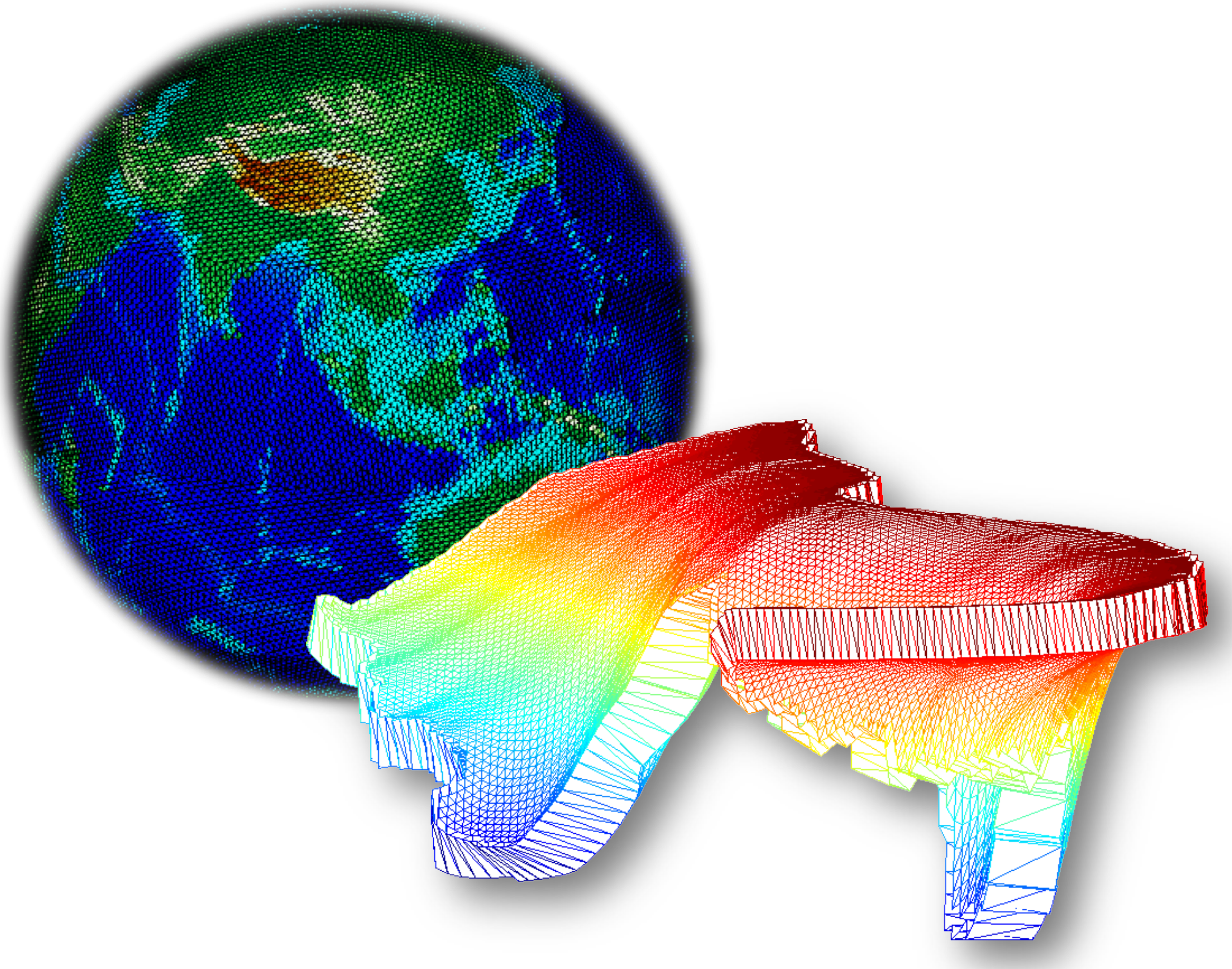

GEEC USER'S GUIDE

GAL EOTVOS EARTH CALCULATOR

Gravity and gravity gradient forward modelling is extensively used in numerous geosciences applications. *GEEC*, stands for Gal Eötvös Earth Calculator, is an open-source software dedicated to compute precisely the gravitational fields of a mass body. This software is using the MATLAB^{TM} language. It is designed to be easily used and accessible for users with no prior knowledge of MATLAB^{TM} programming language.

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GEEC USER'S GUIDE

GAL EOTVOS EARTH CALCULATOR

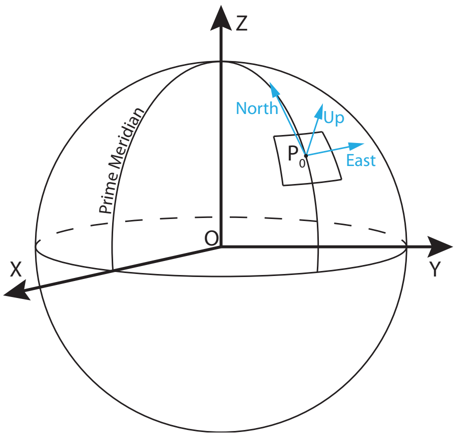
HOW TO CITE *GEEC*

To cite *GEEC* in publications, please refer to the article published in Journal of Geodesy.

Saraswati, A. T., Cattin, R., Mazzotti, S., & Cadio, C. (2019). New analytical solution and associated software for computing full-tensor gravitational field due to irregularly shaped bodies. *Journal of Geodesy*, 1–17, doi:10.1007/s00190-019-01309-y

Description of the algorithms can be found in this article.

GRAVITY AND GRAVITY GRADIENT IN *GEEC*



Spatial Directions

In the *GEEC* computation process, the resulted gravity and gravity gradients are provided in the local right-handed Cartesian frame.

The origin is located at the computation point

- Z-axis is pointing radially outward, parallel to the vector from the geocenter to the origin
- Y-axis pointing North
- X-axis pointing East

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Unit

GRAVITY

The results of gravity forward modelling in three directions are given in mGal unit, where

$$1\ \mathrm{mGal} = 10^{-5}\ \mathrm{m.s^{-2}}$$

GRAVITY GRADIENT

Six gravity gradient tensor components are given in Eötvös unit (E), where

$$\begin{aligned} 1\ \mathrm{E} &= 10^{-9}\ \mathrm{s^{-2}} \\ &= 10^{-4}\ \mathrm{mGal.m^{-1}} \end{aligned}$$

INSTALLING *GEEC*

GEEC is developed under the MATLAB™ language that allow the user perform all processing steps, from input data to results visualization without any need for external programs. *GEEC* can be installed in all systems and platforms as long as MATLAB™ is installed in the system.

- Download *GEEC* from either the website of Geosciences Montpellier Laboratory (http://www.gm.univ-montp2.fr under the section Scientific Softwares), or Form@Ter web site, GitHub or MATLAB File Exchange.
- Put the .*zip file in the desired directory
- Unzip the *.zip file

The unzip directory consists in three files

- `GEEC.m` – the main file.
- `GEEC.fig` – the GEEC interface
- `startup.m` – to add GEEC's paths into the system

and four directories

- `code` – All source code
- `doc` – GEEEC's user manual
- `example` – Script to launch GEEC without interface
- `startstop` – With `stopGEEC.m` to delete GEEC's paths and figures.

Before using *GEEC*, the path of the *GEEC* directory must be set in MATLAB™ environment. To add GEEC's folder to MATLAB™ path, firstly, launch MATLAB™ and type "`pathtool`" in the MATLAB command prompt or click Home > Set Path, and then add GEEC folder. Next, change the first line of `startup.m` to give the path associated with the GEEC folder. The *GEEC's* folder path that is set in the MATLAB path and that is written in `GEECdir` variable must be the same.

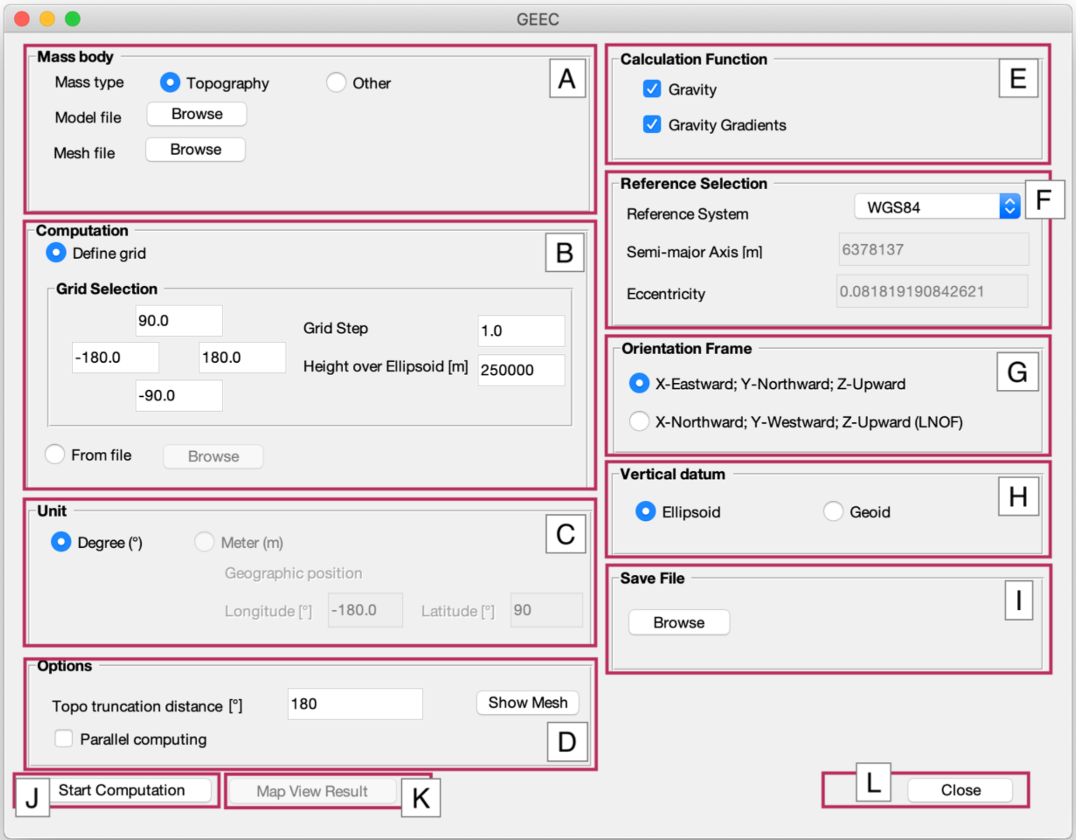
Example of GEEC path: `GEECdir='C:\Users\MyName\GEEC';`

LAUNCH *GEEC*

GEEC can be executed in two ways, by using *GEEC*'s user interface and using MATLAB™ script[1,2].

USING *GEEC* INTERFACE

Run GEEC.m by typing "GEEC" in the MATLAB™ command windows. The *GEEC* interface will be shown.



***GEEC's* interface overview**

A. Mass body

The type of the mass (topography or other body), its geometry, and its density are set on this part in *GEEC* interface.

a. The <u>model file</u>, including the 3D position of the polyhedron point clouds must be inputted in this part. The file could be in ASCII format or *.mat format with 3 columns, including

i. [longitude (°)   latitude (°)   height (m)] if the geometry is defined in the geographic coordinate system (recommended).

ii. [X (m)   Y (m)   Z (m)] if the geometry is defined in the local 3D cartesian system.

[1] For a calculation that includes an extensive number of object's vertices and/or computation points, the use of *GEEC* command line is preferable than the *GEEC* user interface.

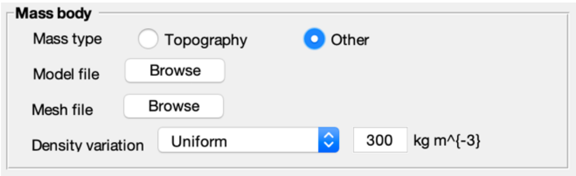
[2] For the computation without taking into account the sphericity (in a planar field), only available by using script function "`geec`"

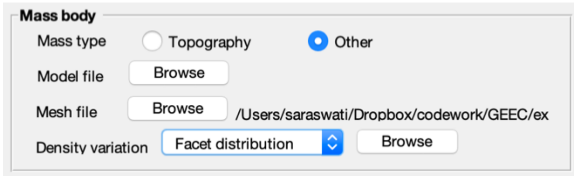
b. The mesh file, including the triangulation connectivity list of the polyhedron. It is represented as a matrix with 3 columns, each row represents a triangle as a facet of the polyhedron, where each element in this matrix mentions the vertex ID of the given model's point clouds. The mesh of the geometry is not an obligation if the selected mass type is the topography.

c. If the chosen mass type is topography, the density of the mass is set as following (default):
   i. Land mass, with a density of 2670 kg.m^{-3}
   ii. Ocean mass, with a density contrast (between ocean and crust density) of -1640 kg m^{-3}

   These densities can be changed in the `gravityterre.m` and `gravitymer.m` for the computation of gravity and `gradientterre.m` and `gradientmer.m` for the computation of gravity gradients.

   If the chosen mass is not topography, the density of the mass body must be defined. The interface on the Panel A will be changed as following:





   If the mesh of the polyhedron is not given, the user can only set the density of the mass body as a uniform mass. If the mesh of the polyhedron is given by user, the density can be set as a uniform mass body or varied at each facet. For the density variation at each facet, an input file which contains the density variation of each facet row must be given, where the size of the matrix is $[f \times 1]$, where f is the number of facets.

⚠ For the use of varied density of each facet, the user must define the density carefully. This function is expected for the use of a mass body with lateral variation of the density or multiple mass bodies with different densities. User must define the density of each facet carefully.

B. Computation point

The position of computation point must be set in this panel. The coordinate system of the computation points must be same with the geometry model. There is two types of the computation point distributions:

a. Regular grid distribution

   If the user wants to generate a set of computation point with regular grid distribution, the user must define the northern-southern-western-eastern limit of the point distributions and set the spacing grid in the field of grid step. The altitude of the computation is constant in this type of distribution.

b. Pre-defined computation points distribution

   The user can also input a pre-defined position of computation points. The file should be in ASCII or *.mat format file, where it must contains three columns to define the position of point, including
   i. [longitude (°) latitude (°) height (m)] if the geometry is defined in the geographic coordinate system (recommended). For computation of topography effect, we recommend to add these locations into the DEM file to avoid computation with measurements below the topographic surface.
   ii. [X (m) Y (m) Z (m)] if the geometry is defined in the local 3D Cartesian system.

C. Unit of the geometry and position of the mass body and the computation point

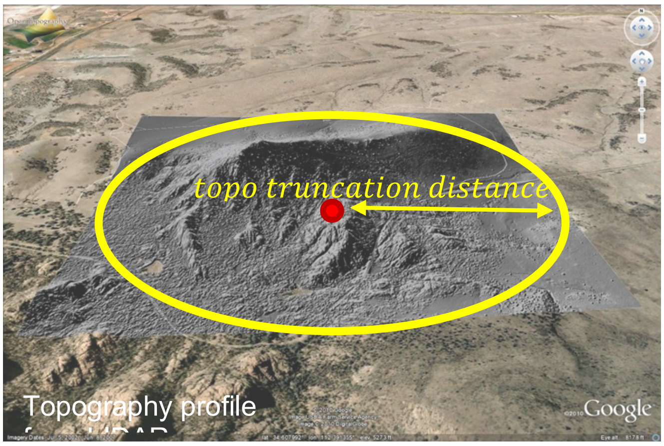
a. In the computation of topography effect, inputted topography model and its computation points must be given in the geographic coordinate system, where the unit of the coordinate is in degree (°).

b. For the computation of other mass body than topography, the mass model and computation point can be defined in the local 3D Cartesian system, where the unit is in meter (m). If this option is chosen, the user must input the geographic position of the mass (longitude, latitude), thus the ellipticity factor of the Earth can be always taken into account. The position of the center of the mass is recommended as the input.

D. Options

a. Topo truncation distance

If topography is chosen as the computed mass, user can set the distance until where topography effect is considered in the computation from a station's position. The distance can be set with a value between 0° and 180°. To take into account the effect of whole topography, set the topo truncation distance with 180°.



b. Show mesh

This button is useful to show the geometry of the inputted mass body.

c. Parallel computing

To allow a parallel computation in the process, select this option. MATLAB parallel toolbox has to be installed to do this task. To know the number of the maximum workers can be obtain by run a command parcluster in the MATLAB command window.

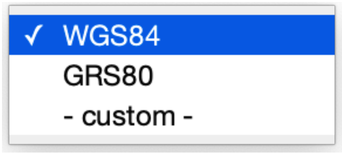
To set the maximum number of the parallel pool, go to MATLAB toolstrip Home > Parallel > Parallel Preferences, and in the preferred number of workers in a parallel pool, specify the preferred number of workers.

E. Calculation functions

To select which function that is executed in the computation, user can select gravity or both gravity and gravity gradients.

F. Reference Ellipsoid

To take into account the Earth's curvature, the parameters to specify the reference ellipsoid must be set, including semi-major axis (m) and eccentricity. In the Reference system pop-up menu, user can select *GEEC's* predefined reference system or define it himself.



G. Orientation Frame

The default computation process in *GEEC* is performed in the X-East, Y-North- Z-Up orientation frame. If the user want to obtain the result in the Local North Oriented Frame (LNOF), where X-North, Y-West- Z-Up, choose this option.

H. Vertical Datum

The user can specify the vertical datum that is used in the geometry model. Ellipsoid is set as a default. If geoid is chosen, geoid height from EGM96 will be introduced in the process.

⚠ Most of the available digital terrain models use mean sea level (msl) as the vertical reference, where this surface is close to the geoid surface.

I. Save file

User need to specify the location to save the result. If it is not specified, the result will be saved in a file `saveresults`, both in the ASCII and *.mat formats.

J. Start computation

Press this button to start the computation.

K. Map view result

Use this button to visualize the results.

L. Close

To close the window, press Close button.

Close *GEEC* by typing “`stopGEEC`” in the MATLAB™ command windows.

USING MATLAB™ SCRIPT

Besides using the user interface, *GEEC* is also can be launched using MATLAB script. To initialize *GEEC*, run "startup.m" in the MATLAB™ command windows to add GEEC's paths into the system. For getting started, a file `script_example.m` is given in the directory `example`.

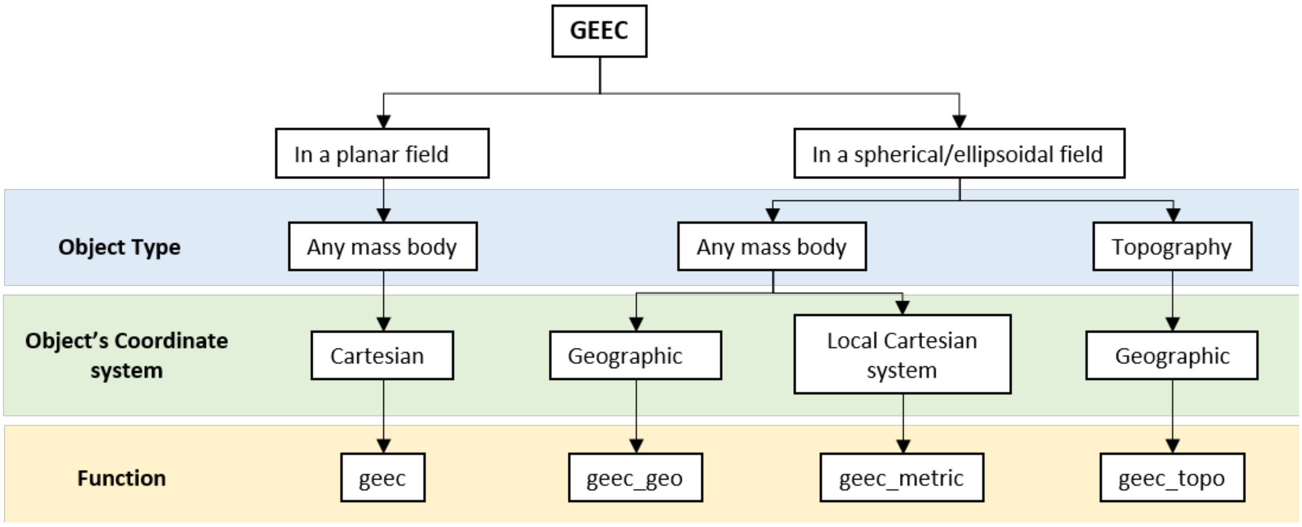


Figure 1. *GEEC*'s flows to compute the gravitational effect of a mass body. The functions are distinguished based on the type and the coordinate system of the object.

As explained before, *GEEC* is capable to calculate the gravitational effect of any type of mass body, either in a planar field or in a spherical/ellipsoidal field. To calculate the effect of a mass body defined in the classical Cartesian system, with the metrical unit, we can simply use `geec` function. To choose other functions, please refer to the flow in Fig. 1.

Calculate the gravitational effect of a mass body

To calculate the gravitational fields of a mass body that is defined in the local Cartesian system and in the planar field, use this function:

```
R = geec(coord_calc,mass_model,tri,dens,Gcalc)
```

Where each input variable must be:

- `coord_calc` : the position of the computation point (x, y, z) in meter
- `mass_model` : the coordinates of model's point clouds (x, y, z) in meter
- `tri` (optional) : the geometric topology of the topography model (e.g. triangle mesh). It consists of a matrix with f rows and n columns, where each element in this matrix mentions the vertex ID of the given model's point clouds. If tri is not defined, define `tri=[]` and then *GEEC* will generate the mesh using *convhull* function.
- `dens` : density of the body (in kg/m^3).
    - If the density is uniform, specify dens with a single value.
    - If tri is not empty, user can define the density of each facet. dens must be a matrix representing the density of each facet, where each row of dens indicate the density

of the facet in the same row. The size of matrix dens must be $[f \times 1]$, where f is the number of tri's rows.

- `Gcalc` : function of the calculation, specify 'grav' for gravity and 'grad' for gravity and gravity gradients.

The output of the computation process is gathered in the matrix R, where the definition of each column is detailed in the Output file section. This function is only working on the script, unavailable for computation process using *GEEC* interface.

Calculate the gravitational effect of a mass body on a spherical/ellipsoidal field

Gravity and gravity gradients datasets that can be easily accessed for geodetic or geophysical applications are defined in the geographic coordinate system. Previous studies explained that the curvature of the Earth is important to the accuracy in the gravity data analysis, especially for the study on a regional to a global scale. To overcome this issue, *GEEC* provides functions to calculate the gravitational effects on a spherical or ellipsoidal field.

- To calculate the gravitational fields of a mass body that is defined in the geographical coordinates, use this function:
  `R = geec_geo(coord_calc,mass_model,tri,dens,vdatum,a,ecc,Gcalc)`

Where each input variable must be:

- `coord_calc` : the coordinates of the computation point (longitude, latitude, altitude)
- `mass_model` : the coordinates of model's point clouds (longitude, latitude, height)
- `tri` (optional) : the geometric topology of the topography model (e.g. triangle mesh). It consists of a matrix with f rows and n columns, where each element in this matrix mentions the vertex ID of the given model's point clouds. If tri is not defined, define tri=[] and then GEEC will generate the mesh using *convhull* function.
- `dens` : density of the body (in kg/m^3).
  - If the density is uniform, specify dens with a single value.
  - If tri is not empty, user can define the density of each facet. dens must be a matrix representing the density of each facet, where each row of dens indicate the density of the facet in the same row. The size of matrix dens must be $[f \times 1]$, where f is the number of tri's rows.
- `vdatum` : the vertical reference of the model coordinates, insert 'ellipsoid' or 'geoid'
- `a` : semi-major axis of ellipsoid (in meter)
- `ecc` : eccentricity of ellipsoid
- `Gcalc` : function of the calculation, specify 'grav' for gravity and 'grad' for gravity and gravity gradients.

The output of the computation process is gathered in the matrix R, where the definition of each column is detailed in the Output file section

- To calculate the gravitational fields of a mass body that is defined in the local Cartesian system while taking into account the curvature of the Earth, use this function:

```
R = geec_metric(coord_calc,mass_model,tri,geo_position,dens,
vdatum,a,ecc,Gcalc)
```

Where each input variable must be:

- `coord_calc` : the position of the computation point (x, y, z) in meter
- `mass_model` : the coordinates of model's point clouds (x, y, z) in meter
- `tri` (optional) : the geometric topology of the topography model (e.g. triangle mesh). It consists of a matrix with f rows and n columns, where each element in this matrix mentions the vertex ID of the given model's point clouds. If tri is not defined, define `tri=[]` and then GEEC will generate the mesh using *convhull* function.
- `geo_position` : the geographic location of the mass model (longitude, latitude). An approximate coordinate of the center of the model is recommended.
- `dens` : density of the body (in kg/m^3).
  - If the density is uniform, specify dens with a single value.
  - If tri is not empty, user can define the density of each facet. dens must be a matrix representing the density of each facet, where each row of dens indicate the density of the facet in the same row. The size of matrix dens must be $[f \times 1]$, where f is the number of tri's rows.
- `vdatum` : the vertical reference of the model coordinates, insert 'ellipsoid' or 'geoid'
- `a` : semi-major axis of ellipsoid (in meter)
- `ecc` : eccentricity of ellipsoid
- `Gcalc` : function of the calculation, specify 'grav' for gravity and 'grad' for gravity and gravity gradients.

The output of the computation process is gathered in the matrix R, where the definition of each column is detailed in the Output file section.

Calculate topography effect

GEEC provides a dedicated function to calculate gravitational effect of topography that is defined in a geographic coordinate system. To calculate topography effect using *GEEC*, use this function:

```
R = geec_topo(coord_calc,dem,tri,vdatum,a,ecc,Gcalc,extension)
```

Where each input variable must be:

- `coord_calc` : the coordinates of the computation point (longitude, latitude, altitude)
- `dem` : the coordinates of model's point clouds (longitude, latitude, height)
- `tri` (optional) : the geometric topology of the topography model (e.g. triangle mesh). It consists of a matrix with f rows and n columns, where each element in this matrix mentions the vertex ID of

the given model's point clouds. If tri is not defined, define `tri=[]` and then GEEC will generate the mesh.

- `vdatum` : the vertical reference of the model coordinates, insert 'ellipsoid' or 'geoid'
- `a` : semi-major axis of ellipsoid (in meter)
- `ecc` : eccentricity of ellipsoid
- `Gcalc` : function of the calculation, specify 'grav' for gravity and 'grad' for gravity and gravity gradients.
- `extension` : indicates the topography truncation distance (in degree). The value must be varied between 0° and 180° (default 180°).

A standard density of 2670 $kg.m^{-3}$ is used for land body computation, and a contrast density of -1640 $kg.m^{-3}$ between ocean and land is used to calculate the ocean body. These densities can be changed in the `gravityterre.m` and `gravitymer.m` for the computation of gravity and `gradientterre.m` and `gradientmer.m` for the computation of gravity gradients.

The output of the computation process is gathered in the matrix R, where the definition of each column is detailed in the Output file section

Close *GEEC* by typing "`stopGEEC`" in the MATLAB™ command windows.

Visualize the results

Visualize gravity

To plot the result of gravity in 3 components, run this function in the command window:

```
plotfig(X,Y,gx,gy,gz)
```

where :

a. X is the longitude or point coordinate in X-axis
b. Y is the latitude of point coordinate in Y-axis
c. gz, gy, gz is the gravity in 3 directions

Visualize gravity gradients

To plot the result of full tensor gravity gradient, run this function in the command window:

```
plotfig(X,Y,Txx,Txy,Txz,Tyy,Tyz,Tzz)
```

where :

d. X is the longitude or point coordinate in X-axis
e. Y is the latitude of point coordinate in Y-axis
f. T_{ij} is the gravity gradients in 6 directions

OUTPUT FILE

The results of the computation are given in two formats, ASCII and *.mat files. The location of the file is in the directory that has been specified by user, or if not, in the "outputdir" directory. The contents of the result depend on the unit and the type of the calculation function.

I. In degree unit

a. Gravity calculation

The output files consist in a 6 columns:

1. Longitude (°)
2. Latitude (°)
3. Altitude (m)
4. g_x (mGal)
5. g_y (mGal)
6. g_z (mGal)

b. Gravity and gravity gradients calculation

The output files consist in a 12 columns

1. Longitude (°)
2. Latitude (°)
3. Altitude (m)
4. g_x (mGal)
5. g_y (mGal)
6. g_z (mGal)
7. T_{xx} (Eötvös)
8. T_{xy} (Eötvös)
9. T_{xz} (Eötvös)
10. T_{yy} (Eötvös)
11. T_{yz} (Eötvös)
12. T_{zz} (Eötvös)

II. In meter unit with considering Earth's ellipticity

a. Gravity calculation

The output files consist in a 8 columns:

1. X (m)
2. Y (m)
3. Longitude (°)
4. Latitude (°)
5. Altitude (m)
6. g_x (mGal)
7. g_y (mGal)
8. g_z (mGal)

b. Gravity and gravity gradients calculation

The output files consist in a 14 columns

1. X (m)
2. Y (m)
3. Longitude (°)
4. Latitude (°)
5. Altitude (m)
6. g_x (mGal)
7. g_y (mGal)
8. g_z (mGal)
9. T_{xx} (Eötvös)
10. T_{xy} (Eötvös)
11. T_{xz} (Eötvös)

12. T_{yy} (Eötvös)
13. T_{yz} (Eötvös)
14. T_{zz} (Eötvös)

III. In meter unit in planar field

a. Gravity calculation

The output files consist in a 6 columns:

1. X (m)
2. Y (m)
3. Z (m)
4. g_x (mGal)
5. g_y (mGal)
6. g_z (mGal)

b. Gravity and gravity gradients calculation

The output files consist in a 12 columns

1. X (m)
2. Y (m)
3. Z (m)
4. g_x (mGal)
5. g_y (mGal)
6. g_z (mGal)
7. T_{xx} (Eötvös)
8. T_{xy} (Eötvös)
9. T_{xz} (Eötvös)
10. T_{yy} (Eötvös)
11. T_{yz} (Eötvös)
12. T_{zz} (Eötvös)

GENERATE UNIFORM TRIANGULAR MESH OF A SPHERE OR ELLIPSOID

To create triangular mesh of a spherical or ellipsoidal body with nearly uniform mesh size (i.e. average distance between pair of points), user can run this function:

```
[lon,lat,tri] = equidistantsphere( res,a,ecc )
```

Where each input variable must be:

- `res` : resolution or size of the triangle (in meter)
- `a` : semi-major axis of ellipsoid (in meter)
- `ecc` : eccentricity of ellipsoid

The output of this function are:

- `lon` : the coordinate of the vertices in longitude (in degree)
- `lat` : the coordinate of the vertices in latitude (in degree)
- `tri` : the topologic connection of the triangular mesh (tri)

In this function, the point cloud is generated using the principle of golden angle and golden ratio.