University of New Brunswick
Department of Geodesy and Geomatics Engineering

SHGEO software package

An UNB Application to Stokes-Helmert Approach for Precise Geoid Computation

Reference Manual II.

Software User's Guide

Fredericton, New Brunswick, Canada
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Preface

The Stokes-Helmert Geoid software (SHGeo software) is a scientific software package for a precise geoid determination based on the Stokes-Helmert theory of determination of the gravimetric geoid. The software has been developed during a period of more then 10 years under the leadership of professor Petr Vaníček at the Department of Geodesy and Geomatics Engineering, University of New Brunswick in Fredericton. Authors of particular programs are: Juraj Janák, Pavel Novák, Mehdi Najafi-Alamdari, Jianliang Huang, Sander van Eck van der Sluijs, Robert Tenzer and Artu Ellmann. We also have to mention Z. Martinec, A. Kleusberg, L.E. Sjöberg, W.E. Featherstone and W. Sun whose research presented in their papers was incorporated into the SHGeo software. SHGeo software uses global geopotential models (e.g., GRIM4-S4, EGM-96, GGM-02) and a global elevation model (TUG-87 or JGP95 for instance). These global models play an important role in the geoid computation scheme. Therefore we acknowledge the contribution of all research teams that have developed these or other global models.

The present software version (SHGEO 3.1) is an upgrade of the three earlier SHGeo packages:
SHGEO vers. 1 (standard Helmert approach) was compiled by Dr. J. Janak in 2001
SHGEO vers. 2 (formulated for the NoTopography space) was compiled by Dr. R. Tenzer in 2003
SHGEO vers. 3 (capable of standard Helmert and the NoTopography) was compiled by Dr. A. Ellmann in 2005

This reference manual and the current version of the package, SHGEO 3.1 (standard Helmert and NoTopography) is compiled by D. Avalos in 2009. New programs (dwnc08.c, res_anomaly.c and cogeoid2geoid.c) as well as bug-fixes for the Stokes integral computation are included in this version.

The manual consists of three parts. Part I contains the theoretical description of the Stokes-Helmert method of the geoid determination by Dr. A. Ellmann. Part II is the reference user's guide with the description of the particular programs for the geoid computation, and Part III has the description of auxiliary programs, which can be used for data manipulation and format transformations.

Contents:

1. Software User's guide

The Stokes-Helmert geoid software package for computation of the precise geoid consists of a set of independent programs to compute particular quantities separately. These are intended to follow the process of gravimetric data starting from a set of scattered observations of free air gravity anomaly on the topography to the best estimate of mean geoidal height in a grid of continuous coverage. Next is a brief description of the main programs involved:

*** Data preparation and gridding of gravity anoamlies**

dte_dp.c for computation of simple Bouguer gravity anomalies, terrain correction and complete Bouguer gravity anomalies from a database of scattered free-air anomalies.

An interpolation and averaging process takes place from the results of **dte_dp.c** to obtain mean values of complete Bouguer gravity anomaly on a regular grid. No particular programs are provided in **SHGeo** to perform this step.

dte_pm.c for computation of mean values on a regular grid: the near-zone contribution to the terrain correction, condensed terrain correction and direct topographical effect.

fair.c for computation of the mean free-air gravity anomalies from the mean complete Bouguer gravity anomalies.

dtf.f for computation of the far-zone contribution to the direct topographical effect.

*** Computing the grid of Helmert anomaly on the topography and downward continuation**

dtep.f for computation of the contribution of the anomalous density to the direct topographical effect.

DTE_Helmert_global.c for computation of the near-zone and far-zone contributions of the direct topographic effect.

SITE.cc: for the computation of point values of the secondary indirect effect of topographical masses on the gravitational attraction referred to the Earth's surface.

DAE_H_and_NT.cc: for the computation of point values of the direct effect of atmospheric masses on the gravitational attraction referred to both: the Earth's surface and on the geoid.

Geoid_quasigeoid_cor.c: for the computation of mean values of the geoid-quasigeoid correction to the fundamental formula of physical geodesy.

Surf_anomaly.c: for the computation of mean values of the Helmert gravity anomalies referred to the Earth's surface from the mean free-air gravity anomalies by accounting for the effects of the topographical and atmospheric masses on the gravitational attraction, and the geoid-quasigeoid correction to the fundamental formula of physical geodesy. This program integrates the result of all the former mentioned.

Dwnc08.c: for the downward continuation of the mean gravity anomalies from the Earth's surface onto the geoid (solving Dirichlet's inverse boundary value problem). The point values are then obtained on the geoid. Dirichlet's inverse problem is described by the Poisson integral equation. The Poisson integral equation (of which the generic form is the Fredholm integral equation of the first kind) is evaluated by Jacobi's iteration method to solve the inversion of the system of linear equations. The accuracy of Jacobi's iteration is given in the meaning of Cebyshev's norm. The free-air gravity anomalies at the Earth's surface can be used as starting values for the iterative process.

*** Computations on the geoid level**

Ellips_corrections.for: for the computation of mean values of the ellipsoidal corrections to the fundamental formula of physical geodesy, i.e., the ellipsoidal correction to the gravity disturbance and the ellipsoidal correction for the spherical approximation.

Reference_field.f: for the computation of the Helmert reference gravity field, i.e., Helmert's reference gravity anomalies referred to the geoid from the reference disturbing gravity potential, applying the ellipsoidal approximation to the fundamental formula of physical geodesy. Helmert's reference gravity anomalies are then subtracted from the Helmert's gravity anomalies to obtain Helmert's residual gravity anomalies. Program also computes the reference direct topographical effect on the gravitational attraction in the Helmert gravity space, and the vertical gradient of Helmert's gravity anomaly referred to the geoid surface.

Res_anomaly.c: for computation of residual anomalies from anomalies at the geoid level by adding Ellipsoidal corrections and subtracting a gravity reference field.

Stokes_integral.for: for the computation of the Helmert residual co-geoid using modified spheroidal Stokes's function from Helmert's residual gravity anomalies referred to the geoid (solving Stokes's boundary value problem in the Helmert gravity space). Program can estimate the truncation errors due to truncation of the integration domain (i.e., the far-zone contribution to the high frequency part of the co-geoid) from the global geopotential model EGM-96.

Reference_spheroid.f: for the computation of the Helmert reference spheroid (which is added after solving Stokes' boundary value problem to the Helmert residual co-geoid to obtain the Helmert co-geoid). Program also computes the reference primary indirect topographical effect on the geoidal heights, and the reference direct and secondary indirect topographical effects on the gravitational attraction in the Helmert gravity space.

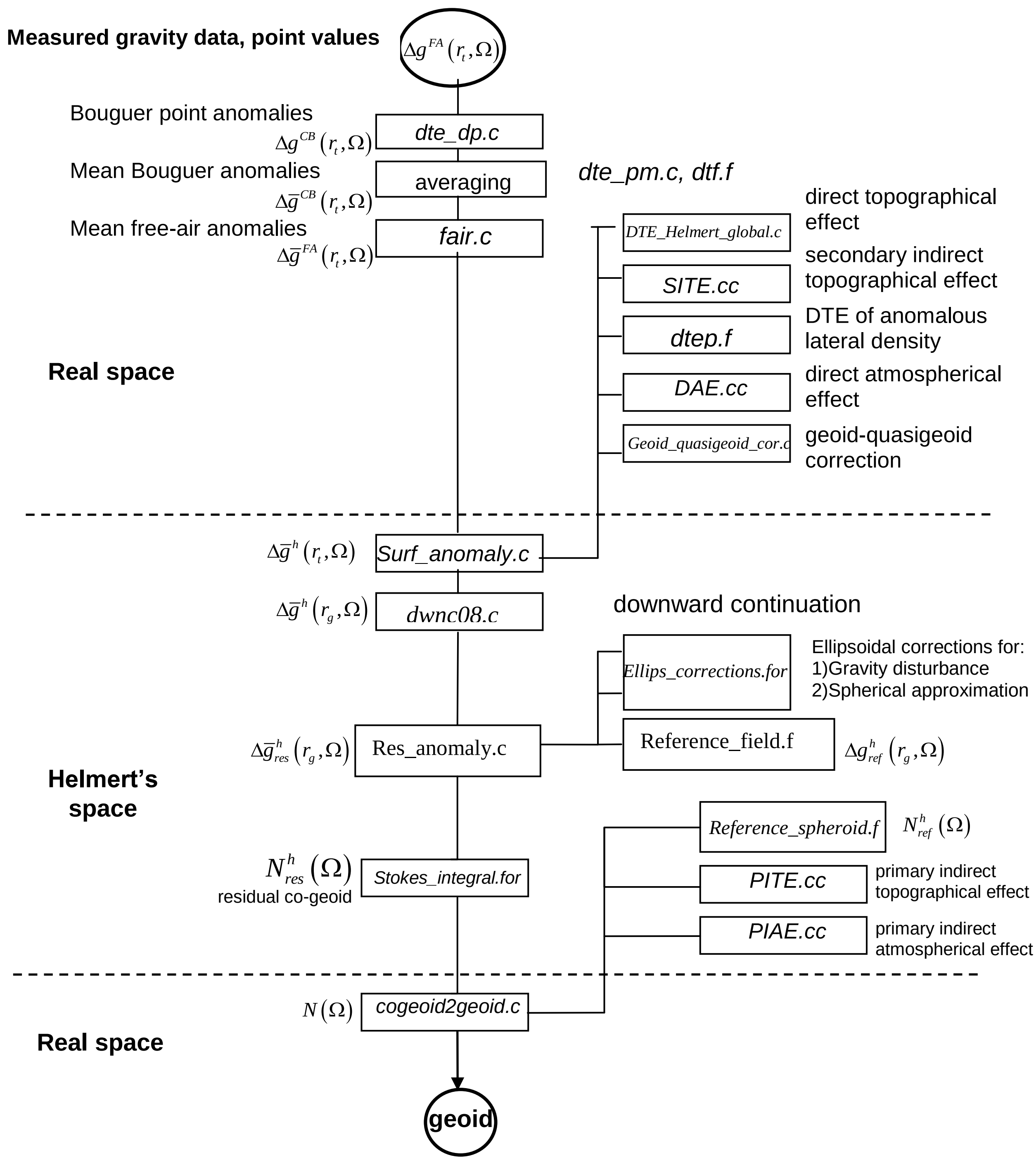
*** Transfering the geoid to the real space**

PIAE.cc: for the computation of point values of the primary indirect atmospheric effect on the geoidal heights. This effect is negligible.

PITE.cc: for the computation of point values of the primary indirect topographical effect on the geoidal heights.

Cogeoid2geoid.c: for the computation of geoid heights in the "real space" from the residual cogeoid by adding the reference spheroid and correcting the by the PITE and PIAE effects.

2. Scheme of the Stokes-Helmert's GEOid software for the precise geoid computation



2.0 A brief review

To formulate the fundamental formula of physical geodesy at the Earth's surface in the real space, the mean gravity anomalies are evaluated and the geoid-quasigeoid correction to the fundamental formula of physical geodesy ("**Geoid_quasigeoid_cor.c**") are added to the mean values of the free-air gravity anomalies.

To transform the gravity anomalies at the Earth's surface from the real space into the Helmert gravity space, the effects of the topographical and atmospheric masses on the gravitational attraction (stipulated as being at the Earth's surface) have to be subtracted from them. The Helmert gravity anomalies (referred to the earth's surface) are computed by the program "**Surf_anomaly.c**".

The effect of topographical masses on the gravitational attraction consists of the direct and secondary indirect topographical effects. The direct topographical effect is evaluated as a sum of the near-zone and the far-zone (global) contributions to the spherical terrain roughness term, the gravitational attraction of the spherical Bouguer shell, and the effect of the anomalous topographical density on the gravitational attraction. The whole direct effect is computed by the program "**DTE_Helmert_global.c**". The secondary indirect effect of topographical masses on the gravitational attraction (point values) referred to the Earth's surface is computed by the program "**SITE.cc**". In all cases, when the point values are used instead of mean values to determine the mean values, the differences between the point and mean values are negligible.

The program "**DAE_H_and_NT.cc**" computes the direct effect of atmospheric masses on the gravitational attraction, (both in the Helemert and No Topogrpahy spaces). Secondary indirect atmospheric effect in the Helmert space is negligible.

To obtain the gravity anomalies on the geoid, Dirichlet's inverse boundary value problem is solved by the program "**Downward_contin.c**". The Poisson's downward continuation of the mean Helmert gravity anomalies from the Earth's surface onto the geoid is used. The Helmert gravity anomalies are then obtained on the geoid surface as point values.

The ellipsoidal correction to the gravity disturbance and the ellipsoidal correction for the spherical approximation are computed by the program: "**Ellips_corrections.for**"),

The full "ellipsoidal" anomalies on the geoid level are obtained by correcting the downward continued spherical Helmert anomalies by the two ellipsoidal corrections. This is realized by the program **"Geo_anomaly.c"**.

After computation of the Helmert gravity anomalies on the geoid surface, these are separated into the reference part and the high-frequency (residual) part. Helmert's reference gravity anomalies (up to degree of n = 20, or higher) are computed by the program "**Reference_field.f**". The Helmert residual gravity anomalies are then evaluated by subtracting the reference part from the Helmert's gravity anomalies.

To obtain the Helmert residual co-geoid from Helmert's residual gravity anomalies referred to the geoid, the Stokes boundary value problem is solved in the Helmert gravity space ("**Stokes_integral.for**"). The Stokes integration is employed over the terrestrial gravity data up to 6 degrees spherical cap around the computation point. The far-zone contribution to the high-frequency part of the Helmert co-geoid, i.e., the truncation errors, is evaluated from the geopotential model (EGM-96).

The Helmert co-geoid is given by a sum of the Helmert reference spheroid (computed by the program "**Reference_spheroid.f**") and Helmert's residual co-geoid.

Finally, the geoid in the real space is obtained so that the primary indirect topographical effect on the geoidal heights is added from the Helmert co-geoid. The primary indirect topographical effect is computed by the program "**PITE.cc**". The primary indirect atmospheric effect is neglected (or can be computed by the program "**PIAE.cc**".).

And finally the program **cogeoid2geoid.c** is used for the computation of geoid heights in the "real space" by correcting the Helmert co-geoid by the PITE and PIAE effects.

3. Source code, Data format and other Conventions

Programs in SHGeo are coded in more than one programing language given the diversity of the authors. SHGeo is provided as open software to promote a transparent understanding of the internal procedures. Programing languages like C, C++ and Fortran have been used to construct the programs. It is recommended for every user to obtain the appropriate compilers to build executables that work properly in every computer used.

Most data formats handled by SHGeo are text based. Commonly text arranged in columns depending on the needs of every program. Gravimetric quantities and topographic heights should follow the format required in order to guarantie a correct functioning. Examples of every input and output file formats are provided through the manual according to the specifications of each program. Next is a general description of the formats used:

- Files named *.xyz refer to text file arranged in three columns: (latitude, longitude, parameter) values. These have no header and are assumed to correspond with data on a regular grid.
- Files named *.dat are text files where the number of columns and their content depends on the needs of every program.
- Files named *.grdt are text values listed in grid array. It contains a single-line header at the first record, containing extreme coordinates of the grided values and step size as follows:
  [min. latitude, max. latitude, min. longitude, max. longitude, step in latitude, step in longitude].
- Files named *.byn are binary values listed in grid array. These contain a complete information header which is described in Section 3.5. This format is particularly used for detailed elevation models (1"x1" or 3"x3").

3.1 Standard input data

- Normal gravity field parameters: Reference Ellipsoid GRS-80
- Satellite geopotential model: e.g. GRIM4-S4, EIGEN-GRACES02
- Combined (satellite and terrestrial) geopotential model: EGM-96
- Global elevation model: TUG-87 (linear and square coefficients)
- Digital terrain models (1 x 1 or 3 x 3 [sec], 30 x 30 [sec], 5 x 5 [min], 1 x 1 [deg])
- Topographical density model (laterally varying)
- Free-air gravity anomalies or Bouguer gravity anomalies (simple or complete)

3.2 Mean heights

Mean heights should be stored in ASCII grid files sorted in *.grdt for some programs and *xyz for others.
Recommended resolution is 30" by 30" (e.g. GTOPO30).

3.3 Gravity Data

The mean values of the free-air, Simple or Compete Bouguer gravity anomalies are considered. This data should be stored in an ASCII data file in the following format: latitude [deg], longitude [deg], orthometric height [m], gravity anomaly [mGal].

If the mean values are not available then scattered values of the free-air gravity anomalies are the first input. See program **dte_dp.c** for a full description of the formats accepted.

3.4 Topo Density Data

The topographical density model (if available) can improve the accuracy of the geoid model. See program dtep.f for a full description of the input format.

3.5 Format for detailed Digital Terrain Model

Extension of the file name is "byn". These files are binary. The "byn" file is split into two sections: header and data. The size of the header is exactly 80 bytes and the elements of the header are as follows

Content	Format type	Number of bytes	Units or options
South boundary	long integer	4	arcseconds
North boundary	long integer	4	arcseconds
West boundary	long integer	4	arcseconds
East boundary	long integer	4	arcseconds
North-South spacing	short integer	2	arcseconds
East-West spacing	short integer	2	arcseconds
Global	short integer	2	0: Local model 1: Global model
Data type	short integer	2	0: Undefined 1: Geoid heights 2: NS Deflections of the vertical 3: EW Deflections of the vertical 4: Gravity 5: Elevations 6: Sea surface heights 7: Sea surface topography 8: Other
Factor	double	8	Multiplication factor for data
Size of data	short integer	2	2: short integer 4: long integer
Standard deviation	short integer	2	0: Std. dev. not available in file
Factor for std. dev.	double	8	Multiplication factor for std. dev.
Geodetic datum	short integer	2	0: ITRF 1: NAD83 (CSRS)
Ellipsoid	short integer	2	0: GRS80 1: WGS84 2: TOPEX/EGM96 3: GRS67
Bytes order	short integer	2	0: HP, Sun, ... 1: PC (Windows, Linux)
Scale for boundaries	short integer	2	0: No scale 1: Scale applied
Spare	-	28	-

The data are sorted by rows starting from north. Each row is stored from west to east. All data are stored as short or long integer, as indicated in the header (see Size of data). For the transformation from integer to float, the user must divide the integer value by the Factor. The file may contain undefined values. These values are indicated by 9999*Factor when the data are stored as long integers. For the data in short integers, the undefined values are expressed as 32767.
The size of the file is 80 bytes plus the number of rows multiplied by the number of columns times the Size of data in bytes.

This description can also be found at: www2.geod.nrcan.gc.ca:80/~marc/Html/Data/Format.html

This format is used e.g. for the CDED (Canadian Digital Elevation Data). One file contains the elevation within 1 x 1 degree area, elevations are stored as a short integer and the multiplication factor is 1. Recommended resolution of the detailed DEM is 1" by 1" or at most 3" by 3". SHGeo requires digital elevation model in a geographical grid.
Note that the header of AUS-SDEM is different.

4. PROGRAMS

The programs are listed in sequential order of the computations according to the flow chart.

4.1 Program dte_dp.c

Program for computation of the simple Bouguer gravity anomalies, complete Bouguer gravity anomalies, terrain correction (spherical approximation) and the difference between the heights obtained from gravity database and interpolated from detailed Digital Terrain Model (DTM). The program can compute the differences between the terrain corrections obtained from database and computed using detailed DTM. The program also produces some statistics. The program works in point mode. Input data are free-air gravity anomalies at the observation sites.

Option file:

"dte_dp.opt"

```
------------------------------------------B of F--------------------------------------
gWest.dat 338986 0
dtm.list
h30_nw.grd
h5_nw.grd
N42W109.out
1650 10800
-------------------------------------------E of F-------------------------------------
where:
```

gWest.dat : input file containing free-air gravity anomalies and other information
338986 : number of lines in an input file
0 : code 0 or 1 according to input file format
dtm.list : input file containing the names of the binary DTM files
h30_nw.grd : input file of the mean 30" x 30" DTM
h5_nw.grd : input file of the mean e.g. 5' x 5' DTM
N52W121.out : output file of the simple and complete Bouguer anomalies
1650 : radius of the inner integration domain [sec]
10800 : radius of the middle integration domain [sec]

Input files:

''dtm.list''

```
/DTM/N53W122_H.byn
/DTM/N53W121_H.byn
/DTM/N53W120_H.byn
/DTM/N52W122_H.byn
/DTM/N52W121_H.byn
/DTM/N52W120_H.byn
/DTM/N51W122_H.byn
/DTM/N51W121_H.byn
/DTM/N51W120_H.byn
```

where:

-binary 1" x 1" or 3" x 3" DTM files for the computation of the terrain correction. Above shows the list of detailed DTM surrounding the computation area.

''gWest.dat''
According to the mode, there are two possible formats. The following example is corresponding to mode 0.

```
65.502833 -149.062500   748.900      0.0   55.90    3.00   3.5  1 30   206904
65.528500 -149.564000   726.600      0.0   53.40    3.00   2.0  1 30   206905
65.504667 -149.601000   295.700      0.0    8.60    3.00   1.7  1 30   206906
.
.
.
40.000000 -110.151660  1859.600      0.0  -27.60    2.00   1.4  1 21  1436957
40.000000 -109.119660  1696.700      0.0  -22.30    2.00   0.4  1 21  1437434
```

where:

φ λ H^O $-H^O$ Δg^{FA} $\sigma_{\Delta g^{FA}}$ TC codes

```
65.502833 -149.062500   748.900      0.0   55.90    3.00   3.5  1 30   206904
```

φ - *latitude [deg]*

λ - *longitude [deg]*

H^O - *orthometric height [m]*

$-H^O$ - *deep [m]*

Δg^{FA} - *Free-Air gravity anomaly [mGal]*

$\sigma_{\Delta g^{FA}}$ - *standard deviation of Free Air anomalies [mGal]*

TC - *terrain correction (planar model up to radius 50 km) [mGal]*

The following example corresponds to mode 1.

```
206904  65.502833 -149.062500   748.900    55.90   1 30
206905  65.528500 -149.564000   726.600    53.40   1 30
206906  65.504667 -149.601000   295.700    8.60    1 30
.
.
.
1436957 40.000000 -110.151660  1859.600    -27.60   1 21
1436957 40.000000 -109.119660  1696.700    -22.30   1 21
```

where:

codes φ λ H^O Δg^{FA} TC

```
206904  65.502833  -149.062500  748.900   55.90     1 30
```

φ - *latitude [deg]*

λ - *longitude [deg]*

H^O - *orthometric height [m]*

Δg^{FA} - *Free-Air gravity anomaly [mGal]*

TC - *terrain correction (planar model up to radius 50 km) [mGal]*

Output file:

''N52W121.out'' example

```
337
 51.72315 239.93511    0.0    0.0    0.0   0.100  -0.677   0.777  -23.600  -23.600  -23.600  -23.500  -24.277  -23.500  -24.277
 51.74815 239.73843    0.0    0.0    0.0   0.100  -0.704   0.804  -23.100  -23.100  -23.100  -23.000  -23.804  -23.000  -23.804
.
.
.
 51.00946 239.91863  105.8  111.0   -5.2   8.900   9.639  -0.739  -22.000  -33.840  -34.425  -24.940  -24.201  -25.525  -24.786
 51.00646 239.68930    0.9   26.7  -25.8   1.200   0.424   0.776   -7.300   -7.402  -10.290   -6.202   -6.978   -9.090   -9.866
```

Number of points in the area /home/DTM/N52W121_H.byn: 337, int.radius: 3.0 (deg)

```
hdif:  min  -64.476 max   92.590 mean   -2.500 (m)
tcdif: min   -6.893 max    5.427 mean    0.583 (mGal)
fa:    min  -61.100 max  145.500 mean   10.990 std  30.5868 (mGal)
sb1:   min  -61.100 max   35.100 mean   -0.798 std  15.7979 (mGal)
sb2:   min  -61.100 max   35.100 mean   -1.078 std  15.7565 (mGal)
cb1:   min  -61.100 max   37.066 mean    2.644 std  14.6094 (mGal)
cb2:   min  -61.556 max   36.379 mean    2.062 std  14.6635 (mGal)
cb3:   min  -61.100 max   42.718 mean    2.365 std  14.7309 (mGal)
cb4:   min  -61.556 max   39.716 mean    1.782 std  14.7716 (mGal)
```

where:

337 - *number of points from database (input file),*
338

φ	λ	H^O	$H^O{}_{DTM}$	$H^O - H^O{}_{DTM}$	TC	TC_{sph}	$TC - TC_{sph}$	Δg^{FA}
50.72315	232.93511	0.0	0.0	0.0	0.100	-0.677	0.777	-23.600

Δg^{SB}	Δg^{SB}_{DTM}	$\Delta g^{SB} + TC$	$\Delta g^{SB} + TC_{sph}$	$\Delta g^{SB}_{DTM} + TC$	$\Delta g^{SB}_{DTM} + TC_{sph}$
-23.600	-23.600	-23.500	-24.277	-23.500	-24.277

Code ID:

φ - *latitude [deg]*

λ - *longitude [deg]*

H^O - *orthomertic height from gravity database [m]*

$H^O{}_{DTM}$ - *orthomertic height from DTM 1" x 1" or 3" x 3" [m]*

$H^O - H^O{}_{DTM}$ - *difference between height from gravity database and DTM [m]*

TC - *terrain correction from gravity database (planar approximation) [mGal]*

TC_{sph} - *computed terrain correction (spherical approximation) [mGal]*

$TC - TC_{sph}$ - *difference between terrain correction from gravity database and computed terrain correction [mGal]*

Δg^{FA} - *Free Air gravity anomaly from gravity database [mGal]*

Δg^{SB} - *simple Bouguer gravity anomaly as a function of height from gravity database [mGal]*

Δg^{SB}_{DTM} - *simple Bouguer gravity anomaly as a function of height from DTM [mGal]*

$\Delta g^{SB} + TC$ - *complete Bouguer gravity anomaly computed from* Δg^{SB} *and* TC *[mGal]*

$\Delta g^{SB} + TC_{sph}$ - *complete Bouguer gravity anomaly computed from* Δg^{SB} *and* TC_{sph} *[mGal]*

$\Delta g^{SB}_{DTM} + TC$ - *complete Bouguer gravity anomaly computed from* Δg^{SB}_{DTM} *and* TC *[mGal]*

$\Delta g^{SB}_{DTM} + TC_{sph}$ - *complete Bouguer gravity anomaly computed from* Δg^{SB}_{DTM} *and* TC_{sph} *[mGal]*

2.2 Program fair.c

Program for computation of the mean free-air gravity anomalies from the mean complete Bouguer gravity anomalies or/and from the mean simple Bouguer gravity anomalies.

Option file:

"fair.opt" example

```
------------------------------------------B of F------------------------------------------
Simple_Bouguer.xyz
Complete_Bouguer.xyz
rockies_hgt.grd
all_dte.dat
rockies_fa.dat
------------------------------------------E of F------------------------------------------
```

where:

Simple_Bouguer.xyz : input file of simple Bouguer gravity anomalies,
Complete_Bouguer.xyz: input file of complete Bouguer gravity anomalies,
rockies_hgt.grd : input file of 5' x 5' DTM,
all_dte.dat : input file of terrain corrections 5' x 5' computed by program dte_pm.e,
rockies_fa.dat : output file of Free-Air gravity anomalies.

Input files:

''Simple_Bouguer.xyz'' example

```
51.72315 239.93511     -23.600
51.74815 239.73843     -23.100
   .
   .
   .
51.00646 239.68930     -10.290
```

where:

φ λ Δg^{SB}

```
50.72315 232.93511  -23.600
```

φ *- latitude*

λ *- longitude*

Δg^{SB} *- simple Bouguer gravity anomaly*

''Complete_Bouguer.xyz'' example

```
51.72315 239.93511    -24.277
51.74815 239.73843    -23.807
.
.
.
51.00646 239.68930     -9.869
```

where :

φ λ Δg^{CB}

```
51.72315 239.93511   -24.277
```

φ *- latitude [deg]*

λ - *longitude [deg]*

Δg^{CB} - *complete Bouguer gravity anomaly [mGal]*

''rockies_hgt.grdt'' example

```
40.04167  65.95833  210.04167  251.95833 0.0833333 0.0833333

216  300  399  270  212  215  164  129  125  108  114  141  142  176  208  209  222  211
251  219  263  279  293  288  304  322  334  429  440  389  355 ...
```

where:

φ_{min} φ_{max} λ_{min} λ_{max} $\Delta\varphi$ $\Delta\lambda$

```
40.4167       65.95833  210.04167  251.95833 0.0833333 0.0833333
```

```
list of 30'' x 30'' mean orthometric heights
216  300 399 ...
```

Output file:

''rockies_fa.dat'' example

```
65.95830 210.04170    0.330    1.508    1.178
65.95830 210.12500   13.652   13.884    0.232
65.95830 210.20830   24.918   24.022   -0.896
.
.
.
40.04170 251.87500  -43.349  -43.864   -0.515
40.04170 251.95830  -46.128  -46.604   -0.476

fa1    : min  -167.677 max   378.390 mean     2.200
fa2    : min  -167.724 max   325.521 mean     2.814
fa2-fa1: min  -105.685 max    56.170 mean     0.614
```

φ λ Δg^{FA1} Δg^{FA2} $\delta\Delta g^{FA}$

```
65.95830 210.04170    0.330    1.508    1.178
```

where:

φ - *latitude [deg]*

λ - *longitude [deg]*

Δg^{FA1} - *Free-air gravity anomaly computed via simple Bouguer gravity anomaly [mGal]*

Δg^{FA2} - *Free-air gravity anomaly computed via complete Bouguer gravity anomaly [mGal]*

$\delta\Delta g^{FA} = \Delta g^{FA1} - \Delta g^{FA2}$ - *Free-Air gravity anomalies difference [mGal].*

2.3 Program dte_pm.c

Program for computation of the near-zone contribution to the terrain correction, condensed terrain correction and the direct topographical effect (DTE). This program can produce 2 output files. One contains the point values computed in the chosen grid and the second contains the mean values computed from point values.

Option file:

''dte_pm.opt'' example

```
------------------------------B o F --------------------------------
dtm.list
DTM_30s.grdt
DTM_5m.grdt
dte_m_N52W121.dat
dte_p_N52W121.dat
0.08333333 0.08333333
1650 10800
5
9
------------------------------E o F -------------------------------
```

where:

dtm.list : file consisting of the binary DTM input files
DTM_30.grdt : input file of the mean 30" x 30" DTM
DTM_5.grdt : input file of the mean 5' x 5' DTM
dte_m_N52W121.dat : output file of mean values of the terrain correction, condensed terrain correction and the direct topographical effect
dte_p_N52W121.dat : output file of point values of the terrain correction, condensed terrain correction and the direct topographical effect
0.08333333 0.08333333: step of mean values (e.g. 5' x 5') [deg]
1650 10800 : radius of the inner and middle integration domain [sec]
5 : mode (1–6) for step of computation
9 : number of detailed DTM files (for modes 2-6 must be 9, for mode 0 must be 1)

mode 0 : 1 point values for output cell, (mean DTM is used for heights of integration elements)
1 : 1 point values for output cell,
2 : 4 point values for output cell, 2 in lat and 2 in lon,
3 : 10 point values for output cell, 5 in lat and 2 in lon,
4 : 25 point values for output cell, 5 in lat and 5 in lon,
5 : 50 point values for output cell, 10 in lat and 5 in lon,
6 : 100 point values for output cell, 10 in lat and 10 in lon.

Input files:

''dtm.list'' example

```
/DTM/N53W122_H.byn
/DTM/N53W121_H.byn
/DTM/N53W120_H.byn
/DTM/N52W122_H.byn
/DTM/N52W121_H.byn
/DTM/N52W120_H.byn
/DTM/N51W122_H.byn
/DTM/N51W121_H.byn
/DTM/N51W120_H.byn
```

where:

-binary 1" x 1" or 3" x 3" DTM files for the computation of the terrain correction. Above shows the list of detailed DTM surrounding the computation area.

''DTM_30s.grdt '' example

```
45.00417  54.99583  230.00417  244.99583 0.0083333333 0.0083333333

    0    0    2     26    16    19  125  251  313 ...
    0    0    0      0     0     1   17   49   49 ...
```

where:

$\varphi_{\min}$	$\varphi_{\max}$	$\lambda_{\min}$	$\lambda_{\max}$	$\Delta\varphi$	$\Delta\lambda$
45.00417	54.99583	230.00417	244.99583	0.0083333333	0.0083333333

```
list of 30'' x 30'' mean orthometric heights
0 0 2 ...
```

''DTM_5m.grdt'' example

```
40.04167  65.95833  210.04167  251.95833 0.0833333 0.0833333

216  300  399  270  212  215  164  129  125  108  114  141  142  176  208  209  222  211
251  219  263  279  293  288  304  322  334  429  440  389  355 ...
```

where:

$\varphi_{\min}$	$\varphi_{\max}$	$\lambda_{\min}$	$\lambda_{\max}$	$\Delta\varphi$	$\Delta\lambda$
40.4168	65.95833	210.04167	251.95833	0.0833333	0.0833333

```
list of 5' x 5' mean orthometric heights
216  300  399 ...
```

Output file:

''dte_m_N52W121.dat'' example

```
52.9583 239.0417    6.255    7.476   -1.221
52.9583 239.1250    2.779  -11.860   14.640
52.9583 239.2083    3.665    3.676   -0.012
.
.
.
52.0417 239.8750   10.537   12.111   -1.573
52.0417 239.9583    8.981   -2.820   11.801
```

where:

φ	λ	$\overline{TC}$	$\overline{CTC}$	$\overline{DTE}$
52.9583	239.0417	6.255	7.476	-1.221

φ - *latitude [deg]*

λ - *longitude [deg]*

$\overline{TC}$ - *topographical correction, mean values [mGal]*

$\overline{CTC}$ - *condensed topographical correction, mean values [mGal]*

$\overline{DTE}$ - *direct topographical effect* $\overline{DTE} = \overline{TC} - \overline{CTC}$ *, mean values [mGal]*

''dte_p_N52W121.dat'' example

```
52.9958 239.0083    5.995    3.293    2.702
52.9958 239.0250    7.263    1.348    5.915
52.9958 239.0417    6.622   -9.327   15.949
.
.
.
52.0042 239.9750    9.374    6.332    3.042
52.0042 239.9917    7.997    5.302    2.695
```

where:

φ	λ	TC	CTC	DTE
52.9958	239.0083	5.995	3.293	2.702

φ - *latitude [deg]*

λ - *longitude [deg]*

TC - *topographical correction, point values [mGal]*

CTC - *condensed topographical correction, point values [mGal]*

DTE - *direct topographical effect* $DTE = TC - CTC$, *point values [mGal].*

2.4 Program dtf.f

Program for computation of the far-zone contribution to the direct topographical effect (DTE). The contribution is computed from heights obtained from a 180 degree spherical harmonic global elevation model (TUG-87).

Option file:

"terf.opt" example

```
------------------------------------B of F----------------------------------------
hg1.cof                            ! global elevation model
hg2.cof                            ! global elevation model
60.0 230.0 0.0833333 0.0833333    ! boundaries N, W and step
204    408                         ! dimensions of data (rows and columns)
003.0 180.0                        ! integration domain [degree]
------------------------------------E of F-----------------------------------------
```

where:

hg1.cof : harmonic coefficients of the global elevation model
hg2.cof : harmonic coefficients of the squared heights of the global elevation model
60.0 230.0 : north and west boundary of the computation area
0.0833333 0.0833333 : step of computation points at latitude and longitude [deg]
204 408 : dimensions of data (rows columns)
003.0 180.0 : far-zone integration domain [deg].

Input files:

"hg1.cof" example

```
  0  0     246.3170843218       0.0000000000
  1  0      30.6334400313       0.0000000000
  1  1      70.4074820691      74.3058914180
  .
  180 180       0.2868384117      -0.4611470112
```

"hg2.cof" example

```
  H2 (H. squred) coefficients up to 90/90 in m2 originated from TUG87 data
  90   6378137.0  298.257  0.108263D-02
   0  0   0.4464025065D+06   0.0000000000D+00
   1  0  -0.2161658303D+05   0.0000000000D+00
   1  1   0.8572045522D+05   0.2030582602D+06
   .
  90 90  -0.5677450265D+03   0.5021506734D+03
  99 99   0.0                0.0
```

Output file:

"dtf.dat" example (default name of the output file)

```
52.9583 239.0417    0.241   0.020   0.221
52.9583 239.1250    0.060   0.020   0.040
52.9583 239.2083    0.010   0.008   0.002
.
.
.
52.0417 239.8750    0.114   0.041   0.073
52.0417 239.9583    0.003   0.002   0.001
```

where:

φ	λ	$TC_{far-zone}$	$CTC_{far-zone}$	$DTE_{far-zone}$
52.9583	239.0417	0.241	0.020	0.221

φ - *latitude [deg]*

λ - *longitude [deg]*

$TC_{far-zone}$ - *far-zone contribution to the topographical correction [mGal]*

$CTC_{far-zone}$ - *far-zone contribution to the condensed topographical correction [mGal]*

$DTE_{far-zone}$ - *far-zone contribution to the direct topographical effect, mean value [mGal],*
$DTE_{far-zone} = TC_{far-zone} - CTC_{far-zone}$.

2.5 Program dtep.f

Program for computation of the contribution of the anomalous density to the direct topographical effect. All options must be chosen inside the code. The names of the input files must be changed by editing the source code.

```
C INPUT AND OUT PATHS
       HF = "hgt30t60.dat"
       DF = "b2den30t60.dat"
       OF = "dte_residual.dat"

C BOUNDARIES OF COMPUTATION AREA
       SOUTH = 49 + 2.5/60
       NORTH = 49 + 2.5/60
       WEST = 224 + 2.5/60
       EAST = 250 - 2.5/60

C RADIUS OF INTEGRATION AREA
       PSI0=1.0
```

where:

hgt30t60.dat : input file of the mean 30"x30" DTM
b2den30t60.dat : input file of the mean 30"x 30" anomalous density
dte_residual.dat : output file of the mean 30"x30" effect of the anomalous density

Input files:

"height.dat" example

```
       2040         1560
       43  0 15     224  0 30
       30           60
 14880 17540 20480 19470 14630 10610 10990 12670  9560  9220 11200 14250 17490 20290 20710
18650 17810 18800 19200 16210 13780 11300 10110 12240 13480 …
```

where:

```
43  0 15     224  0 30 : the latitude and longitude of the first point of
                         the data file [deg, min, sec]
2040         1560      : dimensions of data (number of the rows and columns)
30           60        : size of a grid cell in latitude and longitude [min]
14880 ……               : the orthometric height [cm]
```

"density.dat" example

```
        1560            2400
        49 0 15         221 0 30
        30              60
 268 269 269 269 269 269 269 269 270 270  269 269 269 269 269 269 269 269 269 269 269 269
269 269 269 269 269 269 269 269 269 269 269 269 269 269 269 269 269 269 269 269 269 269 269
269
```

where:

```
49 0 15      221 0 30  : the latitude and longitude of the first point of
                         the data file [deg, min, sec]
1560         2400      : dimensions of data (number of the rows and columns)
30           60        : size of a grid cell in latitude and longitude [min]
```

268 269 269 …… : the actual density $\rho(\Omega)\times 100$ [$g.cm^{-3}$]

Output file:

"dte_residual.dat" example

```
224.0417     49.0417    249.9583     49.0417   312     1
49.0417    224.0417     -0.0110      0.8500
49.0417    224.1250     -0.0020      0.8690
.
.
49.0417    249.8750     -0.0190      0.8570
49.0417    249.9583     -0.0047      0.8710
```

where:

λ_{min}	φ_{min}	λ_{max}	φ_{max}	I_{λ}	J_{φ}
224.0417	49.0417	249.9583	49.0417	312	1

φ	λ	$DTE_{\delta\rho}$	
49.0417	224.0417	-0.0110	0.8500

φ - latitude [deg]

λ - longitude [deg]

$DTE_{\delta\rho}$ -contribution of the anomalous density to the direct topographical effect [mGal].

λ_{min} , φ_{min} , λ_{max} , φ_{max} : boundary of the output data [deg]

I_{λ} , J_{φ} : number of data in longitude and latitude.

2.6. Program DTE_Helmert_global.c

Computation of the near-zone and far-zone contributions of the direct topographic effect. The far-zone contribution is computed from GLOBAL integration**. Computes a 1°x1° area at a time.**
This program should be executed in conjunction with an option file: ./dte.e DTE_Helmert_global_.opt
The required input files and computational characteristics are listed in the option file.

Option file:

" DTE_Helmert_global_.opt" example

```
--------------------------------  B of F --------------------------------------------
dtm.list
DTM_30s.dat
DTM_5m.dat
Global_60m.dat
DTE_point_S23E133.xyz
STC_mean_S23E133.xyz
DTE_mean_S23E133.xyz
CSTC_mean_S23E133.xyz
DTE_global_S23E133.log
0.083333333 0.083333333
1650 10800
6
9
--------------------------------- E of F --------------------------------------------
```

where:

dtm.list : file consisting of the names of binary DTM input files
DTM_30s.dat : input file of the mean 30" x 30" DTM
DTM_5m.dat : input file of the mean 5' x 5' DTM
DTM_60m.dat : input file of the global 60' x 60' DTM
DTE_point_S23E133.xyz : output file of 5' x 5' point values of the direct topographic effect
STC_mean_S23E133.xyz : output file of the spherical terrain correction
DTE_mean_S23E133.xyz : output file of 5' x 5' mean of the direct topographic effect
CSTC_mean_S23E133.xyz : output file of the sperical condensed terraine correction
DTE_global_S23E133.log : output log file
0.083333333 0.083333333 : step of mean values (5' x 5') [deg]
1650 10800 : radius of the inner and middle integration domain [sec]
6 : mode for step of computation
9 : number of 1" x 1" or 3" x 3" DTM (for modes 1-6 must be 9, for mode 0 must be 1)

mode 0 : 1 point value for output cell, (mean DTM is used for heights of integration elements)
1 : 1 point value for output cell,
6 : 100 point values for output cell, 10 in latitude and 10 in longitude.
Mode 6 is recommended!! Computations in the ZERO mode are commented separately later on.

Input files:

Constraints:

The BORDERS of the 60'x60' cells should exactly coincide with the BORDERS of the 5'x5' cells.
The mean TC values are computed from: (i) the point heights (3" x 3"), and (ii) from the mean heights with the resolution of 30" x 30", 5'x5', and global heights 60'x60' DTM.
The datasets 30" x 30" and 5' x 5' are assumed to be obtained from direct averaging of 3"x3" DTM-s.
The 5'x5' DTM cell CENTERS are supposed to coincide with the CORNERS of the 30" DTM cells (so the 5'x5' cell centers do not coincide with the 30" cell centers)!!!

List of 3"x3" DTM-s to be used is defined in the file:

"dtm.list" example

```
/ AUS_SEGM_15whole/HB_S22E132.byn
/ AUS_SEGM_15whole/HB_S22E133.byn
/ AUS_SEGM_15whole/HB_S22E134.byn
/ AUS_SEGM_15whole/HB_S23E132.byn
/ AUS_SEGM_15whole/HB_S23E133.byn
/ AUS_SEGM_15whole/HB_S23E134.byn
/ AUS_SEGM_15whole/HB_S24E132.byn
/ AUS_SEGM_15whole/HB_S24E133.byn
/ AUS_SEGM_15whole/HB_S24E134.byn
```

where:

-binary 1" x 1" or 3" x 3" DTM files for the computation of the terrain correction. Above shows the list of detailed DTM surrounding the computation area.

"DTM_30s.grdt" example

```
45.00417  54.99583  230.00417  244.99583 0.0083333333 0.0083333333

    0    0    2     26    16    19  125  251  313 ...
    0    0    0      0     0     1   17   49   49 ...
```

where:

$\varphi_{\min}$ $\varphi_{\max}$ $\lambda_{\min}$ $\lambda_{\max}$ $\Delta\varphi$ $\Delta\lambda$

```
  45.00417  54.99583  230.00417  244.99583 0.0083333333 0.0083333333
```

list of 30" x 30" mean orthometric heights $\overline{H}^{O}(\Omega)$:

```
    0    0    2   26   16 ...
```

"DTM_5m.grdt" example

```
  45.04167  54.95833  230.04167  244.95833 0.0833333333 0.0833333333

  112.0  240.0  406.0  444.0  462.0  508.0 1137.0 1271.0 1053.0 ...
  536.0  722.0  853.0 1101.0 1007.0  520.0 1242.0 1372.0 1381.0 ...
```

where:

$\varphi_{\min}$ $\varphi_{\max}$ $\lambda_{\min}$ $\lambda_{\max}$ $\Delta\varphi$ $\Delta\lambda$

```
45.04167  54.95833  230.04167  244.95833 0.0833333333 0.0833333333
```

list of 5' x 5' mean orthometric heights $\overline{H}^{O}(\Omega)$:

```
  112  240  406  444  ...
```

"Global_60m.grdt" example

```
-89.49125000  89.49125000   0.50875000 359.50875000 1.00000000 1.00000000
     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
```

where:

$\varphi_{\min}$ $\varphi_{\max}$ $\lambda_{\min}$ $\lambda_{\max}$ $\Delta\varphi$ $\Delta\lambda$

```
-89.49125000  89.49125000   0.50875000 359.50875000 1.00000000 1.00000000

list of 60' x 60' mean orthometric heights
0.0  0.0  0.0 ...
```

Output files:

The program produces 2 output files. One contains the mean values computed from point values.
Output file (MEAN) of the full (=NZ+FZ) Helmert terrain correction referred at the Earth's surface:

"DTE_point_S23E133.dat" example

```
  -8.9929 111.9929     0.0    -0.179          0.037          0.216
  -8.9929 111.9946     0.0    -0.179          0.037          0.216
  -8.9929 111.9963     0.0    -0.179          0.037          0.216
   .
  -9.9913 112.9913     0.0    -0.138          0.011          0.149
```

where:

φ	λ	$\overline{H}^{O}(\Omega)$	*TC*	*DTE*	*SCTC*
-8.9929	111.9929	0.0	-0.179	0.037	0.216

"STC_mean_S23E133.xyz" example

```
-9.0004 112.0004   -19.764
-9.0004 112.0171   -19.763
-9.0004 112.0338   -19.762
 .
-9.9838 112.9838   -19.555
```

where:

φ	λ	*DTE (mean value)*
-9.0004	112.0004	-19.764

"DTE_mean_S23E133.xyz" example

```
  -9.0004 112.0004    0.046
  -9.0004 112.0171    0.046
  -9.0004 112.0338    0.046
   .
  -9.9838 112.9838    0.019
```

where:

φ	λ	*DTE (mean value)*
-9.0004	112.0004	0.046

"CSTC_mean_S23E133.xyz"example

```
  -9.0004 112.0004   19.810
  -9.0004 112.0171   19.809
  -9.0004 112.0338   19.809
   .
```

```
 -9.9838 112.9838   19.575
```

where:

φ	λ	*DTE (mean value)*
-9.0004	112.0004	19.810

"**DTE_global_S23E133.log** " example

```
COMPUTATION MODE = 6

Locations of the OUTPUT files:
  /BRAZIL/DTE/Global_Helm/TC_Helm_global_S23E133.mean
  /BRAZIL/DTE/LOG_files/DTE_global_S23E133.log
Integration radius (outer) of 5' resolution DTM-data : 3 arc-degrees

NEGATIVE heights will be switched to ZERO (since the terrain correction is not
applicable beneath the geoid surface)
5'x5' INPUT FILE:   384 columns, bh5max=  -18.0504 dbh5= 0.083333 lh5min=
128.0504 dlh5= 0.083333
30'x30' INPUT FILE:  2880 columns, bh30max=  -22.0129 dbh30= 0.008333 lh30min=
132.0129 dlh30= 0.008333
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
Check of the meridianial borders of the used 3'' DTM data-files
Note that in files 31,32 and 33 last 50 rows (of total 1201) ONLY are checked
whereas in files 37,38 and 39 first 50 rows (of total 1201) ONLY are checked
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!


AREA 31
-23.008750 -22.008750 132.008750 133.008750
```

…… etc ….. etc ……………………

2.6.1 Output in the ZERO mode.

Use the program: **DTE_Helmert_global_austrRIO_0mode_5x5.c**

Output files:

The program produces 2 output files. One contains the POINT values.
Output (POINT) file: A text file with for the following structure:
`latit[deg],longit[deg],height H3s[m],height H5m[m],roughness term of DTE-NT[mGal],`**`Helmert TC[mGal]`**`,roughness term of DTE-HA(on geoid)[mGal], Bouguer shell(at the surface) [mGal], Bouguer shell(on the geoid) [mGal], Total STC for NT (referred to the surface,column 5+8) [mGal], Total SCTC (on the geoid,columns 7+9) [mGal].`

"**`TC_Helm_global.point`**" example

Latitude	Longitude	H/3sDTM	H/5mDTM	tc/surf	dte/Helm-surf	ce/geoid	Bshell_tc	Bshell_ce	TOTAL_TC	TOTAL_CE
-23.0504	133.0504	612.8	613	48.17	**0.13**	-48.11	-137.18	137.21	-89.01	89.10
-23.0504	133.1337	586.9	589	45.50	**0.42**	-45.44	-131.83	131.86	-86.33	86.42
-23.0504	133.2171	595.8	597	46.39	**0.37**	-46.33	-133.58	133.60	-87.18	87.28

The second output file is a log file, which contains error messages and statistics (see the log file for MODE 6).

2.7 Program SITE.cc

Computes the secondary indirect topographic effect (referred to the earth's surface).

The program is interactive, i.e., when starting execution, it asks for user`s options. Then the user gives names of the following files:

- file with the integration points for the inner-zone:
- file with the integration points for the near-zone:
- file with the integration points for the far-zone:
- file with the coordinates of the calculation points:
- output file:

where:

inner zone : input file of the mean 30" x 30" DTM
near zone : input file of the mean 5' x 5' DTM
far zone.. : input file of the global 60' x 60' DTM
calculation points : input file with coordinates of calculation points
output file : output file of 5' x 5' point values of the secondary indirect topographic effect

The program is set by default as follows:

inner zone integration radius: size = 25x25 minute
near zone integration radius : size = 5x5 degree

Input files:

Constraints:

The BORDERS of the 60'x60' cells should exactly coincide with the BORDERS of the 5'x5' cells.
All the input files are assumed to cover a discrete number of degrees.
The 5-minute data is supposed to coincide with corners of the 30-second data grid cells (so that the calculation points should not coincide with the 30 second integration points).
The inner-zone input file should be extended at least 12.5 arc-min off from each border of the computation area.
The near-zone input file should be extended at least 3 arc-degrees off from each border of the computation area.
For instance: if the file of the computation points covers a 10x10 degree area, then the inner-zone file should cover 10.25x10.25 degrees (at least).

"Inner_zone.xyz" example

φ λ $\overline{H}^{O}(\Omega)$

```
60.9958 209.0083    340.0
60.9958 209.0250    326.0
.
49.0042 220.9917   1210.0
```

"Near_zone.xyz" example

```
64.95830 205.04170    528.0
64.95830 205.12500    624.0
.
45.04170 224.95830    756.0
```

"GlobalH.xyz" example

φ λ $\overline{H}^{\mathrm{O}}(\Omega)$

```
 89.5    0.5    0.0
 89.5    1.5    0.0
 89.5    2.5    0.0
. . .
-89.5  359.5  848.2
```

"Computation_points.xyz" example : this input file should contain coordinates and heights of the points of interest. These points may or may not be arranged in a grid.

φ λ $\overline{H}^{\mathrm{O}}(\Omega)$

```
59.95830 210.04170    320.0
59.95830 210.12500    204.0
.
50.04170 219.95830   1126.0
```

"Near-zone.xyz" and "GlobalH.xyz" can be common to different computation areas

Output file:

"SITE_1.xyz" example

φ λ $2\delta V^{t}\left(r_{t},\Omega\right)/r_{t}\left(\Omega\right)$

```
59.95830 210.04170    0.014
59.95830 210.12500    0.047
.
50.04170 219.95830    0.057
```

where:

$2\delta V^{t}\left(r_{t},\Omega\right)/r_{t}\left(\Omega\right)$ is the secondary indirect effect of topographical masses on the gravitational attraction referred to the Earth's surface [mGal].

2.8 Program DAE_H_and_NT.cc

This program calculates three types of gravitational attraction of the atmospheric masses referred either to the earth's surface or to the geoid level.

The program is interactive, i.e., when starting execution, it asks for user`s options. Then the user gives names of the following files:

- file with the integration points for the inner-zone:
- file with the integration points for the near-zone:
- file with the integration points for the far-zone:
- file with the coordinates of the calculation points:
- output file:

where:

inner zone : input file of the mean 30" x 30" DTM
near zone : input file of the mean 5' x 5' DTM
far zone.. : input file of the global 60' x 60' DTM
calculation points : input file with coordinates of calculation points
output file : output file of 5' x 5' point values of the secondary indirect topographic effect

The program is set by default as follows:

inner zone integration radius: size = 25x25 minute
near zone integration radius : size = 5x5 degree

Input files:

Constraints:

The BORDERS of the 60'x60' cells should exactly coincide with the BORDERS of the 5'x5' cells.
All the input files are assumed to cover a discrete number of degrees.
The 5-minute data is supposed to coincide with corners of the 30-second data grid cells (so that the calculation points should not coincide with the 30 second integration points).
The inner-zone input file should be extended at least 12.5 arc-min off from each border of the computation area.
The near-zone input file should be extended at least 3 arc-degrees off from each border of the computation area.
For instance: if the file of the computation points covers a 10x10 degree area, then the inner-zone file should cover 10.25x10.25 degrees (at least).

"Inner_zone.xyz" example

φ λ $\overline{H}^{O}(\Omega)$

```
60.9958 209.0083    340.0
60.9958 209.0250    326.0
.
49.0042 220.9917   1210.0
```

where:

φ is latitude [deg], λ is longitude [deg], and $\overline{H}^{O}(\Omega)$ is the mean orthometric height [m].

"Near_zone.xyz" example

```
64.95830 205.04170    528.0
64.95830 205.12500    624.0
.
45.04170 224.95830    756.0
```

"GlobalH.xyz" example

φ λ $\overline{H}^{O}(\Omega)$

```
 89.5    0.5    0.0
 89.5    1.5    0.0
 89.5    2.5    0.0
. . .
-89.5  359.5  848.2
```

"Computation_points.xyz" example : this input file should contain coordinates and heights of the points of interest. These points may or may not be arranged in a grid.

φ λ $\overline{H}^{O}(\Omega)$

```
59.95830 210.04170    320.0
59.95830 210.12500    204.0
.
50.04170 219.95830   1126.0
```

Output files:

DAE_Helmert is a residual quantity. DAE is obtained by subtracting the condensation effect from the direct atmospheric effect (both accounted on the surface of the earth)
DAE_NT is the direct atmospheric effect (radial derivative of the potential of atmospheric masses), referred to the earth's surface
DAE_H is the condensed atmospheric effect, computed on the geoid

Appearance of each output file is as follows

"DAE_Helmert.xyz" example

φ λ DAE

```
59.95830 210.04170    -0.014
59.95830 210.12500    -0.017
.
50.04170 219.95830    -0.057
```

where:

DAE is $\partial V^{a}(r,\Omega)/\partial r$ is the direct effect of atmospheric masses on the gravitational attraction referred to the Earth's surface [mGal].

2.9 Program Geoid_quasigeoid_cor.c

Program Geoid_quasigeoid_cor.c for the computation of the geoid-quasigeoid correction to the fundamental formula of physical geodesy. Requires an option file.

Option file:

"Geoid_quasigeoid_cor.opt" example

```
---------------------------------------------------------B of F---------------------------------------------------------------
FA_anomaly.mean 69696
H5.mean
Geoid_quasigeoid_cor.mean
---------------------------------------------------------E of F---------------------------------------------------------------
```

where:

"FA_anomaly.xyz" : input file of the free-air gravity anomalies (step of data: 5' x 5'),
69696 : number of datapoints.
"H5.xyz" : input file of the orthometric heights [m] (step of data: 5' x 5'),
"Geoid_quasigeoid_cor.xyz" : output file of the geoid-quasigeoid correction to the fundamental formula of physical geodesy [mGal],

Note: Program assumes that all input files cover the same area and the grid nodes have the same position and step.

Input files:

The input files with the free-air gravity anomalies and the orthometric heights.

"FA_anomaly.xyz" example

φ λ $\overline{\Delta g}^{\mathrm{FA}}(r_t(\Omega))$

```
65.9583 210.0417     1.508
65.9583 210.1250    13.884
.
40.0417 251.9583   -46.604
```

where:

$\overline{\Delta g}^{\mathrm{FA}}(r_t(\Omega))$ is the mean value of the free-air gravity anomaly [mGal].

"H5.xyz" example

φ λ $\overline{H}^{\mathrm{O}}(\Omega)$

```
65.9583 210.0417   216.3
65.9583 210.1250   300.0
.
40.0417 251.9583  1938.1
```

Output file:

"Geoid_quasigeoid_cor.xyz" example

φ λ $\overline{\chi}(r_t(\Omega))$

```
65.9583 210.0417   -0.002
```

```
65.9583 210.1250   -0.002
.
40.0417 251.9583   -0.160
```

where:

$\bar{\chi}(r_t(\Omega))$ is the mean value of the geoid-quasigeoid correction to the fundamental formula of physical geodesy [mGal].

2.10 Program Surf_anomaly.c

Formula used to compute the Helmert gravity anomaly referred at the earth surface is:
Helmert_top_anomaly = FA_anomaly + TC_whole + SITE + ksi_cor + DTE_density + DAE ;

Option file:

"Surf_anomaly.opt" example

```
--------------------------------------------------------B of F--------------------------------------------------------------
FA_anomaly.xyz
DTE_whole.xyz
SITE_whole.xyz
Geoid_quasigeoid_cor.xyz
DAE_whole.xyz
DTE_density.xyz
HA_anomaly_top.xyz
264 264
--------------------------------------------------------E of F-------------------------------------------------------------
```

where:

FA_anomaly.xyz : input file of the mean free-air gravity anomalies: latitude [deg], longitude [deg], FA gravity anomaly [mGal].
DTE_whole.xyz : topographical correction (Near+ Far-zone contributions) to the Helmert anomaly (mean values).
SITE_whole.xyz : input file of the secondary indirect topographical effect (point values).
Geoid_quasigeoid_cor.xyz : input file of the geoid-quasigeoid correction to the fundamental formula of physical geodesy (mean values).
DAE_whole.xyz : input file of the direct atmospheric effect (point values).
DTE_density.xyz : input file of the direct topographical effect of the laterally varying topographical density.
HA_anomaly_top.xyz : output file of the helmert anomaly at surface level.
264 264 : number of data in latitude and longitude

Input files:

The program assumes that all input files cover the same area and the grid nodes have the same position and step. All input files are assumed to have a 3 colum format, below is an example of this format.

''FA_anomaly.xyz'' example

```
65.95830 210.04170   1.178
65.95830 210.12500   0.232
65.95830 210.20830  -0.896
.
.
.
40.04170 251.87500  -0.515
40.04170 251.95830  -0.476
```

φ λ $\delta\Delta g^{FA}$

```
65.95830 210.04170  1.178
```

where:

φ *– latitude [deg]*

λ *- longitude [deg]*

$\delta \Delta g^{FA}$ *- Free-Air gravity anomalies difference [mGal].*

Output file:

"HA_anomaly_top.xyz" example

φ λ $\overline{\Delta g}^{FA}(r_t,\Omega)$

```
65.95833 210.04167    1.508
65.95833 210.12500   13.884
.
40.04167 251.95832  -46.604
```

where:

$\overline{\Delta g}^{FA}(r_t,\Omega)$ is the mean value of the Helmert gravity anomaly referred to the Earth's surface [mGal].

2.11 Program Downward_continuation.c

The option file:

"Downward_continuation.opt" example

```
-----------------------------------B o F -------------------------------------
H.mean
HA_anomaly_top.xyz 40.0 66.0 210.0 252.0
HA_anomaly_top.xyz 40.0 66.0 210.0 252.0
HA_anomaly_geo.xyz
84 84 300 300
0.01
47.0 54.0 234.0 241.0
-----------------------------------E o F -------------------------------------
```

where:

"H.mean" : input file of the mean orthometric heights
"HA_anomaly_top.xyz" : input file of the Helmert gravity anomalies referred to the Earth's surface.
"HA_anomaly_top.xyz" : input file of the free air gravity anomaly to serve as 0^{th} iteration.
"HA_anomaly_geo.xyz" : output file of the Helmert gravity anomalies referred to the geoid.
`84 84 300 300` : number of the height data in latitude and longitude.
`0.01` : accuracy of iteration process of the upward continuation in the meaning of Cebyshev's norm.
`47.0 54.0 234.0 241.0`: are the minimal and maximal latitude of the computation area.

Note: The default computation area is 7 x 7 degrees of geodetic latitude and longitude (84 x 84 rows and columns for 5' x 5' (300" x 300")) and the result 5 x 5 degrees is stored to the output file.

Input files:

"HA_anomaly_top.mean" example

φ λ $\overline{\Delta g}^{\mathrm{FA}}(r_t,\Omega)$

```
65.95833 210.04167    1.508
65.95833 210.12500   13.884
.
40.04167 251.95832  -46.604
```

where:

$\overline{\Delta g}^{\mathrm{FA}}(r_t,\Omega)$ is the mean value of the Helmert gravity anomaly referred to the Earth's surface [mGal].

"H.mean" example

φ λ $\overline{H}^{\mathrm{O}}(\Omega)$

```
53.9583 234.0417  1260.0
53.9583 234.1250   251.6
.
47.0417 240.9583  1250.1
```

Output file:

"HA_anomaly_geo.dat" example

φ λ $\overline{\Delta g}^{\mathrm{h}}(r_t,\Omega)$ $\delta\Delta g^{\mathrm{h}}(\Omega)$ $\Delta g^{\mathrm{h}}(r_g,\Omega)$

```
52.95833 235.04167  -33.988    0.000  -33.988
52.95833 235.12500  -26.314    0.000  -26.314
.
48.04167 239.95833  -49.024  -17.524  -66.548
```

where:

$\overline{\Delta g}^{\mathrm{h}}(r_t,\Omega)$ is the anomaly on the surface (before DWC).

$\delta\Delta g^{\mathrm{h}}(\Omega)$ is the value of the downward continuation contribution.

$\Delta g^{\mathrm{h}}(r_g,\Omega)$ is the Helmert gravity anomaly referred to the geoid surface.

2. 12. Program: Ellips_correctrions.for

Calculation of the ellipsoidal corrections to the fundamental formula of physical geodesy:
- ellipsoidal correction to the gravity disturbance,
- the ellipsoidal correction for the spherical approximation.

These corrections are referred to the geoid level in the HELMERT SPACE.

Options:

The program is interactive, i.e., when starting execution, it asks for user`s options. Then the user gives names of the files of geopotential model (e.g. EGM-96) and spherical harmonic model of squared topographical heights (e.g. TUG-87 based H^2 coefficients). The program also asks what degree and order of geopotential/topographical coefficients should be used . The user is also asked to specify the cell center coordinates of the computation area, and the computataion steps in NS and WE directions and mean heigt above the reference ellipsoid

Input files:

"GLOBAL GEOPOTENTIAL MODEL COEFFICIENTS" (EGM96) example

```
C An input file with geopotential coefficients MUST be in following format
C (arranged as columns, altogether 6 columns, no header)
C :degree N; order M; coeff. Cnm; coeff. Snm; st.err dCnm; st.err dSnm
C Assumed that input file contains also 0.0; 1,0 and 1,1 terms
C
C Example of the required data format of input file EGM96
   0   0 +1.000000000000d+00 +0.000000000000d+00  0.00000000d+00  0.00000000d+00
   1   0 +0.000000000000d+00 +0.000000000000d+00  0.00000000d+00  0.00000000d+00
   1   1 +0.000000000000d+00 +0.000000000000d+00  0.00000000d+00  0.00000000d+00
   2   0 -0.484165371736d-03  0.000000000000d+00  0.35610635d-10  0.00000000d+00
   2   1 -0.186987635955d-09  0.119528012031d-08  0.10000000d-29  0.10000000d-29
   2   2  0.243914352398d-05 -0.140016683654d-05  0.53739154d-10  0.54353269d-10
   3   0  0.957254173792d-06  0.000000000000d+00  0.18094237d-10  0.00000000d+00
```

"spherical harmonic model of squared topographical heights" (e.g. TUG-87 based H^2) example

```
C An input file with topographical H2 coefficients MUST be in following format
C (arranged as columns, altogether 4 columns, NO HEADER!!!!)
C :degree N; order M; coeff. HCnm; coeff. HSnm;
C Assumed that input file contains also 0.0; 1,0 and 1,1 terms
C Example of the required data format of input file H2_tug87.cof
C   0  0   0.4464025065D+06   0.0000000000D+00
C   1  0  -0.2161658303D+05   0.0000000000D+00
C   1  1   0.8572045522D+05   0.2030582602D+06
C   2  0   0.2837114475D+06   0.0000000000D+00
C   2  1  -0.2092626193D+05   0.2064845705D+06
C   2  2  -0.2356146467D+06   0.3491766549D+05

NO HEADER is assumed for both input files!!!!
```

Output files:

Computed quantities are stored into the following files:
1) ELL_correction.LOG is a log file, which contains input parameters and the statistics
2) ELL_sphr_appr.xyz is a file of the ellipsoidal corrections for the spherical approximation (three colums)
3) ELL_grav_dist.xyz is a field of ellipsoidal corrections to the gravity disturbance (three colums)

"ELL_grav_dist.xyz" example

φ λ $\varepsilon_{\delta g}\left(r_t(\Omega)\right)$

```
65.9583 210.0417  -0.003
65.9583 210.1250  -0.003
.
40.0417 251.9583  -0.005
```

"ELL_sphr_arrr.xyz" example

φ λ $\varepsilon_{\mathrm{n}}\left(r_t(\Omega)\right)$

```
65.9583 210.0417  -0.054
65.9583 210.1250  -0.054
.
40.0417 251.9583  -0.008
```

where:

$\varepsilon_{\delta g}\left(r_t(\Omega)\right)$ is the ellipsoidal correction to the gravity disturbance.
$\varepsilon_{\mathrm{n}}\left(r_t(\Omega)\right)$ is the ellipsoidal correction for the spherical approximation.

2.13 Program Reference_field.f

Options:

The program is interactive, i.e., when starting execution, it asks for user`s options. Then the user gives Helmert's condensation technique (mass-conservation condensation or conservation of the origin of mass), boundaries of the computation area, the step of data in latitude and longitude, and the degree of the reference spheroid (in our exercise nmax=60, nmin=0). Latitude and longitude are given in degrees and minutes.
The program uses the file with the geopotential coefficients of a geopotential model (Note that the "Potsdam GFZ" format of geopotential coefficients is assumed, see e.g. GRIM4.S4) and the file "TUG-87_Square.coef" with the square coefficients of the global elevation model TUG-87.

Names of output files are predefined inside the code!!

Computed quantities are stored in the files created by the program and named as:
"Helmert_anomaly.ref" : Helmert's reference gravity anomalies [mgal],
"anomaly_gradient.ref" : vertical gradient of Helmert's reference gravity anomalies.
"DTE.ref" : reference direct topographical effect on the gravitational potential.
"SITE.ref" : reference secondary indirect topographical effect on the gravitational potential.
"PITE.ref" : reference primary indiredt topographical effect on the geoid.

Input files:

"EGM96_150.coef" example

```
Earth Gravity Model EGM96                  Coefficients up to degree/order 150
 150   6378136.30  0.3986004415D15
GRCOF2    0    0 +1.00000000000D+00 +0.00000000000D+00 0.0000D+00 0.0000D+00
GRCOF2    1    0 +0.00000000000D+00 +0.00000000000D+00 0.0000D+00 0.0000D+00
GRCOF2    2    0 -4.84165371736D-04 +0.00000000000D+00 3.5611D-11 0.0000D+00
GRCOF2    3    0 +9.57254173792D-07 +0.00000000000D+00 1.8094D-11 0.0000D+00
…..
```

" TUG-87_Square.coef" example

```
  H2 (H. squared) coefficients up to 90/90 in m2 originated from TUG87 data
  90    6378137.0  298.257  0.108263D-02
   0  0   0.4464025065D+06   0.0000000000D+00
   1  0  -0.2161658303D+05   0.0000000000D+00
   1  1   0.8572045522D+05   0.2030582602D+06
   2  0   0.2837114475D+06   0.0000000000D+00
   2  1  -0.2092626193D+05   0.2064845705D+06
………………..
```

Output files:

"Helmert_anomaly.ref" example

φ λ $\Delta g^{\mathrm{H}}_{\mathrm{ref}}\left(r_g(\Omega)\right)$

```
43.0417  230.0417  -14.344
43.0417  230.1250  -14.289
.
58.9583  245.9583  -10.223
```

where:

$\Delta g^{\mathrm{H}}_{\mathrm{ref}}\left(r_g(\Omega)\right)$ is Helmert's reference gravity anomalies referred to the geoid surface [mGal].

Warning: the writing of the output "Helmert_anomaly.ref" starts from the Southermost latitude!

"Anomaly_gradient.ref" example

```
  φ         λ     reference anomaly gradient
43.0417  230.0417      -0.00002
43.0417  230.1250      -0.00002
.
58.9583  245.9583      -0.00001
```

"DTE.ref" example

```
  φ         λ      reference DTE
43.0417  230.0417       0.000
43.0417  230.1250       0.000
.
58.9583  245.9583       0.000
```

where:

$\Delta g^{\mathrm{H}}_{\mathrm{ref}}\left(r_g(\Omega)\right)$ is Helmert's reference gravity anomalies referred to the geoid surface.

Warning: the writing of the output "Helmert_anomaly.ref" starts from the Southermost latitude!

"SITE.ref" example

```
  φ         λ       reference SITE
43.0417  230.0417      0.000
43.0417  230.1250      0.000
.
58.9583  245.9583      0.000
```

"PITE.ref" example

```
  φ         λ      reference PITE
43.0417  230.0417      0.000
43.0417  230.1250      0.000
.
58.9583  245.9583      0.000
```

2.14. Program: Res_anomaly.c

For computation of residual anomalies from gravity anomalies at the geoid level by adding Ellipsoidal corrections and subtracting a gravity reference field.

The option file:

"Res_anomaly.opt" example

```
----------------------------------------------B of F------------------------------------------------------
1 HA_anomaly_geo.xyz
0 ell_grav.xyz
0 ell_sphr.xyz
1 Helmert_anomaly_2-20_extended.xyz
0 Residual_anomaly20_SN.xyz
-47.992083 -3.992083 105.992083 159.992083
0.08333 0.08333
-----------------------------------------------------E of F------------------------------------------------------
```

where:

"HA_anomaly_geo.xyz" : input file of the mean Helmert gravity anomalies at geoid level
"Ell_grav.xyz" : input file of the ellipsoidal corrections to gravity disturbance
"Ell_sphr.xyz" : input file of the ellipsoidal corrections for the spherical approximation.
"Helmert_anomaly_2-20_extended.xyz" : input file of the reference field gravity anomaly.
"Residual_anomaly20_SN.xyz" : output file of the residual gravity anomaly at the geoid level.
-47.992083 -3.992083 105.992083 159.992083 : extreme coordinates of the computation area (cell borders).
0.08333 0.08333 : step size (lat. and long.)

Code 0 in front of the output file only (Residual_anomaly20_SN.xyz): suggests that it will be sorted South-North.
Code 1 in front of the output file only(Residual_anomaly20_SN.xyz): suggests that it will be sorted North-South.

Code 0 in front of the input file: the file will be neglected in the computation.
Code 1 in front of the input file: the file will be used in the computation.

For instance, in the option file located above the residual anomaly is computed using HA_anomaly_geo.xyz and Helmert_anomaly_2-20_extended.xyz and the 2 ellipsoidal corrections will not be read.

Coverage in the input files does not need to be the same as long as they all cover the output area. Input files are not required to be sorted in the same direction. Grid nodes are assumed to have the same position and step in all input files.

Input :

"HA_anomaly_geo.dat" example

φ	λ	$\overline{\Delta g}^{h}(r_t,\Omega)$	$\delta\Delta g^{h}(\Omega)$	$\Delta g^{h}(r_g,\Omega)$
52.95833	235.04167	-33.988	0.000	-33.988
52.95833	235.12500	-26.314	0.000	-26.314
.				
48.04167	239.95833	-49.024	-17.524	-66.548

where:

$\overline{\Delta g}^{\mathrm{h}}(r_t, \Omega)$ is the anomaly on the surface (before DWC).

$\delta\Delta g^{\mathrm{h}}(\Omega)$ is the value of the downward continuation contribution.

$\Delta g^{\mathrm{h}}(r_g, \Omega)$ is the Helmert gravity anomaly referred to the geoid surface.

"ELL_grav.xyz" example

φ λ $\varepsilon_{\delta g}(r_t(\Omega))$

```
65.9583 210.0417  -0.003
65.9583 210.1250  -0.003
.
40.0417 251.9583  -0.005
```

"ELL_sphr.xyz" example

φ λ $\varepsilon_{\mathrm{n}}(r_t(\Omega))$

```
65.9583 210.0417  -0.054
65.9583 210.1250  -0.054
.
40.0417 251.9583  -0.008
```

where:

$\varepsilon_{\delta g}(r_t(\Omega))$ is the ellipsoidal correction to the gravity disturbance.

$\varepsilon_{\mathrm{n}}(r_t(\Omega))$ is the ellipsoidal correction for the spherical approximation.

"Helmert_anomaly.xyz" example

φ λ $\Delta g^{\mathrm{H}}_{\mathrm{ref}}(r_g(\Omega))$

```
43.0417  230.0417  -14.344
43.0417  230.1250  -14.289
.
58.9583  245.9583  -10.223
```

where:

$\Delta g^{\mathrm{H}}_{\mathrm{ref}}(r_g(\Omega))$ is Helmert's reference gravity anomalies referred to the geoid surface.

Output:

The format in the output file is ready for input in program Stokes_integral.for.
Note: In order to use the output Res_anomaly.xyz as input for the Stokes_integral.for, the Res Anomaly file needs to be sorted South-North.

"**Res_anomaly.xyz**" example

$\lambda_{\min}$ $\varphi_{\min}$ $\lambda_{\max}$ $\varphi_{\max}$ $\Delta\lambda$ $\Delta\varphi$ i j

```
230 043 246 059 300 300 192 192
```

φ	λ	$\Delta g_{\text{res}}^{\text{H}}\left(r_g\left(\Omega\right)\right)$
43.0417	230.0417	-25.460
43.0417	230.1250	-23.107
.		
58.9583	245.9583	-17.133

where:

$\varphi_{\min}$, $\varphi_{\max}$: minimal and maximal latitude**.**
$\lambda_{\min}$, $\lambda_{\max}$: minimal and maximal lngitude**.**
$\Delta\lambda$, $\Delta\varphi$: step size in longitude and latitude.
i, j : number of rows and columns in the grid of the output file.
$\Delta g_{\text{res}}^{\text{H}}\left(r_g\left(\Omega\right)\right)$: residual anomaly.

2.15 Program Stokes_integral.for

This program computes the stokes integral using near zone and far zone (truncation error) contributions. In the standard case, it is applied to residual anomalies to obtain residual cogeoid heights.

The option file:

"Stokes_interal.opt" example

```
---------------------------------- B o F ------------------------------------------------
Residual_gravity.geo      ! name of the file with input Helmert's residual
                            gravity anomalies
egm96.dat                 ! name of the file with input geopotential model
049.0 236.0 053.0 240.0   ! computation limits s/w/n/e (deg)
6.0                       ! radius of the spherical cap (deg)
20                        ! degree of spheroidal Stokes's function / of the
                            reference spheroid
180                       ! maximum degree for evaluation of the far-zone
                            truncation errors
0                         ! evaluation of the reference field quantities
                            (yes = 1 / no = 0)
1                         ! evaluation of truncation errors (yes = 1 / no = 0)
0                         ! test the program (yes = 1 / no = 0)
---------------------------------- E o F ------------------------------------------------
```

where:

`049.0 236.0 053.0 240.0` correspond to cell BORDERS rather than cell centres!

Input files:

This program requires 2 input files, one is to describe the global gravity field (egm96.dat) and another with residual anomalies grided values.

"egm96.dat" example

```
egm96: geopotential coefficients up to degree and order 360
   360    6.3781363d6         0.3986004415d15
   2   0 -0.484165371736d-03  0.000000000000d+00  0.35610635d-10  0.00000000d+00
   2   1 -0.186987635955d-09  0.119528012031d-08  0.10000000d-29  0.10000000d-29
   2   2  0.243914352398d-05 -0.140016683654d-05  0.53739154d-10  0.54353269d-10
   .
 360 360 -0.447516389678d-24 -0.830224945525d-10  0.50033977d-10  0.50033977d-10
```

Note: The file "egm96.dat" with geopotential coefficient of the Geopotential model EGM-96 is needed to evaluate the far zone contribution.

"Residual_gravity.geo" example

$\lambda_{\min}$ $\varphi_{\min}$ $\lambda_{\max}$ $\varphi_{\max}$ $\Delta\lambda$ $\Delta\varphi$ i j

```
230   043  246  059   300  300  192 192
```

φ λ $\Delta g^{H}_{res}\left(r_g(\Omega)\right)$

```
43.0417 230.0417    -25.460
43.0417 230.1250    -23.107
.
```

```
58.9583 245.9583    -17.133
```

where:

$\varphi_{\min}$, $\varphi_{\max}$ are minimal and maximal latitude **(i.e BORDERS rather than cell centres!)** of the area for input data [deg], $\lambda_{\min}$, $\lambda_{\max}$ are minimal and maximal longitude **(i.e BORDERS rather than cell centres!)** of the area for input data [deg], $\Delta\lambda, \Delta\varphi$ are step of data in longitude and latitude [sec], i, j are number of data in longitude **(i.e number of columns)** and latitude **(number of rows)**, and $\Delta g_{\mathrm{res}}^{\mathrm{H}}\left(r_g\left(\Omega\right)\right)$ is Helmert's residual gravity anomaly on the geoid surface [mGal].

Output file:

Note : the writing of the output "Residual_cogeoid.dat" starts from the Southermost latitude!

"Residual_cogeoid.dat" example **(**default name of the output file)

φ	λ			$\varepsilon_N(\Omega)$	$N_{\mathrm{res}}(\Omega)$
49.0417	236.0417	11.225	0.003	1.644	1.647
49.0417	236.1250	1.881	-0.002	1.070	1.068
.					
52.9583	239.9583	22.617	-0.012	1.668	1.656

where:

$\varepsilon_N(\Omega)$ is the far-zone contribution to the residual co-geoidal height (i.e., truncation error).
$N_{\mathrm{res}}(\Omega)$ is the residual co-geoidal height.

2.16. Program Reference_spheroid.f

Options:

The program is interactive, i.e., when starting execution, it asks for user`s options. Then the user gives Helmert's condensation technique (mass-conservation condensation or conservation of the origin of mass), boundaries of the computation area, the step of data in latitude and longitude, and the degree of the reference spheroid (in our exercise nmax=60, nmin=0). **The degrees should be consistant with the computations of the reference anomalies**. Latitude and longitude are given in degrees and minutes.
The program uses the file with the geopotential coefficients of a geopotential model (Note that the "Potsdam GFZ" format of geopotential coefficients is assumed, see e.g. GRIM4.S4) and the file "TUG-87_Square.coef" with the square coefficients of the global elevation model TUG-87.

Input files:

"EGM96_150.coef" example

```
Earth Gravity Model EGM96                   Coefficients up to degree/order 150
 150   6378136.30  0.3986004415D15
GRCOF2    0    0 +1.00000000000D+00 +0.00000000000D+00 0.0000D+00 0.0000D+00
GRCOF2    1    0 +0.00000000000D+00 +0.00000000000D+00 0.0000D+00 0.0000D+00
GRCOF2    2    0 -4.84165371736D-04 +0.00000000000D+00 3.5611D-11 0.0000D+00
GRCOF2    3    0 +9.57254173792D-07 +0.00000000000D+00 1.8094D-11 0.0000D+00
…..
```

"TUG-87_Square.coef" example

```
  H2 (H. squared) coefficients up to 90/90 in m2 originated from TUG87 data
  90   6378137.0  298.257  0.108263D-02
   0  0   0.4464025065D+06   0.0000000000D+00
   1  0  -0.2161658303D+05   0.0000000000D+00
   1  1   0.8572045522D+05   0.2030582602D+06
   2  0   0.2837114475D+06   0.0000000000D+00
   2  1  -0.2092626193D+05   0.2064845705D+06
………………..
```

Output files:

Computed quantities are stored in the files created by program and named as:
"PITE.ref" : reference primary indirect topographical effect on the geoidal heights [m],
"SPHEROID.ref" : Helmert's reference spheroid [m],
"DTE.ref" : reference direct topographical effect on the gravitational attraction [mgal],
"SITE.ref" : reference secondary indirect topographical effect on the gravitational attraction [mgal].

"SPHEROID.ref " example

φ	λ	$N_{\text{ref}}(\Omega)$
50.9583	236.0417	-17.030
50.9583	236.1250	-17.021
.		
49.0417	238.9583	-17.599

where:

$N_{\text{ref}}(\Omega)$ is the reference co-geoidal height [m].
Warning: the writing of the output "Spheroid.ref" starts from the Southermost latitude!

2.17 Program PIAE.cc

The program is interactive, i.e., when starting execution, it asks for user`s options. Then the user gives names of the following files:

- file with the integration points for the inner-zone:
- file with the integration points for the near-zone:
- file with the integration points for the far-zone:
- file with the coordinates of the calculation points:
- output file:

where:

inner zone : input file of the mean 30" x 30" DTM
near zone : input file of the mean 5' x 5' DTM
far zone.. : input file of the global 60' x 60' DTM
calculation points : input file with coordinates of calculation points
output file : output file of 5' x 5' point values of the secondary indirect topographic effect

The program is set by default as follows:

inner zone integration radius: size = 25x25 minute
near zone integration radius : size = 5x5 degree

Input files:

Constraints:

The BORDERS of the 60'x60' cells should exactly coincide with the BORDERS of the 5'x5' cells.
All the input files are assumed to cover a discrete number of degrees.
The 5-minute data is supposed to coincide with corners of the 30-second data grid cells (so that the calculation points should not coincide with the 30 second integration points).
The inner-zone input file should be extended at least 12.5 arc-min off from each border of the computation area.
The near-zone input file should be extended at least 3 arc-degrees off from each border of the computation area.
For instance: if the file of the computation points covers a 10x10 degree area, then the inner-zone file should cover 10.25x10.25 degrees (at least).

"Inner_zone.xyz" example

φ λ $\overline{H}^{O}(\Omega)$

```
60.9958 209.0083    340.0
60.9958 209.0250    326.0
.
49.0042 220.9917   1210.0
```

where:

φ is latitude [deg], λ is longitude [deg], and $\overline{H}^{O}(\Omega)$ is the mean orthometric height [m].

"Near_zone.xyz" example

```
64.95830 205.04170    528.0
64.95830 205.12500    624.0
```

```
.
45.04170 224.95830    756.0
```

"GlobalH.xyz" example

φ λ $\overline{H}^{O}(\Omega)$

```
 89.5    0.5    0.0
 89.5    1.5    0.0
 89.5    2.5    0.0
. . .
-89.5  359.5  848.2
```

"Computation_points.xyz" example : this input file should contain coordinates and heights of the points of interest. These points may or may not be arranged in a grid.

φ λ $\overline{H}^{O}(\Omega)$

```
59.95830 210.04170    320.0
59.95830 210.12500    204.0
.
50.04170 219.95830   1126.0
```

"Near-zone.xyz" and "GlobalH.xyz" can be common to different computation areas

Output file:

"PIAE.xyz" example

φ λ $\delta N^{a}(\Omega)$

```
59.95830 210.04170   -0.001
59.95830 210.12500   -0.001
.
50.04170 219.95830   -0.001
```

where:

$\delta N^{a}(\Omega)$ is the primary indirect atmospheric effect on the geoidal heights referred to the geoid surface.

2.18 Program PITE.cc

The program is interactive, i.e., when starting execution, it asks for user`s options. Then the user gives names of the following files:

- file with the integration points for the inner-zone:
- file with the integration points for the near-zone:
- file with the integration points for the far-zone:
- file with the coordinates of the calculation points:
- output file:

where:

inner zone : input file of the mean 30" x 30" DTM
near zone : input file of the mean 5' x 5' DTM
far zone.. : input file of the global 60' x 60' DTM
calculation points : input file with coordinates of calculation points
output file : output file of 5' x 5' point values of the secondary indirect topographic effect

The program is set by default as follows:

inner zone integration radius: size = 25x25 minute
near zone integration radius : size = 5x5 degree

Input files:

Constraints:

The BORDERS of the 60'x60' cells should exactly coincide with the BORDERS of the 5'x5' cells.
All the input files are assumed to cover a discrete number of degrees.
The 5-minute data is supposed to coincide with corners of the 30-second data grid cells (so that the calculation points should not coincide with the 30 second integration points).
The inner-zone input file should be extended at least 12.5 arc-min off from each border of the computation area.
The near-zone input file should be extended at least 3 arc-degrees off from each border of the computation area.
For instance: if the file of the computation points covers a 10x10 degree area, then the inner-zone file should cover 10.25x10.25 degrees (at least).

"Inner_zone.xyz" example

φ λ $\overline{H}^{O}(\Omega)$

```
60.9958 209.0083    340.0
60.9958 209.0250    326.0
.
49.0042 220.9917   1210.0
```

where:

φ is latitude [deg], λ is longitude [deg], and $\overline{H}^{O}(\Omega)$ is the mean orthometric height [m].

"Near_zone.xyz" example

```
64.95830 205.04170    528.0
64.95830 205.12500    624.0
```

```
.
45.04170 224.95830    756.0
```

"GlobalH.xyz" example

φ λ $\overline{H}^{O}(\Omega)$

```
 89.5    0.5    0.0
 89.5    1.5    0.0
 89.5    2.5    0.0
. . .
-89.5  359.5  848.2
```

"Computation_points.xyz" example : this input file should contain coordinates and heights of the points of interest. These points may or may not be arranged in a grid.

φ λ $\overline{H}^{O}(\Omega)$

```
59.95830 210.04170    320.0
59.95830 210.12500    204.0
.
50.04170 219.95830   1126.0
```

Output file:

"PITE.xyz" example

φ λ $\delta N^{t}(\Omega)$

```
59.95830 210.04170   -0.014
59.95830 210.12500   -0.047
.
50.04170 219.95830   -0.057
```

where:

$\delta N^{t}(\Omega)$ is the primary indirect topographical effect on the geoidal heights referred to the geoid surface.

2.19 Program cogeoid2geoid.c

This program computes the sum of the following contributions: residual co-geoid, Reference Spheroid, Primary Indirect Topographic effect (PITE), Primary Indirect Atmospheric Effect (PIAE).

Structure of option file:

"cogeoid2geoid.opt" example

---B of F---

```
1 Residual_cogeoid_whole.dat
1 SPHEROID_2-60.ref
1 PITE_whole.xyz
0 PIAE_whole.xyz
Geoid_final.xyz
-41.992083 -10.992083 115.992083 151.992083
0.01666667 0.016666667
```

---E of F---

where:

"Residual_cogeoid_whole.dat" : input file of the residual co-geoid
"SPHEROID_0_60_NS.ref" : input file of the reference spheroid heights
"PITE_whole.out" : input file of the PITE values
"PIAE_whole.xyz" : input file of the PIAE values
"Geoid_final.xyz" : output file of the final geoidal heights

```
0.01666667:step size
```

Code 1 in front of the input file: the file will be used in the computation.
Code 0 in front of the input file : the file will be neglected in the computation.

For instance, in the option file located above, three out of the four input files (Residual_cogeoid_whole.dat, SPHEROID_2-60.ref and PITE_whole.xyz) are used in the computation where one of the input files (PIAE_whole.xyz) is neglected.

Coverage in the input files does not need to be the same as long as they all cover the output area. Input files are not required to be sorted in the same direction. Grid nodes are assumed to have the same position and step in all input files.

Input :

"Residual_cogeoid_whole.dat" example **(**default name of the output file)

φ	λ			$\varepsilon_N(\Omega)$	$N_{\mathrm{res}}(\Omega)$
49.0417	236.0417	11.225	0.003	1.644	1.647
49.0417	236.1250	1.881	-0.002	1.070	1.068
.					
52.9583	239.9583	22.617	-0.012	1.668	1.656

where:

$\varepsilon_N(\Omega)$ is the far-zone contribution to the residual co-geoidal height (i.e., truncation error).

$N_{\mathrm{res}}(\Omega)$ is the residual co-geoidal height.

"SPHEROID_2-60.ref " example

φ	λ	$N_{\mathrm{ref}}(\Omega)$
50.9583	236.0417	-17.030
50.9583	236.1250	-17.021
.		
49.0417	238.9583	-17.599

where:

$N_{\mathrm{ref}}(\Omega)$ is the reference co-geoidal height [m].

"PIAE_whole.xyz" example

φ	λ	$\delta N^{a}(\Omega)$
59.95830	210.04170	-0.001
59.95830	210.12500	-0.001
.		
50.04170	219.95830	-0.001

where:

$\delta N^{a}(\Omega)$ is the primary indirect atmospheric effect on the geoidal heights referred to the geoid surface [m].

"PIT_wholeE.xyz" example

φ	λ	$\delta N^{t}(\Omega)$
59.95830	210.04170	-0.014
59.95830	210.12500	-0.047
.		
50.04170	219.95830	-0.057

where:

$\delta N^{t}(\Omega)$ is the primary indirect topographical effect on the geoidal heights referred to the geoid surface.

Output:

"Geoid_final.xyz"

φ	λ	$N(\Omega)$
59.95830	210.04170	-15.397
59.95830	210.12500	-16.000
.		
50.04170	219.95830	-16.000

where:

$N(\Omega)$ is the geoidal height

5. List of authors:

- dte_dp.c – Juraj Janák; December 2000
- fair.c – Juraj Janák; October 2000,
- dte_pm.c – Juraj Janák; October 2000,
- dtf.f – Pavel Novák; January 1998
- dtep.f – Jianliang Huang , July 1999
- DTE_Helmert_global.c – Juraj Janák; R. Tenzer October 2000; Ellmann 2005
- SITE.cc – Robert Tenzer, Sander van Eck van der Sluijs; October 2001, A. Ellmann 2005
- DAE_H_NT.cc – Robert Tenzer, Sander van Eck van der Sluijs; January 2003, A.Ellmann 2005
- Geoid_quasigeoid_cor.c – Robert Tenzer; August 2002
- Dwnc08.c – David Avalos, J. Janak 2008
- Surf_anomaly.c – Artu Ellmann; August 2005
- Ellips_corrections.for – Artu Ellmann; August 2005
- Res_anomaly.c – David Avalos, 2008
- Reference_field.f – Mehdi Najafi-Alamdari; June 1994
- Stokes_integral.for – Pavel Novák; August 1998
- Reference_spheroid.f – Mehdi Najafi-Alamdari; August 1994
- PIAE.cc – Robert Tenzer, Sander van Eck van der Sluijs; October 2001
- PITE.cc – Robert Tenzer, Sander van Eck van der Sluijs; October 2001
- Cogeoid2geoid.c – David Avalos, 2008.