P-VELOCITY TO CORRECT ELEVATION : 5.80

S-VELOCITY TO CORRECT ELEVATION : 3.46

E.g., for Jeffreys-Bullen:

P-VELOCITY TO CORRECT ELEVATION : 5.56

S-VELOCITY TO CORRECT ELEVATION : 3.37

Station specific onset time corrections can be added in an extra file. If local seismic velocities at the stations are known, one can list them in this file and then, these values will be used to calculate station-elevation effects. Also fixed station corrections can be additionally used to correct for constant time shifts and are listed in this file.

These corrections are separate for P and S waves. For more details on station-correction calculations see Schweitzer (2025). The velocity value can also be used to correct for a known velocity anomaly below a station. The input is format free. If a station is not on this list, the default velocity values as defined by the input parameters **P-VELOCITY TO CORRECT ELEVATION** and **S-VELOCITY TO CORRECT ELEVATION** are used. In the case that one wants to use only static time corrections (*e.g.*, because of a known digitizer problem) but no special velocity values for elevation corrections, one can set the velocities to **0.** and only add the static time corrections.

------------------ example for an ASCII file containing station corrections -------------------------------

```
* This is a file containing values to calculate station corrections (only
* for the stations listed here!).
*
* All lines starting with a star '*' or empty lines are ignored.
*
* Minimum input:
* Station name and local P and S velocities to calculate elevation effects
* Vp or Vs given in this file for a specific station always overrides values
* given by the parameters P-VELOCITY TO CORRECT ELEVATION and
* S-VELOCITY TO CORRECT ELEVATION or defined by CRUST 1.0:
*
* Stat Vp  Vs
GERES 5.2 3.2
*
* Optional input (e.g., to correct for results from tomographic studies
* or known clock errors) of static time shifts. Static corrections for P-
* and S-body waves.
* No corrections are applied to IS- or T-phase onsets. These correction
* values will be added (!) to the observed travel times:
*
* Stat Vp  Vs dtp dts
GERES 5.2 3.2 0. 0.
*
* Additional static time corrections for surface-wave type onsets (LQ, LR, Lg, Rg).
* The corrections are added (!) to the observed travel times:
*
* Stat Vp  Vs dtp dts dtsurface
GERES 5.2 3.2 0. 0. 0.
* In the case that one wants to use only static time corrections, one can
* set the velocities to 0. (then they will be ignored) and only the static
* time corrections are used:
*
* Stat Vp  Vs dtp dts
XYZ 0. 0. 1.0 1.0 1.0
```

------------------- end of example--

CAUTION: the constant time shifts, as defined in the correction file, are used to calculate travel-time residuals, but they are not changing (correcting) the observed onset times as given in ***hyposat-in*** or written in the output files with the **HYPOSAT** location results.

STATION CORRECTION FILE : _

By default, static station corrections are used for all onsets from the particular station. If the static station corrections in the **STATION CORRECTION FILE** are only valid for the 1st onsets of P or S phases (if *e.g.*, calculated with *VELEST* (see Kissling, 1988; 1995), this switch must be set to ‘1’.

STATION CORR ONLY 1ST PHASE : 0

In the case of a very local geometry, stations may be located below the surface (*e.g.*, in boreholes or mines) or even below the event. Then, this has to be taken in account when calculating the theoretical travel times and one must set this switch to ‘1’. In this case the parameter **VERY LOCAL GEOMETRY** is also set automatically to ‘1’. By default, this option is switched off (‘0’).

LOCAL STATION BELOW SURFACE : 0

One can consider defining a maximum and a minimum epicentral distance of stations to be used during the inversion. Both distances are by default in [°]. But if the inversion output is set with **OUTPUT IN KM** to [km] (see § 3.8.3), both **MIN EPI DIST OF STAT** and **MAX EPI DIST OF STAT** are also in [km].

MIN EPI DIST OF STAT : 0.

MAX EPI DIST OF STAT : 180.

3.4 SOURCE RELATED PARAMETERS

The program has different ways to apply or calculate a preliminary epicenter and a preliminary source time. This can be steered with different parameters. In any case, any initial value directly given in the parameter list, will overwrite all estimated values. The following parameters define the initial solution including its uncertainties:

3.4.1 Initial Source Time

To set an initial source time the accepted formats are:

Epochal time	(which means number of seconds since 01/01/1970 00:00:00.0) allowed is any number larger than -2840140800.0 (= default source = 1 January 1880 00:00:00.0). Any smaller number will be automatically set to -2840140801.0.
yyyy-doy?hh?mi?ss.sss	with doy (day of the year), and for '?' one can use any character including a blank space ' '. The seconds can be omitted.
yyyy-mm-dd?hh?mi?ss.sss	The seconds can be omitted.

Any time earlier than the default value will be ignored. Here are some examples for the same time in the different allowed formats:

STARTING SOURCE TIME : 1970-001:00.00.00.0

STARTING SOURCE TIME : 1970-001 00 00 00.0

STARTING SOURCE TIME : 1970-01-01 00:00:00.0

STARTING SOURCE TIME : 1970-01-01 00 00 00.0

STARTING SOURCE TIME : 0.

Together with an initial source time one can set the source time uncertainty in [s].

STARTING TIME UNCERTAINTY : 10.

If no **STARTING SOURCE TIME** is set, an initial source time will be estimated from the travel-time differences between direct S-type and direct P-type observations ($t_S - t_P$) by using Wadati's approach (Wadati, 1932; 1933). For this, the program calculates mean Vp/Vs ratios for each observed phase type and estimates a source time, respectively. The phase types (type 1: P & S, type 2: Pg & Sg, type 3: Pn & Sn and type 4: Pb & Sb) are identified based on the global model AK135. Then, the initial source time is calculated as the mean value of all estimated source times.

In the case of only one $t_S - t_P$ observation, the Vp/Vs ratio is set to $\sqrt{3}$.

If no $t_S - t_P$ observation is available, the starting source time is set to the earliest observed onset time.

The Wadati approach can be steered by the length of the allowed $t_{S\text{-type}} - t_{P\text{-type}}$ travel-time differences measured in [s]. By default, the minimum allowed travel-time difference is set to 0 and the maximum to 300 s.

MIN DT FOR WADATI : 0.

MAX DT FOR WADATI : 300.

3.4.2 Initial Epicenter Estimation

If BAZ observations are available from several stations, these data are used to calculate an epicenter by calculating the possible crossing points of these different observations. A start epicenter including its uncertainties is then calculated as the mean value of all crossing points and their spread.

In the case of a single array with BAZ observations and P- and S-onset observations, the program uses these data to estimate a single array location (see *e.g.*, Schweitzer *et al.*, 2012) based on the epicentral distance from the travel-time difference between the phases.

If no BAZ observations but P-type onset observations from several stations are available, the program tries a plane-wave fit through the 1^{st} P-wave onsets at all stations to get a BAZ direction to the epicenter. Then, if possible, S-P travel-time differences are used to estimate an epicentral distance and a start epicenter is calculated. By default, this option is switched on '1'.

PLANE WAVE APPROX : 1

The geographic coordinates of an initial epicenter can also be directly set, together with their uncertainties. This setting will overwrite (but not when the parameter **AUTOMATIC PROCESSING** is set) evaluations based on crossing BAZ observations, the results of a **PLANE WAVE APPROX** setting, or a single array solution.

Latitude

The allowed range is from -90 to +90 degrees, all other values as well as a '_' are ignored and then no starting source latitude is set.

STARTING SOURCE LATITUDE : 999.

or

STARTING SOURCE LATITUDE : _

and

STARTING LATITUDE UNCERTAINTY : 10.

Longitude

The allowed range is from -180 to +180 degrees, all other values as well as a '_' are ignored and then no starting source longitude is set.

STARTING SOURCE LONGITUDE : 999.

or

STARTING SOURCE LONGITUDE : _

and

STARTING LONGITUDE UNCERTAINTY : 10.

The following parameter brings the program in an automatic processing mode. In this case, the program accepts all self-determined initial solutions and does not use in a first step the initial solutions set with the parameters described above. However, if the program cannot determine any initial solution, the set ones are used as backup. This mode can be universally set, or for teleseismic or regional events only. If this switch is set, all onsets in an ISF formatted output file will be marked with an 'a' as automatically measured. By default, automatic processing is switched off, '0'.

AUTOMATIC PROCESSING : 0

AUTOMATIC PROCESSING TELE : 0

AUTOMATIC PROCESSING REGIONAL : 0

In the case of an ISF formatted input file, the input file already contains source location and source time. This epicenter can be used as start (and reference) solution. By default, the flag is switched off, ‘0’.

ISF EPICENTER : 0

3.4.3 Initial Source Depth

One can set an initial source depth in [km] and its uncertainty, respectively. The default depth in the program is 0 km with an uncertainty of 20 km

STARTING SOURCE DEPTH : 0.

STARTING DEPTH UNCERTAINTY : 20.

In the case of an ISF formatted input file the depth solution can be used as start (and reference) solution. By default, this flag is switched off, ‘0’.

ISF DEPTH : 0

An allowed depth range in [km] can be set. Be aware that the program does not allow any sources with negative depth, which may happen *e.g.*, in models with topography above the mean sea level.

MINIMUM DEPTH : 0.

MAXIMUM DEPTH : 800.

The depth of the event can stay fixed, or the program can try to determine the depth based on the observed data and the location of the epicenter. From **HYPOSAT 6.1** onwards, the program can also use the International Seismological Centre (ISC) default-depth definitions (see Bondár & Storchak, 2011). This can be steered with the parameter **DEPTH FLAG**, which takes the following values

f (or **F**) = depth is **f**ixed at **STARTING SOURCE DEPTH**.
d (or **D**) = a new depth is **d**etermined from the beginning for each iteration step.
b (or **B**) = **b**oth, the inversion starts with the fixed depth and when an epicenter is found, the inversion continues with inverting also for the depth.

i (or **I**) = the **I**SC default depth (Bondár & Storchak, 2011) for this epicenter is used as fixed depth.
j (or **J**) = as **b** (or **B**), but the starting depth is the ISC default depth.

By default, this parameter is set to ‘F’.

DEPTH FLAG : F

An additional steering parameter is needed for choosing the default depth if the parameter **DEPTH FLAG** is set to i, I, j or J. Wherever no default ISC-depth information is available, the focal depth can be fixed relative to the Moho depth as defined in CRUST 1.0. There are 3 different default depth-data sets available, which can be differently combined:

i) default depth from ISC well-located seismicity, in a geographical grid with 0.5° x 0.5° resolution (***isc_def_depth.dat***)
ii) default depth derived from the crustal thickness (Moho depth in CRUST 1.0)
iii) default depth as defined by ISC for the different Flinn-Engdahl Regions (***grn_def_depth.ak135.dat***)

Only options (ii) and (iii) cover the entire globe. Therefore, one has to define how to choose the default depth type with another parameter:

1 = search in (i) and if not successful, continue with ii)
2 = search in (i) and if not successful, continue with (iii)
3 = search only in (ii)
4 = search only in (iii)

By default, this parameter is set to ‘1’.

DEFAULT DEPTH TYPE : 1

The following parameter defines how the default depth is extracted from CRUST 1.0 (see **DEFAULT DEPTH TYPE**). Here we use only the solid part of the crust (removing any water layer on top) without topography for calculating the depth and afterwards (if existing) adding the thickness of the water layer again, to avoid a source in the water layer.

uc = upper crust; 0.25 * CRUST 1.0 Moho depth
mc = middle crust; 0.50 * CRUST 1.0 Moho depth
lc = lower crust; 0.75 * CRUST 1.0 Moho depth
mo = Moho depth; CRUST 1.0 Moho depth

By default, this parameter is set to ‘mc’.

CRUST 1.0 DEPTH TYPE : mc

Based on model CRUST 1.0, one can force the program to not accept any source depth in a water layer at the surface (*e.g.*, ocean, big lake). Then, the following flag has to be set to '1' (default value is '0', *i.e.*, no check for a water layer on the top of the model).

CHECK DEPTH FOR WATER LAYER : 0

3.5 STEERING THE USAGE OF OBSERVATIONS

3.5.1 Onset Time Observations and Phase Names

By default, **HYPOSAT** uses travel-time differences between different onsets at the same station as additional constraint. Setting this flag to '0' will overwrite the flag setting 'D' or 'd' for all observations in the input file ***hyposat-in*** and switch off the usage of travel-time differences during the inversion.

FLAG USING TRAVEL-TIME DIFFERENCES : 1

As widely known, the reading uncertainties of seismic onset times do not follow a Gaussian distribution. **HYPOSAT** can use two different standard deviations (STD) for the onset time to weight travel-time data residuals, depending on the sign of the residual (always observation - calculation). The 1st STD will then be used for positive (onset too late with respect to the theoretical value) and the 2nd STD for negative residuals (onset too early with respect to the theoretical value). For more details see Schweitzer (2006). By default, this option is switched off, '0'.

0 = no 2nd STD, the program uses only one STD (see the ***hyposat-in*** description)
1 = reading of a 2nd STD from input file (see the ***hyposat-in*** description)
2 = use the **DBLE SID. UNCERTAINTY FACTOR**

DOUBLE SIDED TIME UNCERTAINTY : 0

If the flag **DOUBLE SIDED TIME UNCERTAINTY** is set to '2', the 2nd STD is defined as (STD * **DBLE SID. UNCERTAINTY FACTOR**). The default value of this factor is '1.'.

DBLE SID. UNCERTAINTY FACTOR : 1.

One can change the weight of whole groups of observations. This can be steered by a 4-digit code:

1st digit: travel-time data
2nd digit: BAZ observations
3rd digit: slowness observations
4th digit: travel-time-difference observations

The digits can have the following values:

0 = no change of input uncertainties (the weighting only depends on the given uncertainties).

1 = the data uncertainty for the inversion is (dynamically) increased by the residual of this observation (observation is getting a lower weight).

2 = the data uncertainty is reduced by a factor of 0.5 (observation is getting a higher weight).

3 = the data uncertainty is increased by a factor of 2 (observation is getting a lower weight).

E.g., 0203 would give all BAZ observation higher weight and reduce the weight of all travel-time-difference observations. The default value is ‘0000’ for all digits, which means no weighting change.

CHANGE WEIGHTING TASD : 0000

If an event location should be only based on P-type onsets, one sets this here. By default, this is switched off, ‘0’.

P-TYPE ONSETS ONLY : 0

One can suppress the usage of Lg or Rg phases as defining observations by setting the following parameters to ‘0’. By default, they are switched on ‘1’ (if present, Lg and Rg are used).

REGIONAL SURFACE WAVES LG : 1

REGIONAL SURFACE WAVES RG : 1

The usage of the phase names Sg and Lg is not always consistent. Following the IASPEI recommendations for seismic phase names (Storchak *et al.*, 2002; 2003; 2006; 2009; 2011; Bormann *et al.*, 2013; Schweitzer *et al.*, 2021a), **HYPOSAT** assumes Lg to be a surface wave with a given group velocity (see **LG GROUP-VELOCITY**).

The following parameter settings can be used to homogenize the input by automatically changing the phase names for all Sg or Lg observations.

By default, both options are switched off, ‘0’. If both flags are set to ‘1’, they will be both ignored.

LG-PHASE TO SG : 0

SG-PHASE TO LG : 0

If one wants to use both the travel times of Sg-type onsets as body-waves and the Lg onsets as surface waves, it can make sense to separate these two phases by the epicentral distance. If the following distance in [km] has a value above zero, this epicentral distance is used as separation between Sg and Lg. Then, all Lg are renamed to Sg if the epicentral distance is shorter and all Sg are renamed to Lg if the epicentral distance is equal or larger than this distance.

SG--LG DISTANCE : -999.

If the onset times of long-period surface waves should be used as defining observations, one must set this switch to '1'.

LP SURFACE WAVES (LQ/LR) : 0

3.5.2 Surface Reflections in the Case of a Water Layer on Top of the Model

In the case of a **WATER LAYER ON TOP** of the model, **HYPOSAT** can correct the travel times (see also parameter settings for CRUST 1.0 and Schweitzer (2025)) for the water layer and eventually add a 'w' to the phase name. The water-layer phase is only added for P-type phases and not for any type of converted phases (*e.g.*, sP or pS). All S-type reflections and S-to-P or P-to-S converted phases are assumed to be reflected from the solid-fluid interface. The steering parameter can have these values (by default the parameter is set to '0'):

0 = the water layer is ignored. This is also the default case. However, the program may correct for the local velocity structure (*e.g.*, topography) as defined with settings for the parameter CRUST 1.0.

1 = all (!) reflections at the Earth's surface are corrected for the water layer, *i.e.*, not only the depth phase pP becomes pwP (Hong & Fujita, 1981; Pearce, 1981; Engdahl & Billington, 1986; Schweitzer, 2025), but also *e.g.*, PP becomes PwP. S-type onsets are then reflected at the solid-fluid interface.

2 = **HYPOSAT** chooses the phase identification (reflection from the solid-water interface or from the water-atmosphere interface), which minimizes the travel-time residual for P-type reflections; for S onsets as (1).

3 = for S-onsets as (1), optimizing for P onsets only if the travel-time difference between the two reflections (solid-water or water-atmosphere interface) is larger than **WATER LAYER DT** seconds. Otherwise, all reflections are assumed to be from the solid-water interface.

4 = as (3), but if the travel-time difference is smaller than **WATER LAYER DT** seconds, all reflections are assumed to be from the water-atmosphere interface.

5 = the program uses the phase name(s) of the input file without any optimization. However, the program will automatically ignore all ‘w’ onset paths without a water layer at the reflection point in CRUST 1.0.

WATER LAYER ON TOP : 0

Minimum travel-time difference in [s] to optimize the phase identification in the case of a water layer on top of the model (for details see parameter **WATER LAYER ON TOP**). The default value is 2 s, which approximately corresponds with a water depth of about 1.5 km (see Engdahl *et al.*, 1998).

WATER LAYER DT : 2.

3.5.3 Other Non-traditional Phase Onsets

If infrasound observations (phase name IS) shall be used as defining, this switch must be set to ‘1’.

IS-PHASE USAGE : 0

If T-phase observations (phase name T) shall be used as defining, this switch must be set to ‘1’.

T-PHASE USAGE : 0

3.5.4 Backazimuth (BAZ) Observations

The backazimuth (BAZ; azimuth from station to epicenter measured from North clockwise over East) is an event location relevant datum. To make this clearer, we consequently use the term BAZ from **HYPOSAT 6.1** on. If available, BAZ information is by default used as defining observation. This can be switched off by setting this parameter to ‘0’.

BAZ AS DEFINING : 1

If one wants to use the BAZ observations only for the estimation of an initial solution (from crossing BAZ observations) and not for the further inversion process, one can set the following parameter to ‘1’. This option is by default switched off, ‘0’.

BAZ ONLY INIT SOL : 0

If one has many BAZ observations and wants to get a location based only on these observations (*e.g.*, several infrasound array observations) one can set this flag. Then, **HYPOSAT** calculates a mean epicenter solution and its standard deviations from all possible crossing points of the BAZ observations. No travel-time information is used. This option is by default switched off, ‘0’.

BAZ ONLY LOC : 0

The next parameter defines the maximum allowed travel-time residual in [s] of a body wave and short-period, regional surface wave (Lg, Rg) onset, for which the BAZ is used as defining observation. This setting is ignored if **USE ALL BAZ INFORMATION** is set to ‘1’. The default value is 30. s.

MAX T RES FOR BAZ OF B USE : 30.

The next parameter defines the maximum allowed travel-time residual in [s] of a long-period surface-wave onset, for which the BAZ is used as defining observation. This setting is ignored if **USE ALL BAZ INFORMATION** is set to ‘1’. The default value is 180. s.

MAX T RES FOR BAZ OF L USE : 180.

If setting the following switch to ‘1’, the observed BAZ of all phases (also the not identified but associated ones as listed in ***hyposat-in***) will be used as defining during the inversion. This option overwrites **MAX T RES FOR BAZ OF B USE** and **MAX T RES FOR BAZ OF L USE**. However, setting the option **BAZ ONLY INIT SOL** to ‘1’ overwrites this flag. By default, this is switched off, ‘0’.

USE ALL BAZ INFORMATION : 0

3.5.5 Slowness Observations

The slowness or ray parameter of an observed onset is either defined by its inverse, the apparent velocity in [km/s] or as spherical slowness or ray parameter in [s/°]. The program handles both, but in one input file (see ***hyposat-in***), only one unit type can be used. By default, and if the input file is in ISF format, the unit is set to [s/°]. If the apparent velocity is provided in ***hyposat-in*** this parameter must be set to ‘0’.

SLOWNESS [S/DEG] : 1

If the slowness observations should not be used as defining, the next switch has to be set to ‘0’. By default, the program uses the slowness observations ‘1’.

SLOWNESS AS DEFINING : 1

The following parameter defines the maximum allowed travel-time residual for which the slowness is used as defining observation for body waves. The default value is set to 10 s.

MAX T RES FOR SLOWNESS USE : 10.

3.5.6 Other Settings for Input Data

If a seismic phase of an onset has a large residual with respect to the theoretical onset time and another seismic phase has a smaller residual, the program may try a new solution after (internally) changing the phase name. The program can also automatically declare observations as undefining (see also the parameter settings for, **MAX T RES FOR BAZ OF B USE**, **MAX T RES FOR BAZ OF L USE**, **MAX T RES FOR SLOWNESS USE**). However, this behaviour is not always desired by the user. If the following flag is set, all observations are used for the inversion according to the setting of **TASDR** (see detailed description in ***hyposat-in***). In this case, phase names remain unchanged and used as provided in ***hyposat-in***, serving as defining observations regardless of the size of the travel-time residuals. BAZ and slowness or ray parameter observations are used as defining, as long as they have residuals less than 50° and 10 [s/°], respectively.

If this flag is set, **CONSTRAIN SOLUTION** (see § 3.6) is automatically switched off, ‘0’**.**

By default, this option is switched off, ‘0’. However, in the case of less than 4 observed phases, this flag is automatically set to ‘1’. This parameter setting is not overwriting the search for the best fitting phase name in the case of using P1 or S1 as input phase names.

FLAG USING INPUT FIXED : 0

The program can check the input for more than one onset of the same phase at a given station and reduce these onsets to one entry. This option is of particular interest whenever onset readings from several sources are merged to one single input file. The reduction (after removing double entries) is done by calculating mean onset parameters and adding the spread of the different onset parameters (time, BAZ and slowness) to the reading uncertainty of this observation.

Any amplitude / period readings will not be changed. By default, this option is switched off, ‘0’.

FLAG CHECKING MULTIPLE ONSETS : 0

If **FLAG CHECKING MULTIPLE ONSETS** is set, the maximum time difference between two observations to be merged into one new observation in [s] has also to be defined.

MAX DT FOR MULTIPLE ONSETS : 5.

3.6 THE INVERSION PROCESS STEERING PARAMETERS

The maximum number of iterations is arbitrarily set by default to 80 iterations.

MAXIMUM # OF ITERATIONS : 80

The iterations stop when two consecutive solutions are separated by less than the given accuracy in [km].

LOCATION ACCURACY : 1.

In some cases, the iteration results oscillate between two or more solutions. The following parameter defines how many iterations back we search for such oscillations. The maximum number allowed is 15; the default value is 4. In the case of an oscillating solution, the program output will internally try to jump out of this loop by changing uncertainties, data used as defining or fixing the depth. If this does not result in a stable solution, the program will list the parameter range of solutions.

ITERATIONS TO SEARCH OSCILLATIONS : 4

In the case that beside onset times also BAZ and slowness or ray parameter observations are used to invert for the source location, the mean residual of all defining travel times can become unequal 0. With this parameter, the program is forced to adjust the source time for this mean shift. By default, this option is switched on '1'.

MEAN T-T RES. CORREC : 1

The last iteration can constrain the solution by concentrating on the most trustable/important data and removing the other from the inversion process by declaring them as undefined (see data input in ***hyposat-in***). Five different cases are implemented. If **FLAG USING INPUT FIXED** is set to '1', this parameter setting is ignored. By default, this option is switched off ('0').

- **0** = no final constraining
- **1** = final constraining of the solution by removing data with large residuals
- **2** = final constraining by removing unimportant data as defined by the Information Density Matrix (see the Generalized Matrix Inversion (GMI) theory *e.g.*, in the textbooks of Aki & Richards (1980) or Menke (1989))

3 = case 1 & 2
4 = case 1 with fixed max residual (default 30 s)
5 = case 4 & 2

CONSTRAIN SOLUTION : 0

An additional parameter is needed for the cases 2, 3, 5 of **CONSTRAIN SOLUTION**, to define the threshold for low importance input data. All data with Information Density Matrix diagonal-element entries smaller than this threshold are then not used in the inversion. The threshold is calculated as the ratio between the actual Information Density Matrix entry for this datum and the datum with the maximum Information-Density-Matrix value. The default value is 0.005 = 0.5 % of the most important datum.

However, if this value is set to any negative value, the program calculates the threshold to (1 / number of defining data).

INF. DENSITY MATRIX THRESHOLD : 0.005

For the cases 4 and 5 of **CONSTRAIN SOLUTION** additional parameters are also needed. Then maximum residuals for travel-time, BAZ and slowness or ray parameter must be defined. The default values for travel-time residuals are 30 s, BAZ 50° and ray parameter 10 s/°.

MAXIMUM ALLOWED P RESIDUAL : 30.

MAXIMUM ALLOWED S RESIDUAL : 30.

MAXIMUM BAZ RESIDUAL : 50.

MAXIMUM SLOWNESS RESIDUAL : 10.

The confidence level of modelled uncertainties is measured in [%] probability. The default value is 68.3 % (*i.e.*, +/- 1 standard deviation).

CONFIDENCE LEVEL : 68.3

3.7 MAGNITUDE CALCULATION PARAMETERS

If the data input file contains amplitude / period readings, station and network magnitudes can be estimated. By default, this option is switched off, '0'.

MAGNITUDE CALCULATION : 0

Three body wave attenuation models are available to calculate mb from 1st P-type onsets. The maximum allowed mb value is 8.5. The default model is set to 'G-R':

G-R = Gutenberg-Richter (1956a; 1956b), file ***MB_G-R.DAT***
V-C = Veith-Clawson (1972), file ***MB_V-C.DAT***
M-R = Rezapour (2003), file ***MB_M-R.DAT***

P-ATTENUATION MODEL : G-R

One can choose between two surface wave attenuation models to calculate MS from LR observations with a signal period larger than 5 s. The maximum allowed MS value is 9.5. The program uses by default 'IASPEI'.

IASPEI = Prague Formula from 1966 (see Willmore (1979) and citations therein)
R-P = formula 18 in Rezapour-Pearce (1998)

MS-ATTENUATION MODEL : IASPEI

For the calculation of local/regional ML from (regional/local) S- and Lg-type onsets one can choose between three models. The maximum allowed ML value is 7.5 and the default model is 'Bath':

Note: 'Richter' ML assumes original Wood-Anderson instrument or Wood-Anderson simulated amplitude measurements in [mm] and the period information is not used.

Model file name (to be used for **ML-CORRECTION FILE**)
Bath = ***MLCORR.TABLE***
This period-depending attenuation relation (Båth *et al.*, 1976) is originally only defined for periods between 0.3 and 1.4 s. The program accepts period measurement values between 0.24 s (= 4.16 Hz) and 1.68 s (= 0.595 Hz).
Richter = ***MLCORR.TABLE.wa***
The original Wood-Anderson attenuation curve for California (Richter, 1935).

Richter = ***MLCORR.TABLE.wa.nicolas***
A Wood-Anderson type curve for Europe modified by Nicolas *et al.* (1982).

ML-ATTENUATION MODEL : Bath

Setting the file name (see above) defines the attenuation **ML-ATTENUATION MODEL**. The file must be either located in the run-directory, or the directory defined by the environment variable **HYPOSAT_DATA**, or one has to give the full file name including directory path information. By default, this is set to '*MLCORR.TABLE*'.

ML-CORRECTION FILE : MLCORR.TABLE

All station magnitude values calculated from the observations are used to calculate (mean) network magnitudes. These magnitudes are then listed in ***hyposat-out*** including their uncertainties.

If of interest, one can limit the distance range in [°] of contributing observations by setting one or more of the following parameters. By default, no distance limits (beside limits of the correction tables) are used.

MIN DISTANCE FOR MS : 0.

MAX DISTANCE FOR MS : 180.

MIN DISTANCE FOR MB : 0.

MAX DISTANCE FOR MB : 180.

MIN DISTANCE FOR ML : 0.

MAX DISTANCE FOR ML : 20.

By default, only one magnitude per station and magnitude type (*i.e.*, the largest one) is used to calculate a network magnitude. If setting the following parameter, all observed station magnitudes are used to calculate the network magnitude (*i.e.*, amplitude and period measurements *e.g.*, from both P and pP or sP onsets as long they are within a time window of 8 s after the 1st onset).

All STATION MAGNITUDES : 0

3.8 I/O RELATED PARAMETERS

3.8.1 Input

The default data-input file name is ***hyposat-in***. Here, a different file name for the data-input file can be given. The default is also used when the parameter is set to '_' or ' '.

INPUT FILE NAME : hyposat-in

The ***hyposat-in*** format has slightly changed from **HYPOSAT 6** on. If the input file still follows the old syntax, one has to set this flag. The default is '0' for using the new syntax.

HYPOSAT-IN OLD SYNTAX : 0

The final **HYPOSAT** solution can be compared with a reference hypocenter location and source time, which can be set with the following parameters. The default is that no reference location is used, '0'.

REFERENCE EVENT : 0

REFERENCE SOURCE LONGITUDE : -999.

REFERENCE SOURCE LATITUDE : -999.

REFERENCE SOURCE DEPTH : -999.

3.8.2 Specific Parameters for ISF 1.0-formatted Input Files

Besides data input in **HYPOSAT** format, **HYPOSAT** can also read ISF (IMS) Bulletin formatted files as data input. The input-file name can be either ***hyposat-in*** or any other name as set with **INPUT FILE NAME**.

By default, the input is in **HYPOSAT** format as described in Chapter 2.

INPUT FORMAT ISF : 0

In the case of an ISF-formatted input file, the information about defining data (**TAS**) may be the result of an earlier location output. To force the program to use **all data** from the input file, one can set the following switch. The default setting is '0', which means using the **TAS** settings as defined by the input file.

ISF ALL PHASES : 0

ISF 1.0-formatted input has no given uncertainties (standard deviations) for the observations. Therefore, these values must be set by the program. To define standard deviations of the observed data, the reported quality of the onset readings is interpreted (see 'detection character' in the ISF/IMS documentation).

For higher precision onset time readings (input in milliseconds), the onset-time uncertainties set here are reduced by 20%. For non-P-type onset times, the values given here are doubled.

Standard deviation for i = impulsive onset readings (default 0.1 s):

ISF_i : 0.1

Standard deviation for e = emergent onset readings (default 0.5 s):

ISF_e : 0.5

Standard deviation for other, non-quality defined or q = questionable onset time readings (default 1 s):

ISF_o : 1.

Standard deviation for BAZ observations (default 20°):

ISF_baz : 20.

Standard deviation for slowness or ray parameter observations default (1 s/°):

ISF_slo : 1.

In ISF-formatted files, the listed origins are identified with an author (source). Different authors are allowed but usually one location is identified as primary location. Here the author of the preferred reference location can be set. This location will then be used as reference location and as starting solution for the inversion process if **ISF EPICENTER** or **ISF DEPTH** are set.

If one wants to use the primary location, independently from the author, one has to give 'PRIME'. If the parameter is set to '_', just the 1st origin line in the input file is used. Here follow some examples:

ISF REFERENCE LOCATION : NAO

ISF REFERENCE LOCATION : PRIME

ISF REFERENCE LOCATION : ISC

ISF REFERENCE LOCATION : _

3.8.3 Output

One can set the author (*e.g.*, the analyst, the network name, the project name, *etc.*) of the event-location inversion: a free character string with maximum 10 characters. The parameter is set by default to '**HYPOSAT**'.

AUTHOR OF SOLUTION : HYPOSAT

Program output is written by default in the file ***hyposat-out***, which is also used when input is '_' or ' '. This name can be changed.

OUTPUT FILE NAME : hyposat-out

With this flag any output to a file can be switched off. By default, this flag is set to '1' and the output is written in the file defined by **OUTPUT FILE NAME**.

OUTPUT SWITCH : 1

HYPOSAT can additionally write out the last location results in an ISF-formatted file. The file name is either ***hyposat-out.isf*** or any other name defined by the parameter **OUTPUT FILE NAME** with the automatically added extension ***.isf***. The option is set by the parameter **OUTPUT FORMAT ISF**, which is set by default to ('0'), no ISF-formatted output is written.

OUTPUT FORMAT ISF : 0

Any file name of the ISF formatted output file can be set with:

ISF OUTPUT FILE : file name

HYPOSAT can additionally write the location results in a JSON file. The file name is either ***hyposat-out.json*** or any other name defined by the parameter **OUTPUT FILE NAME** with the automatically added extension ***.json***. The option is set by the parameter **OUTPUT FORMAT JSON**, which is set by default to ('0'), no JSON-formatted output is written.

OUTPUT FORMAT JSON : 0

Any file name of the JSON formatted output file can be set with:

JSON OUTPUT FILE : file name

The epicentral distance of the observations can be calculated in [km] or [°]. See also **MAX EPI DIST OF STAT** and **MIN EPI DIST OF STAT**.

If setting the flag **OUTPUT IN KM**, no ISF-formatted file can be written (**OUTPUT FORMAT ISF** is then automatically set to '0').

The default value '0' is for an epicentral-distance output in [°].

OUTPUT IN KM : 0

By default, all observations from stations laying outside the defined distance range (see **MIN EPI DIST OF STAT** and **MAX EPI DIST OF STAT**) are not listed in the **HYPOSAT** output files ***hyposat-out*** or ***hyposat-out.isf***. If setting this flag to '1', the program lists all associated data (see the file ***hyposat-in***) independently from the epicentral distance of the observing station.

However, these data are then still not used to calculate the solution or any event location statistics (*e.g.*, mean residuals, azimuthal gaps, *etc*.).

OUTPUT ALL DISTANCES : 0

HYPOSAT can calculate theoretical BAZ and slowness values for all observations and write these values in the ***hyposat-out*** file. If theoretical values are added to the output file, no residuals are calculated, and these fields stay empty. By default, no theoretical BAZ or slowness values are listed ('0'). This parameter setting is ignored in ISF formatted output files.

0 = no output of theoretical values
1 = theoretical BAZ are given in output
2 = theoretical slowness values are given in output
3 = both (BAZ & slowness values) are given in output

OUTPUT OF THEO. BAZ+P : 0

HYPOSAT can also calculate for all identified body-wave onsets the corresponding emergence angles at the seismic source. This flag is by default switched off.

FLAG EMERGENCE ANGLE OUTPUT : 0

If the ISF 1.0-formatted input file contains reported quality of the onset readings (see 'detection character' in the ISF/IMS documentation) such information will be also written out by default in ***hyposat-out*** and ***hyposat-out.isf***. Based on the settings for **ISF_i**, **ISF_e** and **ISF_o** the applied data uncertainty during the last iteration can be translated into an uppercase 'detection character' and listed in the output files instead of the input from the ISF 1.0-formatted ***hyposat-in***. The later also applies to non ISF 1.0-formatted ***hyposat-in*** input. Then, this flag must be set to '1'.

TT DATA UNCERTAINTY OUT : 0

HYPOSAT calculates two types of RMS values: one is the traditional RMS of all residuals from defining travel-time observations and the other value is the RMS calculated from the weighted residuals as done at the ISC. Both values are listed in the ***hyposat-out*** file. In the case of an additional ISF-formatted output file (see **OUTPUT FORMAT ISF**), the origin line contains only one place to write an RMS value. By default, the traditional RMS value is used. If the following switch is set to '1', the ISC-type RMS value is written in the ISF-formatted output file.

ISC-TYPE ISF RMS : 0

HYPOSAT can calculate an epicentral uncertainty ellipse based on the chosen **CONFIDENCE LEVEL** and the estimated hypocenter or epicenter and source time uncertainties. By default, this option is switched on '1'.

EPICENTER UNCERTAINTY ELLIPSE : 1

The primary and secondary azimuthal gaps (see *e.g.*, Bondár, 2011) and the CPQ parameter (Gallacher *et al.*, 2025) can be calculated for

0 = defining observations (default)
1 = all stations with reported observations

In any case, observations are considered only from stations in the allowed distance range (see **MAX EPI DIST OF STAT** and **MIN EPI DIST OF STAT**)

AZIMUTHAL GAP FOR OBSERVATIONS : 0

The applied local/regional model around the source can be listed at the end of the output file ***hyposat-out*** by setting this parameter to '1'. The default setting is no model output.

OUTPUT OF REGIONAL MODEL : 0

In ISF-formatted files, Event and Origin Identifications (IDs) can be defined.

Event ID: Any integer is allowed between 0 and 999999999. By default, it will be set to 0 (but then the number from an eventually used ISF-formatted input file is used).

ISF EVENT ID : 0

An ISF-formatted file can contain several event locations for the same event. The different locations can be separated by Origin IDs. The Origin ID can be any 8- character long string.

By default ('_') **HYPOSAT** uses, if it exists, the ID from the ISF-formatted input file.

ISF ORIGIN ID : _

Based on the location results and after eventually renaming and/or merging onsets, the program can write a new file in input format. The file name will be ***hyposat-in.rev*** or the name defined by **OUTPUT FILE NAME** with the extension ***_rev***. By default, this option is switched off '0'.

FLAG NEW INPUT FILE : 0

HYPOSAT has different verbosity levels for output on the screen during program execution. This level can be defined here.

If **OUTPUT LEVEL** > 10, the output level for the screen is internally calculated and an extra output file ***hyposat_gmi.out*** is written with additional information about the Generalized Matrix Inversion (GMI) results. Then, the Resolution, Covariance, Correlation, and the Information- Density Matrix will be written out. A definition of the matrices can be found in *e.g.*, the textbooks of Aki & Richards (1980) or Menke (1989). The file ***hyposat_gmi.out*** always contains the named matrices for the last inversion. **OUTPUT LEVEL** can be set to the following values:

OUTPUT LEVEL	Output in ***hyposat_gmi.out***	Output Level on Screen
0 – 10	None	0 – 10
11	Resolution Matrix	4
12	Covariance Matrix	4
13	Correlation Matrix	4
14	All Three Matrices	4
15	"	5
16	"	6
17	"	7
18	"	8
19	"	9
20	", plus diagonal elements of the Information-Density Matrix	4
21 – 29	"	as for levels 11 – 19
30	", plus whole Information-Density Matrix	4
31 – 39	"	as for levels 11 – 19

As default value, the output (verbosity) level '**4**' is used.

OUTPUT LEVEL : 4

3.9 LIST OF OBSOLETE PARAMETERS AND THEIR NEW NAMES

Old SYNTAX		New Syntax
ATTENUATION MODEL	now	**P-ATTENUATION MODEL**
AZIMUTH AS DEFINING	now	**BAZ AS DEFINING**
AZIMUTH ONLY INIT SOL	now	**BAZ ONLY INIT SOL**
AZIMUTH ONLY	now	**BAZ ONLY**
CRUST 1.0 PATH	now	ignored
CRUST 5.1	please see for	**CRUST 1.0**
DBLE SID. ERROR FACTOR	now	**DBLE SID. UNCERTAINTY FACTOR**
DOUBLE SIDED TIME ERROR	now	**DOUBLE SIDED TIME UNCERTAINTY**
DOWNWEIGHTING OF TASD	now	**CHANGE WEIGHTING OF TASD**
EPICENTRE ERROR ELLIPSE	now	**EPICENTER UNCERTAINTY ELLIPSE**
IS PHASE GROUP-VEL	now	**IS-PHASE GROUP-VEL**
MAX T RES FOR AZI OF B USE	now	**MAX T RES FOR BAZ OF B USE**
MAX T RES FOR AZI OF L USE	now	**MAX T RES FOR BAZ OF L USE**
MAXIMUM ALLOWED P RESIDUUM	now	**MAXIMUM ALLOWED P RESIDUAL**
MAXIMUM ALLOWED S RESIDUUM	now	**MAXIMUM ALLOWED S RESIDUAL**
MAXIMUM AZIMUTH ERROR	now	**MAXIMUM BAZ RESIDUAL**
MAXIMUM BAZ RESIDUUM	now	**MAXIMUM BAZ RESIDUAL**
MAXIMUM SLOWNESS ERROR	now	**MAXIMUM SLOWNESS RESIDUAL**
MAXIMUM SLOWNESS RESIDUUM	now	**MAXIMUM SLOWNESS RESIDUAL**
S-ATTENUATION MODEL	see now for	**MS-ATTENUATION MODEL**
STARTING DEPTH ERROR	now	**STARTING DEPTH UNCERTAINTY**
STARTING LATITUDE ERROR	now	**STARTING LATITUDE UNCERTAINTY**
STARTING LONGITUDE ERROR	now	**STARTING LONGITUDE UNCERTAINTY**
STARTING TIME ERROR	now	**STARTING TIME UNCERTAINTY**
T PHASE GROUP-VEL	now	**T-PHASE GROUP-VEL**
USE ALL AZIMUTH INFORMATION	now	**USE ALL BAZ INFORMATION**
# TO SEARCH OSCILLATIONS	now	**ITERATIONS TO SEARCH OSCILLATIONS**

4 THE *hyposat-out* FILE

When executing ***../bin/hyposat*** with the input files ***hyposat-parameter.tele*** and ***hyposat-in.tele*** located in the directory ***./example/*** one will get the following ***hyposat-out*** file: This example is the inversion result after running the inversion on a LINUX Centos7 system, on other systems the results might be slightly different due to numerical effects. Explanations are included in brackets [ ]:

--------------------------- example for a ***hyposat-out*** file ---

```
HYPOSAT Version 6.2

Event solution by HYPOSAT

NORTHERN MOLUCCA SEA, 1996 29 June, converted from pIDC's Reviewed Event Bulletin (REB)


Parameters of initial solution (+/- 1 standard deviation):

[ Not all possible backazimuth-observation pairs are used: if one station is more than 170 deg apart from the crossing point, this crossing point is
skipped. ]
Mean epicenter calculated from   136 backazimuth observation pairs
Mean epicenter lat:   35.210 +/-    42.049 [deg]
Mean epicenter lon:  118.957 +/-     6.721 [deg]

[ type 1: S - P  or S1 - P1 observation, type 2: Sg - Pg observation, type 3: Sn - Pn observation, type 4: Sb - Pb observation ]
S-P Travel-time difference type 1 with   2 observation(s)
   to=   836008582.7 +/-  11.6 [s] Vp/Vs= 1.76 +/- 0.04
Mean source time:  836008582.700 +/-  11.636 [s]
Mean       vp/vs:            1.758 +/-   0.035

Iterations        :    9
Number of defining:   45
Reference model   : ak135_A

The new source parameters:

Confidence level of given uncertainties:  68.27 %

Source time  : 1996 06 29 00 36 42.439 +/-    0.089 [s]
        or              836008602.439 +/-    0.089 [s]
        or       1996-181:00.36.42.439 +/-    0.089 [s]

Epicenter lat:                 1.4102 +/-   0.0164 [deg]
Epicenter lon:               126.3106 +/-   0.0345 [deg]
Source depth :                 0.00    [km] Fixed by input

Epicenter uncertainty ellipse:
Major half axis:     4.19 [km]  Minor half axis:     2.49 [km]
Azimuth:      142.1  [deg] Area:          32.78 [km^2]

Flinn-Engdahl Region ( 266 ): Northern Molucca Sea

[ Here network magnitudes for MS and mb could be calculated including their standard deviations based on the single station magnitude observations and
the chosen attenuation model(s) (see magnitude parameter settings in hyposat-parameter). ]
Magnitude:  3.6 +/-  0.3 (    2 obs, MS, R-P)
Magnitude:  4.4 +/-  0.3 (   14 obs, mb, G-R)

[ Stat - station name; Delta - epicentral distance in [deg] or [km]; Azi - azimuth from epicenter in [deg]; Phase - phase name from hyposat-in; [used]
- program chosen phase name (if not identical with Phase); Onset time - hours, minutes & seconds from hyposat-in; Res - travel time residual in [s];
Baz - backazimuth (from station to epicenter) in [deg]; Res - Baz residual in [deg]; Rayp - ray parameter of onset in [s/deg]; ray parameter residual
in [s/deg]; Used - usage of input data as defining; SNR - signal-to-noise ratio; Amplitude - signal amplitude in [nm]; Period - signal period in [s];
MAG - magnitude and magnitude type; Q - onset quality as defined by parameter settings in hyposat-parameter; Em-Ang - emergence angle of seismic onset
at the source in [deg]; ARID - Arrival-id ]
Stat  Delta   Azi    Phase   [used]    Onset time    Res      Baz     Res   Rayp   Res  Used      SNR    Amplitude  Period  MAG     Q Em-Ang ARID

WRA    22.635 160.04 P                 00 41 44.700  -0.536 331.50   -7.23 11.10   0.48 TAS      97.80        4.50  0.300 4.44 mb E  33.63 abcdef01
WRA    22.635 160.04 S                 00 45 48.700  -5.946 338.00   -0.73 17.00  -2.31  A        8.10        2.00  0.900         _  36.94 abcdef02
QIS    25.422 149.87 P1      P         00 42 12.800   0.734                            T  D      35.50                            E  28.27 abcdef03
QIS    25.422 149.87 PcP               00 45 44.800   0.196                            T  D                                       E   6.75 abcdef04
ASAR   25.997 163.95 P                 00 42 16.900  -0.381 346.30    3.84  7.10  -1.96 TA D     35.10        3.40  0.500 4.23 mb E  28.19 abcdef05
ASAR   25.997 163.95 PcP               00 45 45.200  -0.691 345.10    2.64  2.30   0.00 TASD     11.50        2.20  0.500         E   6.88 abcdef06
ASAR   25.997 163.95 S                 00 46 45.300  -3.898 347.60    5.14 20.30   4.49  A        6.10        3.90  0.800         _  29.48 abcdef07
WARB   27.434 179.35 P                 00 42 31.200   1.012 339.40  -19.88  8.20  -0.78 T SD      8.20        6.50  0.700 4.51 mb E  27.91 abcdef08
WARB   27.434 179.35 PcP               00 45 49.400   0.213                            T  D                                       E   7.20 abcdef09
MEEK   28.857 194.38 P                 00 42 42.700  -0.205                            T          6.80                            E  27.62 abcdef10
CMAR   31.745 303.97 P                 00 43  9.000   0.450 109.70   -9.44  7.80  -1.00 TAS       4.30        0.60  0.400 3.88 mb E  27.31 abcdef11
CMAR   31.745 303.97 LR                00 57 48.700  26.463 110.00   -9.14 39.50   0.45                     188.80 19.360 3.87 MS _        abcdef12
FORT   32.054 177.16 P                 00 43 11.300   0.249                            T         10.80                            E  27.27 abcdef13
WOOL   32.603 187.39 P                 00 43 15.600  -0.301   7.90   -0.72  9.90   1.14 TA        8.80        4.10  0.600 4.54 mb E  27.20 abcdef14
SHK    33.484   9.55 P                 00 43 25.400   1.832                                                                       _  27.05 abcdef15
KSAR   35.885   2.14 P                 00 43 46.700   2.438 177.30   -5.38 10.10   1.52  A        7.20        1.70  0.700 4.00 mb _  26.57 abcdef18
[ The following BAZ observation of the LR onset was not used because its travel-time residual became too large. ]
KSAR   35.885   2.14 LR                01 04 25.000 261.541 160.00  -22.68 46.00   6.96                      40.10 19.860 3.24 MS _        abcdef19
STKA   36.139 157.65 P                 00 43 46.800   0.247 323.20  -10.26  9.00   0.44 T SD      8.30        7.20  0.600 4.67 mb E  26.52 abcdef16
STKA   36.139 157.65 PcP               00 46 12.000  -0.544                            T  D                                       E   8.94 abcdef17
MJAR   36.651  16.15 P                 00 43 51.900   1.001 357.10  156.90 18.80  10.27 T                     2.00  0.550 4.10 mb E  26.41 abcdef20
PDY    59.022 351.98 P                 00 46 47.000   3.081 111.20  -52.87  6.60  -0.34   S      23.80        4.30  0.450 4.78 mb _  21.22 abcdef21
ZAL    62.463 333.77 P                 00 47  9.000   1.533                                                                       _  20.42 abcdef22
ABKT   72.023 309.48 P                 00 48  9.500   0.890                            T                                          E  18.23 abcdef23
[ The associated but unnamed phase tx was identified as P onset and the corresponding residuals were calculated. ]
NRI    72.517 346.74 tx      P         00 48  8.700  -2.083 195.90   56.33  3.90  -2.06          11.20        3.00  0.750 4.50 mb _  18.12 abcdef24
MAW    81.448 200.28 P                 00 49  1.100   0.006                            T                                          E  16.04 abcdef25
KVAR   84.422 313.85 P                 00 49 17.200  -0.116                            T                                          E  15.33 abcdef26
NPO    87.365  25.36 P                 00 49 31.000  -0.273                            T                                          E  14.61 abcdef27
ARCES  92.466 339.77 P                 00 49 51.700  -3.391  94.50   15.11  4.10  -0.52   S      10.50        0.80  0.550 4.31 mb _  13.94 abcdef28
SPITS  92.658 348.81 P                 00 49 55.900   0.052 116.60   46.42  3.50  -1.12 T        10.40        3.60  0.900 4.77 mb E  13.93 abcdef29
FINES  93.664 331.72 P                 00 50  0.000  -0.711 111.20   30.86  5.90   1.30 T         6.60        0.60  0.550 4.17 mb E  13.89 abcdef30
HFS    99.860 332.03 P       Pdif      00 50 28.700  -0.136 311.30 -118.20  1.50  -2.95 T         3.70        1.10  0.750 4.58 mb E  13.41 abcdef31
SCHQ  122.908   9.02 PKPdf   PKiKP     00 55 41.200   0.263                            T                                          E   5.91 abcdef33
TXAR  123.329  53.16 PKPdf   PKiKP     00 55 42.700   0.040                            T                                          E   5.92 abcdef32
DBIC  130.605 279.96 PKPdf   PKiKP     00 55 57.100  -0.276                            T                                          E   6.03 abcdef34
PLCA  137.981 160.77 PKPdf             00 56  9.100  -0.689 311.90  106.23  6.40   4.56 T         4.40        0.90  0.900         E   5.51 abcdef35
LPAZ  159.482 136.90 PKPdf             00 56 44.700  -0.492                            T                                          E   3.44 abcdef36

Defining travel-time differences:

 Stat  Delta  Phases           Observed   Res
```

```
QIS    25.422 PcP - P          212.000  -0.538
ASAR   25.997 PcP - P          208.300  -0.310
WARB   27.434 PcP - P          198.200  -0.799
STKA   36.139 PcP - P          145.200  -0.791

Number of usable stations:   28
```

[The azimuth range of the maximum gap without any observations is always given in clockwise direction. For details about the location-accuracy measure CPQ, please see Gallacher *et al.*, 2025.]

```
Maximum azimuthal gap of defining observations:  53.2 -> 136.9 [deg] =  83.7 [deg]; CPQ =  0.854
```

[The azimuth range of the maximum possible secondary gap (see Bondár *et al.*, 2004) without any observations is always given in clockwise direction.]

```
Maximum secondary azimuthal gap of defining observations:  25.4 -> 136.9 [deg] = 111.5 [deg]; CPQ =  0.769
```

[RMS is defined as $\sqrt{\frac{\sum Res^2}{N}}$, MEAN-RES is defined as $\frac{\sum|Res|}{N}$, and MEAN is defined as $\frac{\sum Res}{N}$; all with the above listed residuals *Res* and the corresponding number of data *N* as listed in the first column.]

```
Residuals of defining data          RMS     MEAN-RES       MEAN
    26 onset times            :    0.503       0.412      0.000  [s]
     8 backazimuth values     :    5.238       4.390     -1.484  [deg]
     7 ray parameters         :    0.586       0.508     -0.244  [s/deg]
     4 travel-time differences :    0.642       0.610     -0.610  [s]
```

[The weighted RMS as used at the ISC is defined as $\sqrt{\frac{\sum\frac{Res^2}{w}}{\sum\frac{1}{w}}}$ with the above listed residuals *Res* and the data weights *w* used for the inversion (*i.e.*, the applied standard deviations of the observed onset times)]

```
Weighted RMS of onset times (ISC type):    0.503 [s]
```

[The weighted misfit is here defined for the L1-norm as $\frac{\sum\frac{|Res|}{w}}{N}$ and for the L2-norm as $\sqrt{\frac{\sum\left(\frac{Res}{w}\right)^2}{N}}$ with *N* the number of data as listed in the first column. Input data means here also data not used to locate the event. In this case, all backazimuth and ray parameter observations defined as usable by the switches in ***hyposat-in*** were also included.]

```
Weighted misfit of input data         L1      L2
    33 onset times            :    2.818    4.179
    18 backazimuth values     :    1.421    2.389
    17 ray parameters         :    1.474    2.734
     4 travel-time differences :    1.437    1.514
    72 misfit over all         :    2.075    3.365
```

[The following line is a repetition of the most important inversion results T0 - source time; LAT - source latitude; LON - source longitude; Z - source depth; VPVS - Vp / Vs as estimated by the Wadati approach; DLAT - latitude uncertainty; DLON - longitude uncertainty; DZ - depth uncertainty, if the depth was fixed, this is indicated here; DT0 - source time uncertainty; DVPVS – VPVS uncertainty; DEF - number of defining data; RMS - root-mean-square of defining onset times]

```
T0                        LAT      LON       Z      VPVS   DLAT     DLON      DZ        DT0    DVPVS DEF    RMS
1996-06-29 00 36 42.439   1.410  126.311    0.00   1.76   0.0164   0.0345  Fixed     0.089   0.04   45    0.503
```

[However, we have still a fixed depth. Let us now try to fit the data better with another depth (see **DEPTH FLAG** is set to **b**!)]

```
Iterations        :    3
Number of defining:   54
Reference model   : ak135_A

The new source parameters:

Confidence level of given uncertainties:  68.27 %

Source time  : 1996 06 29 00 36 49.185 +/-    0.496 [s]
        or                836008609.185 +/-    0.496 [s]
        or       1996-181:00.36.49.185 +/-    0.496 [s]

Epicenter lat:                 1.3221 +/-   0.0152 [deg]
Epicenter lon:               126.2942 +/-   0.0360 [deg]
Source depth :                 44.78   +/-   4.43   [km]
```

[The mean travel-time residual was not zero. The source time is therefore corrected for this bias.]

```
Source time corrected for mean travel-time residual (    -0.032 [s])

Source time  : 1996 06 29 00 36 49.153 +/-    0.496 [s]
        or                836008609.153 +/-    0.496 [s]
        or       1996-181:00.36.49.153 +/-    0.496 [s]
```

[Note the change of the epicenter uncertainty ellipse.]

```
Epicenter uncertainty ellipse:
Major half axis:     8.63 [km]  Minor half axis:     1.88 [km]
Azimuth:       45.7  [deg] Area:           51.06 [km^2]

Flinn-Engdahl Region ( 266 ): Northern Molucca Sea

Magnitude:  3.6 +/-  0.3 (    2 obs, MS, R-P)
Magnitude:  4.4 +/-  0.3 (   14 obs, mb, G-R)


 Stat  Delta    Azi   Phase   [used]    Onset time    Res      Baz     Res    Rayp    Res  Used      SNR    Amplitude  Period  MAG    Q Em-Ang ARID

WRA    22.558 159.93 P                00 41 44.700  -0.978 331.50   -7.11 11.10   0.51 TASD     97.80         4.50  0.300 4.36 mb E  50.24 abcdef01
WRA    22.558 159.93 S                00 45 48.700  -1.882 338.00   -0.61 17.00   0.65 TASD      8.10         2.00  0.900         E  41.39 abcdef02
QIS    25.355 149.75 P1      P        00 42 12.800   0.543                             T  D     35.50                              E  41.16 abcdef03
QIS    25.355 149.75 PcP              00 45 44.800   0.556                             T  D                                        E   9.38 abcdef04
ASAR   25.918 163.87 P                00 42 16.900  -0.457 346.30    3.93  7.10  -1.95 TA D     35.10         3.40  0.500 4.19 mb E  41.02 abcdef05
ASAR   25.918 163.87 PcP              00 45 45.200  -0.303 345.10    2.73  2.30   0.00 TASD     11.50         2.20  0.500         E   9.56 abcdef06
ASAR   25.918 163.87 S                00 46 45.300   0.622 347.60    5.23 20.30   4.49 TA D      6.10         3.90  0.800         E  39.71 abcdef07
WARB   27.347 179.32 P                00 42 31.200   1.020 339.40  -19.84  8.20  -0.76 T SD      8.20         6.50  0.700 4.41 mb E  40.54 abcdef08
WARB   27.347 179.32 PcP              00 45 49.400   0.622                             T  D                                        E  10.00 abcdef09
MEEK   28.768 194.39 P                00 42 42.700  -0.169                             T         6.80                              E  40.11 abcdef10
CMAR   31.781 304.10 P                00 43  9.000  -0.591 109.70   -9.59  7.80  -0.99 TAS       4.30         0.60  0.400 3.79 mb E  39.58 abcdef11
CMAR   31.781 304.10 LR               00 57 48.700  18.366 110.00   -9.29 39.50   0.45                     188.80 19.360 3.87 MS _         abcdef12
FORT   31.968 177.13 P                00 43 11.300   0.282                             T        10.80                              E  39.54 abcdef13
WOOL   32.514 187.38 P                00 43 15.600  -0.245   7.90   -0.71  9.90   1.14 TA        8.80         4.10  0.600 4.47 mb E  39.42 abcdef14
SHK    33.573   9.55 P                00 43 25.400   0.349                             T                                           E  39.12 abcdef15
KSAR   35.973   2.15 P                00 43 46.700   1.012 177.30   -5.41 10.10   1.54 TA        7.20         1.70  0.700 4.03 mb E  38.34 abcdef18
KSAR   35.973   2.15 LR               01 04 25.000 251.390 160.00  -22.71 46.00   6.96                      40.10 19.860 3.24 MS _         abcdef19
STKA   36.065 157.58 P                00 43 46.800   0.214 323.20  -10.18  9.00   0.45 T SD      8.30         7.20  0.600 4.72 mb E  38.31 abcdef16
STKA   36.065 157.58 PcP              00 46 12.000  -0.160                             T  D                                        E  12.44 abcdef17
MJAR   36.740  16.14 P                00 43 51.900  -0.416 357.10  156.92 18.80  10.29 T                      2.00  0.550 4.17 mb E  38.09 abcdef20
PDY    59.107 352.00 P                00 46 47.000   2.168 111.20  -52.91  6.60  -0.32   S      23.80         4.30  0.450 4.79 mb _  30.09 abcdef21
ZAL    62.534 333.80 P                00 47  9.000   0.772                             T                                           E  28.90 abcdef22
ABKT   72.066 309.51 P                00 48  9.500   0.459                             T                                           E  25.68 abcdef23
NRI    72.599 346.76 tx      P        00 48  8.700  -2.733 195.90   56.30  3.90  -2.04          11.20         3.00  0.750 4.37 mb _  25.49 abcdef24
MAW    81.360 200.28 P                00 49  1.100   0.397                             T                                           E  22.54 abcdef25
KVAR   84.471 313.86 P                00 49 17.200  -0.406                             T                                           E  21.46 abcdef26
NPO    87.451  25.36 P                00 49 31.000  -0.701                             T                                           E  20.36 abcdef27
ARCES  92.543 339.77 P                00 49 51.700  -3.732  94.50   15.07  4.10  -0.52   S      10.50         0.80  0.550 4.29 mb _  19.52 abcdef28
SPITS  92.741 348.81 P                00 49 55.900  -0.317 116.60   46.38  3.50  -1.11 T        10.40         3.60  0.900 4.74 mb E  19.50 abcdef29
FINES  93.733 331.71 P                00 50  0.000  -1.017 111.20   30.81  5.90   1.30 T         6.60         0.60  0.550 4.19 mb E  19.44 abcdef30
HFS    99.930 332.02 P       Pdif     00 50 28.700  -0.416 311.30 -118.25  1.50  -2.95 T         3.70         1.10  0.750 4.57 mb E  18.77 abcdef31
SCHQ  122.997   9.01 PKPdf            00 55 41.200   0.524                             T                                           E   7.98 abcdef33
TXAR  123.395  53.20 PKPdf            00 55 42.700   0.371                             T                                           E   7.97 abcdef32
DBIC  130.604 279.88 PKPdf            00 55 57.100   0.812                             T                                           E   7.88 abcdef34
PLCA  137.904 160.82 PKPdf            00 56  9.100  -0.319 311.90  106.30  6.40   4.56 T         4.40         0.90  0.900         E   7.65 abcdef35
LPAZ  159.429 137.09 PKPdf            00 56 44.700  -0.178                             T                                           E   4.78 abcdef36

Defining travel-time differences:
```

```
 Stat  Delta  Phases           Observed   Res

WRA    22.558 S - P             244.000  -0.904
QIS    25.355 PcP - P           212.000   0.013
ASAR   25.918 PcP - P           208.300   0.154
ASAR   25.918 S - P             268.400   1.079
ASAR   25.918 S - PcP            60.100   0.925
WARB   27.347 PcP - P           198.200  -0.398
STKA   36.065 PcP - P           145.200  -0.374

Number of usable stations:   28

[ Here we get the number of all iterations e.g., also including an earlier solution for fixed depth. ]
Total number of iterations:    21

Maximum azimuthal gap of defining observations:  53.2 -> 137.1 [deg] =  83.9 [deg]; CPQ =  0.853

Maximum secondary azimuthal gap of defining observations:  25.4 -> 137.1 [deg] = 111.7 [deg]; CPQ =  0.769

Residuals of defining data          RMS     MEAN-RES       MEAN
    31 onset times            :    0.654       0.552      0.000  [s]
     8 backazimuth values     :    5.279       4.416     -1.441  [deg]
     8 ray parameters         :    0.592       0.525     -0.121  [s/deg]
     7 travel-time differences :    0.672       0.550      0.071  [s]

Weighted RMS of onset times (ISC type):    0.614 [s]

Weighted misfit of input data         L1      L2
    33 onset times            :    2.198    3.122
    18 backazimuth values     :    1.421    2.389
    17 ray parameters         :    1.428    2.726
     7 travel-time differences :    0.935    1.075
    75 misfit over all        :    1.719    2.729

T0                         LAT      LON       Z     VPVS   DLAT     DLON      DZ       DT0    DVPVS DEF    RMS
1996-06-29 00 36 49.153    1.322  126.294   44.78   1.76   0.0152   0.0360    4.43    0.496   0.04   54    0.654
```

--------------------------- end of the ***hyposat-out*** example file ---

5 THE PROGRAM HYPOMOD AND THE *hypomod-out* FILE

In some cases, it may be of interest to know how well a set of observations fits with a specific source location. The program **HYPOMOD** calculates for a given seismic hypocenter solution the residuals for all observed data: the travel times, travel-time differences, the backazimuths and the slowness values. With the example given here for a hypocenter inversion with **HYPOSAT**, one has only to modify slightly the ***hyposat-parameter*** file and then one can execute the program **HYPOMOD**. The only modifications needed in ***hyposat-parameter*** are to set as starting source parameters the inversion results. Then, ignoring all inversion related settings in ***hyposat-parameter*** one will get an output-file called by default ***hypomod-out***. This default name can be modified by setting the parameter **OUTPUT FILE NAME** in ***hyposat-parameter*** different than the default ***hyposat-out***. The file ***hypomod-out*** has in principle the same format as ***hyposat-out***.

HYPOMOD calculates residuals and the statistical parameters for this solution from **all(!)** input data as defined in the ***hypomod-in*** input file (default name), which has the same contents and format as ***hyposat-in***. Therefore, the statistical parameters as *e.g.*, mean residuals or RMS values are different from the ones calculated after the final inversion in **HYPOSAT** (please compare with the 2nd solution in the file ***hyposat-out.tele***.

No output can be written in ISF or JSON format.

------------- example for changes in the ***hyposat-parameter*** file --

The following ***hyposat-parameter*** flag is used only with **HYPOMOD**. It allows to search for the best fitting phase name for an associated body wave independently from the name given in the input file. By default, this option is switched off ('0').

FLAG FREE PHASE SEARCH : 0

Then, one has also to give the source parameters. Here, the location results from the teleseismic event example in the directory ***./examples/*** are used (see also Chapter 4), so the file ***hypomod-in*** is identical with the file ***hyposat-in*** of Chapter 2 and which was used for the example in Chapter 4. In this example the parameter **FLAG FREE PHASE SEARCH** was set to '1'.

INPUT FILE NAME : ***hypomod-in***

OUTPUT FILE NAME : ***hypomod-out***

STARTING SOURCE LATITUDE : 1.3221

STARTING SOURCE LONGITUDE : 126.2942

STARTING SOURCE DEPTH : 44.78

STARTING SOURCE TIME : 836008609.155

or

STARTING SOURCE TIME : 1996-181:00.36.49.155

or

STARTING SOURCE TIME : 1996-06-29 00:36:49.155

When running **HYPOMOD** it can also be of interest to ask for the theoretical BAZs and ray parameters (see Chapter 3 for details) from all observations (as also done in our example):

OUTPUT OF THEO. BAZ+P : 3

-------------------- end of example --

When executing on the Linux system the C-shell script ***./run_hypomod_example*** in the directory ***./examples/***, you should get an output file ***hypomod-out*** looking like this, with explanations included again in brackets [ ]:

-------------------- example for a ***hypomod-out*** file --

```
HYPOMOD Version 2.2

Event solution by input from HYPOSAT6.2

NORTHERN MOLUCCA SEA, 1996 29 June, converted from pIDC's Reviewed Event Bulletin (REB)

Reference model   : ak135_A

The source parameters:

Source time  : 1996 06 29 00 36 49.153
        or              836008609.153 [s]
        or       1996-181:00.36.49.153

Epicenter lat:                 1.3221 [deg]
Epicenter lon:               126.2942 [deg]
Source depth :                44.78   [km]

Flinn-Engdahl Region ( 266 ): Northern Molucca Sea

Magnitude:  3.6 +/-  0.3 (    2 obs, MS, R-P)
Magnitude:  4.4 +/-  0.3 (   14 obs, mb, G-R)


 Stat  Delta   Azi   Phase   [used]    Onset time    Res      Baz     Res   Rayp   Res  Used      SNR    Amplitude  Period  MAG    Q Em-Ang ARID

WRA    22.558 159.93 P                00 41 44.700  -0.978 331.50   -7.11 11.10   0.51 TASD     97.80         4.50  0.300 4.36 mb _  50.24 abcdef01
WRA    22.558 159.93 S                00 45 48.700  -1.882 338.00   -0.61 17.00   0.65 TASD      8.10         2.00  0.900         _  41.39 abcdef02
[ For the following phase, no BAZ or ray parameter observations were reported. Because of the setting for  OUTPUT OF THEO. BAZ+P to '3', the program fills in the theoretical values without calculating any residuals. ]
QIS    25.355 149.75 P1      P        00 42 12.800   0.544 327.49          9.07        T  D     35.50                               _  41.16 abcdef03
QIS    25.355 149.75 PcP              00 45 44.800   0.556 327.49          2.25        T  D                                         _   9.38 abcdef04
ASAR   25.918 163.87 P                00 42 16.900  -0.456 346.30    3.93  7.10  -1.95 TASD     35.10         3.40  0.500 4.19 mb _  41.02 abcdef05
ASAR   25.918 163.87 PcP              00 45 45.200  -0.303 345.10    2.73  2.30   0.00 TASD     11.50         2.20  0.500         _   9.56 abcdef06
ASAR   25.918 163.87 S                00 46 45.300   0.623 347.60    5.23 20.30   4.49 TASD      6.10         3.90  0.800         _  39.71 abcdef07
WARB   27.347 179.32 P                00 42 31.200   1.021 339.40  -19.84  8.20  -0.76 TASD      8.20         6.50  0.700 4.41 mb _  40.54 abcdef08
WARB   27.347 179.32 PcP              00 45 49.400   0.622 359.24          2.40        T  D                                         _  10.00 abcdef09
MEEK   28.768 194.39 P                00 42 42.700  -0.169  16.12          8.88        T         6.80                               _  40.11 abcdef10
CMAR   31.781 304.10 P                00 43  9.000  -0.591 109.70   -9.59  7.80  -0.99 TAS       4.30         0.60  0.400 3.79 mb _  39.58 abcdef11
CMAR   31.781 304.10 LR               00 57 48.700  18.367 110.00   -9.29 39.50   0.45  A                   188.80 19.360 3.87 MS _        abcdef12
FORT   31.968 177.13 P                00 43 11.300   0.283 356.67          8.78        T        10.80                               _  39.54 abcdef13
WOOL   32.514 187.38 P                00 43 15.600  -0.244   7.90   -0.71  9.90   1.14 TAS       8.80         4.10  0.600 4.47 mb _  39.42 abcdef14
SHK    33.573   9.55 P                00 43 25.400   0.349 191.60          8.70        T                                            _  39.12 abcdef15
KSAR   35.973   2.15 P                00 43 46.700   1.012 177.30   -5.41 10.10   1.54 TAS       7.20         1.70  0.700 4.03 mb _  38.34 abcdef18
KSAR   35.973   2.15 LR               01 04 25.000 251.389 160.00  -22.71 46.00   6.96  A                    40.10 19.860 3.24 MS _        abcdef19
STKA   36.065 157.58 P                00 43 46.800   0.214 323.20  -10.18  9.00   0.45 TASD      8.30         7.20  0.600 4.72 mb _  38.31 abcdef16
STKA   36.065 157.58 PcP              00 46 12.000  -0.160 333.38          2.98        T  D                                         _  12.44 abcdef17
MJAR   36.740  16.14 P                00 43 51.900  -0.416 357.10  156.92 18.80  10.29 TAS                    2.00  0.550 4.17 mb _  38.09 abcdef20
PDY    59.107 352.00 P                00 46 47.000   2.168 111.20  -52.91  6.60  -0.32 TAS      23.80         4.30  0.450 4.79 mb _  30.09 abcdef21
ZAL    62.534 333.80 P                00 47  9.000   0.773 131.71          6.67        T                                            _  28.90 abcdef22
ABKT   72.066 309.51 P                00 48  9.500   0.459 102.71          5.98        T                                            _  25.68 abcdef23
NRI    72.599 346.76 tx      P        00 48  8.700  -2.733 195.90   56.30  3.90  -2.04  A       11.20         3.00  0.750 4.37 mb _  25.49 abcdef24
MAW    81.360 200.28 P                00 49  1.100   0.398  64.74          5.29        T                                            _  22.54 abcdef25
KVAR   84.471 313.86 P                00 49 17.200  -0.406  93.49          5.05        T                                            _  21.46 abcdef26
NPO    87.451  25.36 P                00 49 31.000  -0.701 267.69          4.81        T                                            _  20.36 abcdef27
ARCES  92.543 339.77 P                00 49 51.700  -3.732  94.50   15.07  4.10  -0.52 TAS      10.50         0.80  0.550 4.29 mb _  19.52 abcdef28
SPITS  92.741 348.81 P                00 49 55.900  -0.317 116.60   46.38  3.50  -1.11 TAS      10.40         3.60  0.900 4.74 mb _  19.50 abcdef29
FINES  93.733 331.71 P                00 50  0.000  -1.017 111.20   30.81  5.90   1.30 TAS       6.60         0.60  0.550 4.19 mb _  19.44 abcdef30
HFS    99.930 332.02 P       Pdif     00 50 28.700  -0.416 311.30 -118.25  1.50  -2.95 TAS       3.70         1.10  0.750 4.57 mb _  18.77 abcdef31
[ Because the parameter FLAG FREE PHASE SEARCH was set to '1', the program identifies the onsets as PkiKP, which has a smaller travel-time residual ]
SCHQ  122.997   9.01 PKPdf   PKiKP    00 55 41.200   0.310 344.29          1.97        T                                            _   8.21 abcdef33
TXAR  123.395  53.20 PKPdf   PKiKP    00 55 42.700   0.133 293.54          1.98        T                                            _   8.22 abcdef32
DBIC  130.604 279.88 PKPdf   PKiKP    00 55 57.100  -0.054  82.53          2.01        T                                            _   8.37 abcdef34
PLCA  137.904 160.82 PKPdf            00 56  9.100  -0.319 311.90  106.30  6.40   4.56 TAS       4.40         0.90  0.900         _   7.65 abcdef35
LPAZ  159.429 137.09 PKPdf            00 56 44.700  -0.178 225.14          1.15        T                                            _   4.78 abcdef36

Defining travel-time differences:

 Stat  Delta  Phases           Observed   Res

WRA    22.558 S - P             244.000  -0.904
QIS    25.355 PcP - P           212.000   0.013
ASAR   25.918 PcP - P           208.300   0.154
```

```
ASAR   25.918 S - P            268.400   1.079
ASAR   25.918 S - PcP           60.100   0.925
WARB   27.347 PcP - P          198.200  -0.399
STKA   36.065 PcP - P          145.200  -0.374

Number of usable stations:   28

Maximum azimuthal gap of all observations:  53.2 -> 137.1 [deg] =  83.9 [deg] CPQ =  0.854

Maximum secondary azimuthal gap of all observations:  25.4 -> 137.1 [deg] = 111.7 [deg] CPQ =  0.769

Residuals of defining data          RMS     MEAN-RES       MEAN
    33 onset times             :    0.968       0.661     -0.087  [s]
    20 backazimuth values      :   55.011      34.014      8.353  [deg]
    17 ray parameters          :    3.151       1.973      0.962  [s/deg]
     7 travel-time differences :    0.672       0.550      0.071  [s]

T0                         LAT      LON       Z     VPVS   DLAT     DLON      DZ       DT0    DVPVS DEF    RMS
1996-06-29 00 36 49.153    1.322  126.294   44.78   0.00   0.0000   0.0000  Fixed     0.000   0.00   77    0.968
```

---------------------------- end of the ***hypomod-out*** file example---

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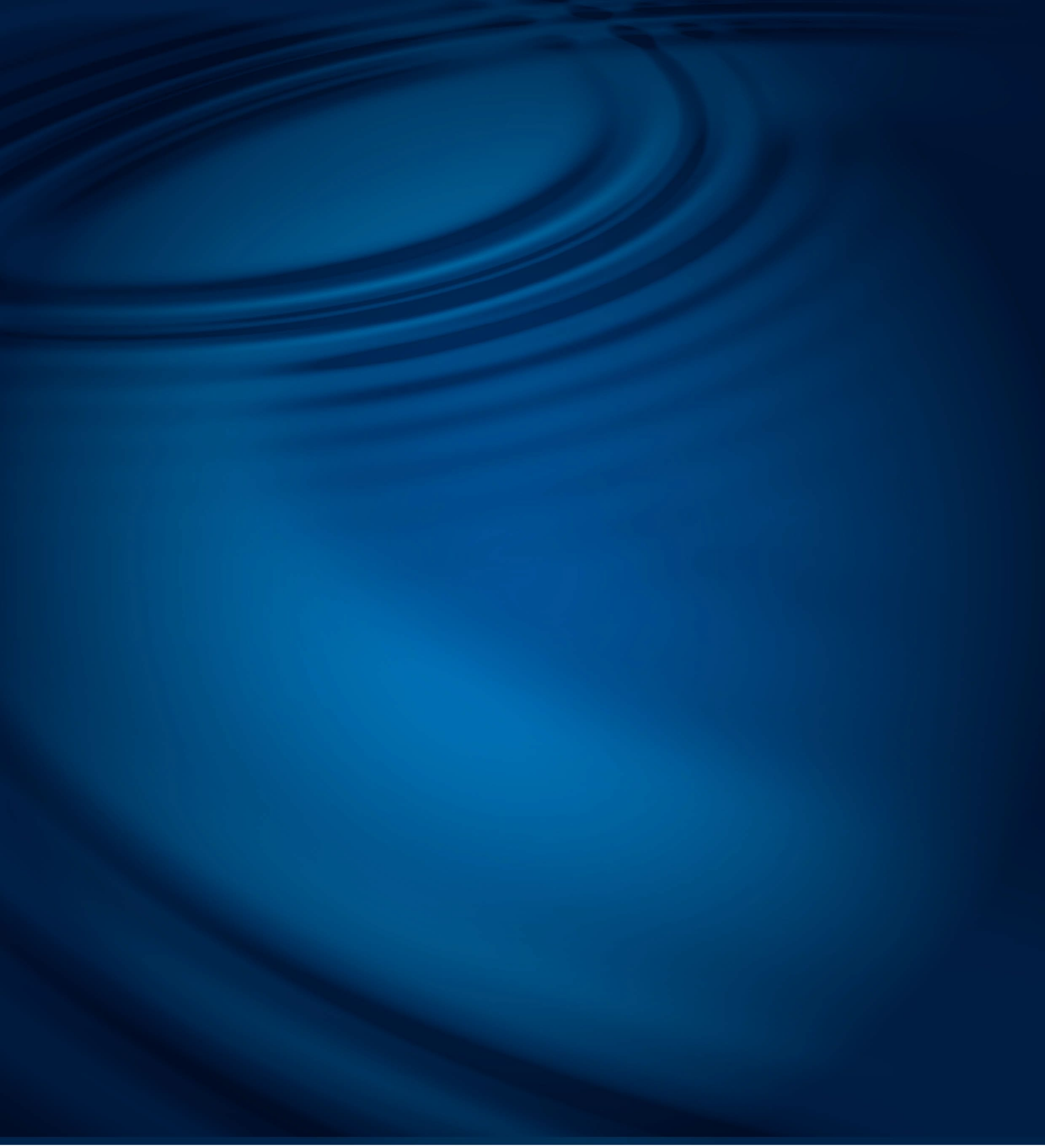
7 INDEX



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info@norsar.no
www.norsar.no