First results of implementing satellite-borne gravity data to GIS and future perspectives

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Abstract—**Gravimetry has not acquired GIS for its own benefits. The reason is the basic difference in tools and demands. The global gravity field is typically described analytically by an infinite set of nearly ellipsoidal layers, which are synthesized to actual values afterwards. In contrary, GIS employs pre-defined data sheets, which inhibits the flexibility of the use of spherical harmonics. The present study discusses how gravity field information can be implemented in GIS keeping its basic approach to data sheets. As a result, a gravity module for a remote sensing GIS, termed Gravity_RS_GIS has been designed and developed.**

I. Introduction

Geographic information systems (GIS) are basic tools for representation, manipulation and analysis of spatial or geographical data. In practice, the strength of GIS with respect to classical map-based representation of location-based quantities is that they are supported by interactive tools, i.e. queries can be defined by the users, and different spatial data analyses can be implemented, even the map content according to the result of the analyses can be edited. All in all, GIS provides a much more flexible platform than electronic maps, therefore they became popular for numerous applications ranging from the simplest visual data screening through location intelligence studies to severe, elaborated geoscientific research.

It is also frequently used for remote sensing data. For such a case a GIS provides a frame, where remote sensing observations from different sources can be integrated into one system, in which location-wise data management can efficiently be done. In contrary, satellite gravimetry has not really acquired GIS for its own benefits. The gravity field is typically a space-dependent physical variable, which is usually described in geosciences by analytical description of the shape of its equipotential surfaces, which is equivalent to an infinite set of nearly ellipsoidal layers [1]. Mathematically these analytical surfaces are described with spherical or ellipsoidal harmonics.

Even though, the GIS era has been started in the late 70s or 80s, its potential has not become clear for the gravimetry community even until the 90s. Among the first papers on use of GIS for the gravity field, some has been inappropriately addressed, e.g. [2] has labeled an analysis on the role of the marine gravity in measuring the sea surface topography as 'GIS data sets optimization'. An expedient attempt to test the applicability of GIS for geodesy has been delivered by [3]. This study has used the GRASS GIS for integrating and processing a geoid model and satellite altimetry data. Basically, the GIS tools, which were actually applied in that study were 1) representation of the data sets (both gridded and sparse data), 2) interpolation of one data to the points of the other, 3) outlier detection by comparison the interpolated data with the other, 4) smoothing of the outlier-eliminated data and interpolation back to the original points. Even though they have concluded that GIS was fast and reliable, they have also found that it may have a little, but meaningful impact on geodesy. By the time, both GIS tools and geodetic observation techniques improved a lot, as so, it makes sense to revisit this conclusion.

An essential progress in geodesy in the last two decades is the globally available high-resolution gravity field models due to the dedicated gravity field missions, CHAMP, GRACE and GOCE [4]. Furthermore, due to these satellite missions temporal variations of the gravity field have became detectable globally on monthly scale. Large scale monitoring of gravity has opened a wide range of applications in geosciences, since every geophysical phenomena can make use of this information, which produce mass variations over a large area on long (i.e. longer than some month) time scales. Most of such mass variations occurs in the fluid envelop of the Earth (also referred as geosphere), which is a 'thin' layer on and above the surface of the Earth enclosing the masses of the atmosphere, hydrological processes, the world ocean and the cryosphere. Considering the effects of these developments, in the present paper the utility of GIS for satellite gravimetric applications is addressed.

II. Benefits of Gravity Information for Remote Sensing GIS and Vice Versa

Processing of satellite gravimetric observations to deliver a gravity field model is a laborious task. It does not provide unique solution, as it is mathematically an inverse problem, so no routinely applicable processing method of gravity satellites observations can be defined. Instead of using GIS for gravity satellite data processing, its resulted gravity field models can more efficiently be used for further applications within a GIS software. Such applications can make benefit of different properties of gravity field; here are three examples.

A. *Gravity field appoints horizontal and vertical directions*

Question of height systems: most Earth-observed satellite-borne data are positioned in WGS-84 ellipsoidal reference frame as (ϕ,λ,h). The data can be transformed to local or regional coordinate systems, which is already implemented in every GIS software (either the latter being already defined in the software or by enabling to load its transformation coefficients in). For large regions, global scale analyses, calculations are performed in the ellipsoidal geographical coordinate system. However, ellipsoidal geographical coordinate systems are not connected to the horizontal and vertical directions, i.e. two points with exactly the same elevation above an ellipsoid can be at different heights. In true geographic coordinates same elevation values defined by their potential difference presented in Geopotential Unit (GPU) refer to the same height. The difference of ellipsoidal and true geographic heights is described by the geoid undulation, which can reach approximately ±100 m. If geoid undulation data is available worldwide with appropriately fine resolution, than the ellipsoidal to true geographical coordinate system transformation, i.e. (ϕ,λ,h) to (Φ,Λ,W) can be defined. It can be substantial if an application is extended over a large region.

B. *Gravity field manifests mass distribution*

As the gravity is generated by mass, gravity anomaly provides information on the mass distribution of the underlying geological features as well. Gravity anomaly can be used as key tool for mineral exploration and geophysical prospecting, even though nowadays the more efficient seismic methods are preferred over time consuming gravimetry. A new role of gravity in prospecting may arise with the development of the satellite gravimetry, as they provide gravity information in a gradually increasing resolution. In the near future it may reach so fine resolution that the test area selection can efficiently be done based on satellite gravity data only. With this, the field work can be reduced notably.

C. *Gravity field is a force field*

The knowledge of the gravity field in fine resolution in space may be useful for aeronautics. Motion of a missile, an aircraft or any other flying object in the gravity field can be precisely predicted by taking into account the effect of the propulsion force and the gravity field. Such orbit integration need may arise for several segments of engineering ranging from telecommunication industry to military applications.

III. GIS APPLICATIONS FOR GRAVITY SO FAR

There are very few published attempts for applying GIS softwares for gravity field variables are known so far. An online GIS service, the Gravity Information System (SIS) has been developed at the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany [5]. This system is presented on a Java platform, which enables query of gravity information (the gravity value, or free-air or Bouguer anomaly, also contour lines of gravity referred to as 'gravity zones') by coordinates (or by clicking on the base map) at the physical surface (approximated by the SRTM DEM model) or at any arbitrarily defined altitude above it. The background of the workspace can either be topographic or gravity anomaly map. This system makes only partially use of the benefits of the GIS in both on data query and on data representation.

The China Regional Gravity Information System (RGIS) has been developed by the China Geological Survey [6]. This system is based on the MapInfo platform with OLE technology. As it is stated in [6], the system can visually interpret data of spatial geography, geology and gravity for China. It furthermore enables graphical data editing and data table operations, and what is really specific is that there are classical gravimetric tools are defined, such as gravity reduction, gravity (and magnetic) field transformation, and gravity anomaly inversion. The system has been developed for regional use. The system is developed for terrestrial gravimetric data. Unfortunately, the system cannot be tested, as no internet availability could be found.

Beyond these two essential examples, few other systems are known world-wide, [7], [8], [9], [10]. However, the abovementioned two examples are sufficient for demonstrating the status of the use of GIS for gravity data: There are some freely accessible softwares, which only partially make benefit of the GIS, and there are others, which are probably much more delicate (usually for regional use), however, these cannot be accessed for common users. In the present study a compromise, a trade-off is suggested: to deliver a GIS software for global use with features developed for both regular and geoscientist users.

IV. EXPECTATIONS WITH A GRAVITY GIS SOFTWARE

In fact, the convenient form of storing data for a GIS is providing them in tables, on data sheets. Therefore all gravity related quantities from a state-of-the-art global gravity model should be determined before hand, and include in gridded form to the GIS. It, however, makes the GIS software inflexible, which may have unlike effects in the long run. It should be remarked that global gravity models are developing quickly in the recent decades, c.f. the tables of global gravity field models at http://icgem.gfz-potsdam.de/ICGEM/modelstab.html [11]. Therefore, to stick to one gravity model is not wise. Furthermore, it excludes the use of local or regional gravity models. Users of the GIS software may have the option to load in local gravity field models according to their requirements and define its eligibility area. This would satisfy a more realistic need, since small features cannot be described by a global model, but a locally optimized one, as it is actually done in the practice of the different state land surveying entities. As local models may be undisclosed to the public, the need of integrating own model into the software is realistic. Therefore, we suggest supplying an appropriate tool for conversion gravity field models to gridded variables. In the present section, feasibility of inclusion of such a module inside the GIS is analyzed.

Basically, the mathematical tools for representing a gravity field model depend on the size of the area of interest. For global scale, the gravity is represented by analytical surfaces using the spherical or ellipsoidal harmonics. For local or regional scales, a gravity model can be equivalent to a set of point values, which are assumed to be sufficiently dense for reliable description between the points by linear interpolation. Analytical functions for regional models are also often defined in practice. In fact, spherical harmonic representation is so convenient and wide-spread that often they are applied for local gravity field models as well, even though those coefficients are valid only within the area of interest, and provides nonsense gravity properties outside of it. Local or regional gravity field models can also be presented in a form of locally defined base functions, such as the spherical radial base functions [12], or by appropriately chosen high order polynomials.

All in all, the spherical harmonic representation is a feasible and regularly applied method, probably the most common tool. As so, a GIS containing gravity information is suggested to be prepared for including gravity field model in spherical harmonic form.

As for a GIS software, zooming in and out of the map is a basic tool, however, the complexity of describing the gravity field is notably different by the scale. Due to zooming into the map, a better spatial resolution should be defined automatically, which increases the number of computational points, e.g. by halving the grid size, the computational load is four times larger. This can be cured by fixing the size of the window, i.e. fixing the number of computational points regardless the extent of zooming. Disregarding this option, in Figure 1 the computational load by increasing the refinement of the grid is displayed with blue color.

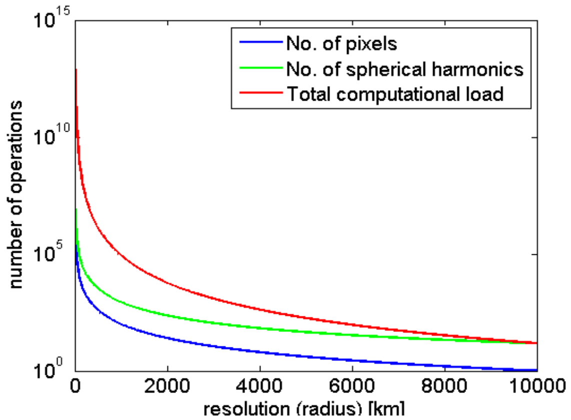

Figure 1. An estimate of computational load by determining the number of operations as function of the resolution of a grid.

The more essential consequence is that gravity information content should also be refined according to the extent of zooming. When using spherical harmonic synthesis for determining gravity from model coefficients, the spatial resolution is controlled by the choice of the maximal degree of spherical harmonics. The resolution is inversely proportional to the maximal degree of spherical harmonics, approximately the radius of a detectable gravity feature on the surface can be determined as

$$r = \frac{2R\pi}{l_{max}} \quad (1),$$

where R is the mean radius of the Earth and l_{max} is the maximal degree of spherical harmonics. According to (1) the computational load by increasing the maximal degree by 1 is increased by

$$\frac{(l_{max}+1)(l_{max}+2)}{2} \quad (2).$$

Fig 1 shows that how the computational load is increasing by increasing the maximal degree of the spherical harmonic expansion with the green curve. The total increase of the computational load, i.e. the sum of the two is displayed with the red curve, showing that by drastically refining the resolution, the computational load may turn to a massive burden; no real-time calculation of gravity is suggested. Or, another option is that real time calculations are only performed occasionally for limited area.

Summarily, the GIS should provide gravity field information in a computationally effective way: the data should be 'quickly' accessible, still precise and up-to-date. Because of this, the inclusion of spherical harmonic synthesis is disregarded. According to that and the previous sections, two scenarios for gravity-involved-GIS are suggested:

1) "Data sheet scenario": Store all gravity related quantities with high resolution calculated up to the available maximal degree of spherical harmonics in data sheets from a global gravity field model, and the GIS software would handle only those data. When the user zooms into too small regions, in order to avoid pixelisation, the fine resolution can be achieved by a 2D spline interpolation.

2) "Semi-active scenario": Store all gravity related quantities with high resolution calculated up to the available maximal degree of spherical harmonics in data sheets from a global gravity field model, and the GIS software would handle only those data. This would serve for the small scale usage, i.e. for large area. When the user zooms into smaller regions, after a limit the software may aware that preferable local gravity model is available over the global one, or if not available, offer an upload of a local model. With an uploaded local model the spherical harmonic synthesis would be performed immediately.

With the use of the latter scenario, the users are more aware of possible choices of gravity models, therefore all parameterization would be done more cautiously. By offering a real time upload of gravity models, and performing the spherical harmonic synthesis real time, the computational load may notably increase. However, as this is suggested for ‘small’ area only, with an appropriate choice of the grid size (which can be relatively rough), but including all available coefficients, the computational load can be decreased compared to the red curve of Fig. 1. Note that for user uploaded models the area of eligibility should also be defined, for which cannot be controlled automatically, the user is expected the mark the borders.

Further alerts are suggested for both scenarios. These alerts are evident for users with satellite gravimetric background, but may cause a misapprehension by non-geodetic users. These are:

1) In order to keep up to date with the gravity field model, a spherical harmonic synthesis module can be included, which can be operated separately from the GIS functions, when no task is loaded in. Anytime, when the program is launched, the program should display the actual gravity model, and also should show a link to the most up-to-date gravity models for keeping the user informed on the most recent gravity models.

2) If temporal variations at a certain location are queried, a warning should inform the user whether new epochs of the gravity model time series are available. Also the link to the used gravity models' download page should be provided.

What gravity related quantities should be involved? As gravity data is considered to be integrated in GIS for non-geodetic users of geosciences, the most useful quantities are probably geoid undulation and gravity anomaly, and for investigating temporal mass variations, surface mass anomaly. Optionally, gravity gradients, deflection of the vertical and geopotential can also be included in case of demand. All variables should be accessible on the physical surface and on the geoid as well. In order to provide these data at any height (outside the mass of the Earth), first and second vertical gradients of these quantities should also be stored in a data sheet, and then the approximate value of a variable at an elevation of h can be estimated by the first two terms of Taylor series of that variable.

If better accuracy is demanded, the use of spherical harmonic synthesis is unavoidable.

The core of the gravity field information in the GIS is the stored high resolution geoid undulation and gravity anomaly. In case of a query, the quantity of interest should be defined before hand, which may be switched to the other with a simple combination of keyboard buttons. When a quire is posed on them for a location, the GIS may pop up a window showing the vicinity of the point displaying the local structure of the quantity of interest, and write the actual value in that point. If the quire refers to an area defined by its corners (graphically selected or typed on keyboard), then the quantity of interest should be displayed for that area.

Temporal variations of the gravity field can also be queried for the selected location. For point-wise query, the GIS should display a time series of (GRACE-borne) surface mass anomalies. On the figure also a best-fit function (in a previously set form) may be plotted, which can be either a polynomial regression, a high-pass or low-pass filtering, or a periodic function.

Further, more elaborated, higher level tools for temporal gravity field variations can also be demanded. A linear trend or an annual variation may have more practical sense, if there are known unlike effects, and they are taken into account. For example, for ice mass balance studies linear trends are also affected by the motions of the tectonic plates, e.g. [13]. These motions are partially effects of the isostatic rebounding process since the relieve of the ice mass of the last glacial cycle, and also of the change of the ocean basins in this period [14]. For ice mass balance investigations, the GIS may offer a GIA models for correction of the linear trend, such as IJ05 [15], ICE6G [16], or W12a [17].

Surface mass anomalies may also contribute to determination of focal mechanism of large earthquakes afterwards [18]. By setting the date and the location of an earthquake, the extent of the change in the bias of the surface mass anomaly time series is informative. At any locations in the vicinity of an earthquake the time series of surface mass anomaly may be supplemented with bias and linear trend estimates before and after the event.

For application temporal gravity data for determining water mass being involved in the hydrological cycle of a basin, surface mass anomaly estimates should be limited to the area of the basin, and exclude masses from outside of the area to leak into the solution. For that, supplementary the shape of the basin should be outlined, and with the use of a hydrological model leakage correction should be applied as described by [19]. As this correction is a complex calculation, which is performed in the spherical harmonic synthesis step, it is suggested to be performed real time in the "semi-active scenario”.

The list of suggestions is incomplete, there may be several other tools invented, e.g. for oceanographic users. These should be delivered in case of demand.

V. THE GRAVITY_RS_GIS MODULE

To illustrate the effectiveness of the proposed framework for gravity application GIS software, a gravity module of the Remote Sensing GIS, termed Gravity_RS_GIS, is designed and developed based on the DotSpatial library. DotSpatial is an open-source geographic information system library, which allows developers to incorporate spatial data, analysis and mapping functionality into their applications [20]. Gravity_RS_GIS is characterized by the integration of actual gravity field data for further GIS applications or gravity field research. The present version of Gravity_RS_GIS is developed according to the "data sheet scenario”.

The actual gravity field data basically includes geoid undulation, gravity anomaly and surface mass anomaly. For the gravity anomaly and the geoid undulation data the 2.5 x 2.5-minute resolution free-air gravity anomaly and geoid undulation grids of EGM2008 were used. [21]. As for the surface mass anomaly, GFZ RL05a GSM models [22] were used in the period of April 2002 to April 2015 up to degree and order 90. The models have been smoothed with a Gaussian filter of 500 km and the de-striping filter of [23] was applied. For more details on the methodology see [24].

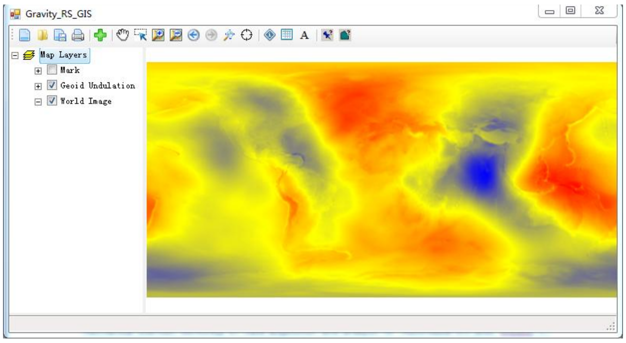

Figure 2. The geoid undulation data visualized in Gravity_RS_GIS.

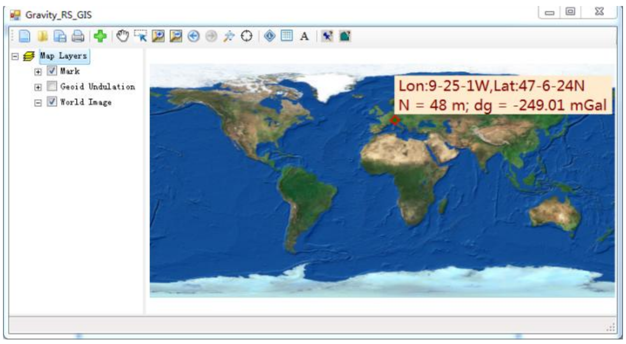

Figure 3. Gravity field data queried as back information after some remote sensing image in Gravity_RS_GIS.

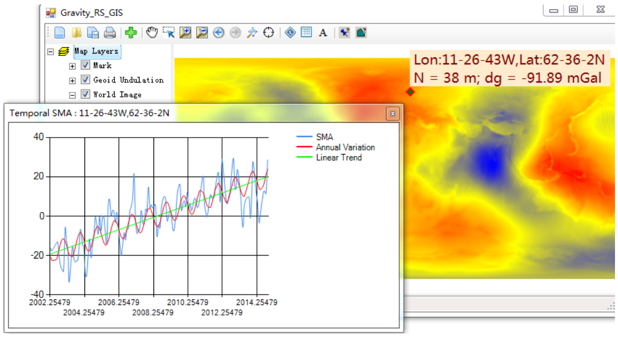

Figure 4. A time series query for temporal SMA data in Gravity_RS_GIS.

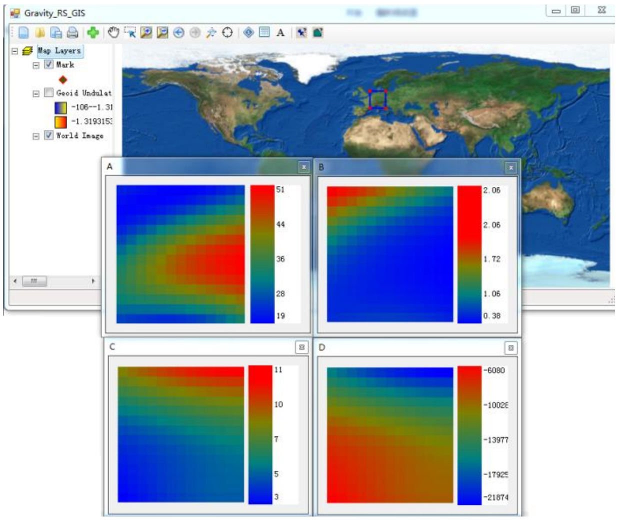

Figure 5. Temporal variations of the gravity field for a specific area in Gravity_RS_GIS.

The geoid undulation data is in a GIS raster data format, the others are not, therefore the data was reorganized and geo-referenced after loaded into Gravity_RS_GIS. And then, the data could be visualized, queried and analysed as gravity field information, as shown in the following figures. The basic features are as follows: (1) The geoid undulation data can be visualized in Gravity_RS_GIS (Fig 2) or as back information after some remote sensing image (Fig 3). (2) A time series query for temporal surface mass anomaly data in Gravity_RS_GIS (Fig 4). (3) Temporal variations of surface mass anomaly for a specific area described by the annual amplitude, annual phase shift, the linear trend and a bias (Fig 5).

VI. Future Perspectives

For later versions, the implementation of the "semi-active scenario" is initiated. For the purpose, the cornerstone is a spherical harmonic solver, which can computationally efficiently, real time perform the spherical harmonic synthesis step. Parallel to the Gravity_RS_GIS, such a software is also developed in C++ language under the name BME Spherical Harmonic Solver (BME-SHS) [25]. At the present stage, the BME-SHS can handle geopotential, gravity anomaly, gravity disturbance, geoid undulation, and the six independent gravity gradients. In order to integrate it into a later version of Gravity_RS_GIS, surface mass variations should also be implemented. The BME-SHS delivers solution both for spherical harmonic synthesis and for spherical harmonic analysis. For the analysis, there are limitations in the applicable maximal degree of the spherical harmonics. This is, however, no concern for the Gravity_RS_GIS, as it make use of the synthesis only.

Even though at the moment, in the second half of 2015 the gravity database included in the Gravity_RS_GIS are definitely up to date, it should be noted that within some years certainly new versions of the GRACE gravity models will be presented, as the present models, produced by different data centers differ notably to each other [24]. Therefore, regular update of the data set is essential, in later releases as well.

VII. Summary

According to the present practice and demands, GIS may not be a central tool for processing satellite geodetic observations; instead, results of satellite gravimetry may efficiently support other applications, such as RS-GIS. Gravity field may work therefore as a tool for GIS.

The core of the study is a theoretical discussion, a stream of thoughts on implementing gravity information to GIS. It is found that though GIS basically works with existing spatial data, for gravity field applications several flexible parameters are demanded, which would make a GIS software inefficient. Therefore, for implementation of the gravity field variables for GIS a "data sheet scenario" and a "semi-active scenario" is proposed. The first case is a classical GIS data base, while the latter is a GIS database supported with physical geodetic applications.

A first version of a Gravity_RS_GIS has been implemented, which has been developed upon the "data sheet scenario". Therefore, it has not made use of all theoretical findings, though the applicable tools have been implemented successfully. In later releases, the implementation of the "semi-active scenario" is proposed.

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