We would like to thank the reviewer for accepting reviewing our paper and submitting his comments within the scheduled time. We appreciate the detailed comments and feedback with high level of expertise which very much helped to improve the paper. In general, we agree with most of the comments and we will further apply or have already applied suggested changes in the revised version. Also, there were parts in the paper where we were uncertain about some ideas, such as whether to add the list of the models in the Appendix and the reviewer just naturally provided us feedback on such items as well. We would like to thank him for his time and respond below to his detailed comments. The reviewer's comments are indicated in italic fonts whereas our responses are given in bold.

Detailed Comments

1. *Introduction*

The list of references in this section seems to be a little bit arbitrary. There are many other publications addressing the various items, which sometimes would be even better suited as they would be more of a review type. I would recommend to go through the list again and may be to cite mostly review papers. As a minimum I would add "e.g." in order to indicate that these are just examples of papers from a larger selection.

In general we tried to refer to the most fundamental (e.g. first of its kind, most cited) publications in the relevant topics but I could see this can be better linked in this section. We scanned through the references carefully and removed some of the references and introduced others that are more of review kind. The revised version should be more consistent in terms of the reference list.

Page 2, line 21 to 32: I would recommend to mention the gravity gradients and measurements of non-gravitational accelerations right before mentioning the satellite missions (i.e. at line 24). Otherwise it sounds like these measurements are not taken from the satellites. Then one could continue after the satellites with: "Other fundamental datasets . . .. are terrestrial gravity measurements from moving platforms . . . and collected on the Earth surface.

We have moved the "gravity gradients and non-gravitational accelerations" to the previous sentence and modified as recommended.

Page 4, line 9: I think the references to Drewes and Toth are not required here.

The content of Drewes and Toth are from ICGEM and we thought they would be good links to the available documents; but they could be removed as well which we did in the revised version.

2. Background of the ICGEM Service

2.1 History of ICGEM

Page 5, Figure 2, Caption: Please make clear that compared to the satellite models the EIGEN6-C4 is based also on terrestrial data. May be re-phrase the following sentence: ". . ... Note that the EIGEN6-C4 is not the truth but a better approximation to the real gravity field, because it includes terrestrial and altimetry derived gravity field information". Last sentence: I think it is EGM96S (and not EGM96).

We have revised the caption indicating clearly the content of the EIGEN-6C4. Thank you for your suggestion, indeed the model is EGM96S and not EGM96 which is also modified in the caption.

Page 6, Line 1: Currently? Please indicate a date because numbers are changing .

"By January 2019" is added.

Page 6, Line 10: Delete last part of the sentence: ". . . and promises future developments".

Removed.

2.2 Scientific Background and ICGEM's Data

In general I think this section should be shortened and reference to the ICGEM documentation should be made. It is impossible to completely write the geodetic gravity theory with all details in such a paper. I think the main purpose should be an explanation that global models are represented by spherical harmonics.

This was a previous discussion we eventually had while writing this section. We agree that the potential theory cannot be given in such a paper as complete. However, while writing the paper, we thought we would like to provide at least the equations which can explain the link between the global models and spherical harmonics. In order to provide a smooth introduction and transition later, we thought including the basics of the Newton's law of gravitation would help to explain the potential theory. Thank you for commenting on this. Not to lose the focus of the paper and to make it more readable, the revised version has this part reduced. We only kept a few formulations representing the widely used functionals and their representation in terms of spherical harmonic coefficients.

Page 9, Line 6-7: Update sentence: ". . ... pure gravitational forces . . ...the Earth's gravitational attraction (V) . . .. and potential of the centrifugal force due to Earth rotation".

Updated.

Page 9, Line 21 to Page 10, Line 7: I think this is not needed here (including equ. (19 to (3). Instead reference to the ICGEM documentation or another book shall be made.

We removed the first 3 equations and referred to the Advanced Physical Geodesy Text book and Scientific report from Barthelmes, 2013.

Page 11, Line 12: Find a better wording. Proposal: ". . .. normalisation is defined such that the average square . . .".

Applied.

Page 13, Line 7-8: The geoid is introduced. In my opinion the definition is a bit misleading. Undisturbed in my view doesn't include the MDT because it is a permanent disturbance and therefore the statement is not correct. I would write as follows: The geoid is an equipotential surface that in average approximates the mean sea surface.

The formulation of geoid is kept simple as recommended and only the equipotential surface is mentioned in the revised version. References are provided for the interested readers.

Page 13, Equation (10): I would recommend to write equation (7) and (10) in the same way.

Written as recommended.

Page 13, Line 24: Why can these quantities be computed approximately? The calculation is correct, just the models are incomplete. Gravity disturbances can be computed exactly, while for geoid oen needs to do assumptions. Please re-phrase.

It is true that the gravity disturbance can be computed exactly. However, here in the paper we introduced the disturbing potential and summarized that the disturbing potential is used in the calculation of some of the functionals such as geoid which can be done only via approximations (especially for the grid calculations). Gravity disturbance however can be computed from W and U (not T), exactly from spherical harmonic coefficients with no approximation introduced. We clarified this in the text to avoid confusion.

Page 14, Line 5: "above the geoid" instead "over"

Indeed, applied as suggested.

Page 14, Equations (11) and (12): I don't think this is needed here. Just refer to the manual. Otherwise one should provide equations for all derived quantities.

We think having these two equations used in the calculation of two main functionals may provide good references for the rest. How the coefficients are included in the computations may be summarized with these two.

2.2.1 Static global gravity field models of the Earth

Page 15, Line 4: EGM2008 expansion to degree and order 2159 is for ellipsoidal harmonics. After conversion to spherical harmonics the expansion is up to degree 2190. Modify the sentence accordingly.

Thank you for reminding. Corrected.

Page 15, Line 9: Write: "As an example one of the high resolution . . .."

Modified.

Page 15, Line 18: Is the gravity attraction really stronger? This depends where you observe it. If you stay on the equipotential surface the gravity attraction becomes smaller because the neighbouring equipotential surfaces are separated by a larger distance. Please rethink this sentence and be more specific.

Maybe our explanation was not clear. The point of observation has to stay exactly the same, which would not be possible anymore under the circumstances introduced (e.g. switch on). Explanation of the features is quite sophisticated as one can imagine; therefore, we decided to remove the above mentioned part and simplify this paragraph, and refer to the dedicated study about the Indian Ocean geoid instead.

Page 15, Lines 19-24: This is confusing and in my view, specifically the sentence about the North Atlantic (why only there?). Please rephrase and leave out unclear statements.

This part has been removed from the text. The same principle applied to other areas as well, but North Atlantic was chosen as an example.

Page 17, Line 5: "over land" not "in the land".

Applied.

2.2.2 Temporal global gravity field models

Page 19, Line 4: I think monthly gravity field models do not provide a resolution of 160 km. May be only when looking to the maximum degree of the SHS but not in the sense of real data content. Please make this clear.

Indeed ~160 km would only be possible with the highest degree/order available which is in fact not the case in practice due to the increasing error of the higher degree/order coefficients. Therefore, this part has been revised and ~300 km for monthly solutions is used instead.

Page 19, Line 16: It is not only water mass, but could also be geophysical signals (solid Earth).

The geophysical signals added in the sentence.

Page 20, Line 9: Reference Wahr, 2007 is missing.

Thank you for noting this; the reference is added to the list.

2.2.3 Topographic global gravity field models

Page 21, Figure 10, Caption: a) and b) is not indicated in the sub-plots. Instead write left and right.

Letters are brought to the front, now they are visible.

Page 21, Table 1: Monitoring sea level variations is a temporal gravity field signal if the pure mass variation is meant. If just the geometric change of the sea level is meant it is no gravity field signal at all. Please correct.

Correct also the Atmosphere section (no underlining).

We have replaced "level" with "mass". We don't mean to go into details with steric and non-steric sea level changes. Underline in Atmosphere is also removed.

3. Services of ICGEM

3.1 Calculation Service

Page 23, Line 7-8: I think the semi major axis is missing here.

Thank you for noticing and noting this. Radius corresponds to the semi-major axis here, we added this information within parenthesis in the text. We will eventually need to replace it in the service as well since this may cause confusion.

Page 23, Lines 19-27: This section is quite confusing and I would recommend to rephrase it in simpler words as it is not very clear to non-experts. May be it would be again sufficient to refer to the ICGEM manual.

Some reductions are applied for clarity purposes.

Page 25, Table 2: For second_r_derivative one could also write vertical gravity gradient. This is a more convenient name.

Added in parenthesis. However, in fact it is not the same for the computations introduced in the ICGEM Calculation Service. "Vertical" (plumb line approx. by normal direction) is not radial (spherical approx.). Therefore, second_r_ direction is an approximation of vertical gravity gradient.

Just a proposal for future development: Why not offering also the horizontal gravity gradients. These might be useful for some purposes.

This has been in our to-do-list. We also added this to the future work in the paper. However, we suspect that providing this in ICGEM is not as easy as it sounds. Some standards (e.g. definition of horizontal, which coordinate system to be used) need to be clarified from the users point of view. The authors would be happy to hear about what would be interesting for the community.

3.2 Visualisation Service

Page 31, Figure 16, Caption: For b) I think it should be written ". . .. Represent the mass change." Instead of "distribution".

Applied.

3.3 Evaluation of global gravity field models

3.3.1 Model evaluation with respect to other models in the spectral domain

Page 32, bottom: wrong font

Replaced with the correct font size.

Page 33, Figure 17: I think the green line are the "Cumulative difference amplitudes . . ..". Please correct

This terminology was recommended in the past, but for the geodetic community indeed the cumulative would be more familiar. In the revised version, it is edited as recommended.

3.3.2 Model evaluation with respect to GNSS/levelling derived geoid undulations

In my view this chapter either needs to be significantly extended or its value is very limited as the procedure to do comparisons with GPS/levelling geoid heights is much more complicated as it is done here. Therefore the numbers provided in figure 18 are not really meaningful, e.g. the omission error is not considered at all. In the last paragraph of page 34 the authors even explain that this is not a fair comparison. So why do they show it or why is it offered in ICGEM at all? There are also missing references to publications dealing with GPS/levelling comparisons. I would consider to delete the complete paragraph and even to consider not to offer this in ICGEM as long as it is not a fair comparison. It only provides misleading results to the not experienced user.

We agree with reviewer's concern on the contribution of GNSS/levelling evaluation to the use of ICGEM Service. Taking into account the omission error, this method can for sure be applied in more sophisticated ways. However, in general, ICGEM would like to compare the models among themselves (e.g. among satellite-only models, among combined models) and does not seek for absolute comparisons for particular degrees. Therefore, we think this kind of comparisons still provide useful information of different models wrt the same external datasets. We try to make use of the GNSS/levelling series we have been delivered in the past which was scanned for outliers initially. We think the evaluation provided in this section is still valuable and should be kept in the ICGEM which may be improved in the future. References concerning the GNSS/leveling evaluation are added in the revised version.

Appendix 2: I am not sure if this is really needed. Why not setting a link to the web site with the models.

This is something we could not decide in the beginning. In the revised version we removed the list of the models.

We would like to thank the reviewer for his comments that have helped to improve the readability of the paper and increase the precision of the language and the statements. We respond to each comment in detail below as indicated in bold. Reviewer's original comments can be found in italic font.

Detailed Comments

Abstract

The manuscript title suggests that in addition to information on models and services presented in sections 2 and 3, something will be said about future plans. Scattered information on future plans can be found in sub- section 2.1 History and 6 Conclusions, but wouldn′t it be better to introduce a separate section on Future Plans or to rename subsection 2.1 into History, Status and Future Planning?

Initially, we wanted to introduce the service, and provide information about its components through the paper. Then we thought collecting all the future plans at the end of the paper would be ideal and conclude the paper. Nevertheless, presenting them in Section 2.1 might be a good idea as well. In the revised version, it is applied as suggested by the reviewer.

P.1, L.17/18: modify to "including those from the 1960s to the 1990s, as well as the most recent ones"

Applied as suggested by the reviewer.

P.1, L.19: "such as satellite" should read "such as satellite altimetry and. . ."

Added.

P.1, L.23/24: polish text

This sentence has been removed from the abstract and included in the rest of the manuscript in different forms.

P.1, L. 25: paper does not present models. Change to ..We present a list of static, temporal. . .

The sentence has been rephrased to "We present the ICGEM's data by means of ….."

1. Introduction

Introduction is too long, needs shortening

Some reductions are applied also to the introduction (e.g. removing Fig. 1), besides data and other sections.

P.2, L.5: change to "..in the 1960s to 1990s"

1990s is added..

P.2, L.6: Better "mass change"

Edited.

P.2, L.17: I suspect "analysis techniques" is meant

We have replaced with the technologies.

P.2, L.18,20 Drewes et al., 2016, why the 3 references in Line 20?

Drewes and Toth include actually the ICGEM reports for different periods which include the mentioned information in the text. But, to avoid confusion and make the text more readable the references are removed.

P.2, L.22: satellite orbit perturbations are derived quantities, not satellite observations

It is mentioned in the text as "…derived from GNSS measurements". Therefore, we agreed that they are not direct observations.

P.2, L.30: imprecise phrasing: "terrestrial" gravity measurements collected on the "Earth surface"

These refer to the gravity measurements collected on the Earth surface. For the purpose of this paper, the details given in this part would be enough from our point of view. But, any suggestion to make it more precise is very welcome.

P.3, L.5: imprecise phrasing: new measurements become available from. . .terrestrial measurements

Since inclusion of such information would further increase the size of the paper, we have avoided adding more information on such items.

P.3, L.7: modify wording in reality ICGEM is not a meeting point, but acts as an interface

We changed as the meeting platform which may replace the interface.

P.3, L.11-L.18. For this paper, the text parts on IAG and IGFS are not of particular relevance. In the opinion of the reviewer it is sufficient to leave the text with the URLs in lines 9 and 10, complemented perhaps by the reference Drewes et al., 2016, and to delete the text part up to line 18. The same applies to page 4 line 17 for the four IGFS services and delete lines 18-26. P.4,

L.9: why these references?

This is also a part where we discussed among the co-authors while writing the paper. We believe adding this part makes the position of such a service clear and complete the content of the paper. The need for the ICGEM Service is made obvious with the information and support provided by the association. Therefore, we would like to keep this part in the paper. However, to save some space, we removed Fig.1 and some more text.

P.4, L.31: modify text into “various types of gravity field models

Modified.

P.5, L.3: and section 7?

Added.

2. The Background of the ICGEM Service

2.1 History

P.5, L.6: change perhaps to History, Status and Future Planning of ICGEM.

Modified as suggested, and we moved some sentences from the Conclusion and Future Plans to this section.

P.5, L8: reference to the 1997 IAGA resolution No 1 for an interna tional Decade of Geopotential Missions would be useful at this point.http://www.iaga- aiga.org/index.php?id=res1-97

Added.

P.5, L.19: add developed “by various institutions”

Added.

P.5, L.20: add “dedicated” gravity missions

Added.

P.6, L.7: add some wording that EIGEN-6C4 is a combination solution derived from. . ..

Added in the caption.

2.2 Scientific background and ICGEM′s Data

P.9, L.1: misleading wording: ICGEM does not provide data but gravity model related quantities.

ICGEM collects and distributes global gravity field models, as well as provides products via calculation service. Within this concept, after some discussions with data service in our institution, our understanding is any of the above mentioned can be called data in general. Therefore, the subtitle includes “Data” to refer to all these in general.

P.9, L.7: polish wording “including on the ground. . ..”

This part has been removed in the revised version.

P.9, L.21 to P.14, L.10: Basic equations of the potential of a solid body, of the spherical harmonics expansion of the gravitational potential and the disturbing potential can be found in many textbooks and this text part should considerably be shortened and reformulated. Eq. 7 should be sufficient to explain the content of the ICGEM product archive and the characteristics of the expansion into spherical harmonics. For the various functionals reference could be made to Barthelmes 2013.

This part has been reduced as well in the revised version. We still think having the equations for the geoid undulation and gravity disturbances can be good references for the other functionals without the need of going to the references in the first place. For detailed information, the complete references either Barthelmes 2013 and other textbooks are given.

2.2.1 Static gravity field models

P.14, L.5: replace by "above geoid "

Indeed. Replaced in the revised version.

P.15, L.22: sloppy formulation . . ..underneath the Earth!

Replaced with "in the deep mantle" as given in the original reference.

P.15, L.25-30: What′s the point at this point of the text? Wouldn′t it better fit to future aspects?

It is a link to the preliminary model of EGM2020, XGM2016 which is shortly covered in one of the examples provided in the paper. Moreover, since these are future aspect of the global gravity field models and not the ICGEM Service directly, it may be more suitable to keep it in this section.

2.2.2 Temporal global gravity field models

P.19, L.2: improve wording:. . ..as for longer

Edited.

P.19, L.4: change to 300 km

This was written considering the maximum degree and order expansion of the temporal models. In the revised version, we have replaced it with ~300 km for monthly solutions.

2.2.3 Topographic global gravity field models

P.21, L.1: designation missing for plots

Letters are added to the figures.

P.21, L.7: in table 1- for sea level, ice and atmosphere only mass change can be meant.

A note to the caption is added for clarity "Note that the variations refer to the mass change".

2.2.4 Models of other celestial bodies

P.22, L.7: polish wording

Original sentence" These models are also developed based on similar observations of the gravity field of the body.

Replacement: **These models are also developed based on similar observations.**

P.22, L.9: add "the presently most detailed (or best) gravitational field"

Revised version:" ….have been used to develop the most detailed gravitational field of the Moon so far".

3. Service of ICGEM

3.1 Calculation Service P.22, L.13: change have to has

Indeed. Replaced.

3.2 3D Visualization Service

P.29, L.27: improve wording by beginning "clearly visible in these representations is. . ."

Applied.

P.31, L.24: mass change is more appropriate

Indeed, applied as suggested.

3.3 Evaluation of global gravity field models

P.32, L.14-L.21: different fond

Edited.

P.34, L.25ff: what is the purpose of the quick check assessments of the service, if not allowing fair comparisons?

Maybe we should have used another wording instead of "fair". The service still performs very useful comparisons among the models but does not apply sophisticated comparisons that are interest of many other studies published individually. Since the ICGEM's aim is to compare various models wrt exactly the same external, independent datasets, the results still serve for basic comparison purposes. In the revised version more explanations and future plans for the GNSS/levelling comparisons are added.

3.5 DOI Service

P.36, L.27: polish text " and is equipped " ??

We have changed the original text "and is equipped with" to "Metadata can be harvested via an Application Programing Interface (OAI-PMH)."

4. Documentation

P.38, L.14: polish wording "scientific disciplines and industry related background" ??

Industry part is removed in the revised version.

P.39, L.4: change to "pays "

Indeed, thank you for noting.

6. Conclusions and future aspects

P.42, L. 6 ff: see remark under Abstract

Applied as recommended in Section 2.1

We would like to thank the reviewer for his time and constructive feedback. We believe the current content of the paper is now clarified from the point of few items the reviewer suggested. Below we added our responses to reviewer's detailed comments in bold.

The paper gives an extensive description of the scientific activities of ICGEM. The paper is unusually long but I think that its length is adequate to fully and properly describe the services provided by ICGEM. Also, the paper is well organised and written in a good English language. I only have some minor comments on the paper that are listed below.

In the revised version, we tried to reduce the size of the paper in some sections as recommended by the other two reviewers to focus on the more important items. To keep the size of the entire paper smaller, we also removed some of the Appendices that included the list of the models. Considering the size of the figures in general, we hope the professional editing from the journal would help the readers to follow the paper easily.

- *page 9, 15: the discussion on the terms "gravitational" and "gravity" is quite misleading. I don't agree with the authors' statement, i.e. to use "gravity" instead of "gravitational". I think that we must stay strictly in the geodetic tradition and use properly the two terms throughout the paper.*

This topic on the terminology has been discussed also among the authors and indeed we agree that we should stick with the correct terminology and be consistent. For the purpose of this paper, the clarification was clearly made from the point of the difference between the two to prevent any confusion. The terminology used through paper that is related to the coefficients of the models provided would refer to "gravitational". For the rest of the paper, we paid more attention to be consistent and correct with the use of the "gravity" and "gravitational". Thank you for noting this very important item.

- *page 10, 10-15: this comment connects to the previous one. The authors stated that "gravity" has to be used and then they write "Geodesy describes the gravitational potential only in empty space,...". This is not in the line that they stated. So, again, I would ask the authors to stick to the standard notation of Geodesy, which is clear, without contradiction and used for many years.*

In the revised version, we have changed at few places gravity into gravitational for the correct use of the terminology and consistency. Thank you for paying attention to this point.

- *page 10: it is frequently used the sentence "real gravity field". I would use "gravity field" only*

This is to prevent the confusion between the model approximations to the gravity field and the actual gravity field itself. One can use "true gravity field" instead as well. Since gravity field is repeated many times, we would like to distinguish them by using "real".

- *page 11, Eq. (8): Pnm is normalised so it should have the bar on top.*

Added.

- *page 13, before Eq. (10): "and valid in space". I would write "in space"*

Replaced.

- *page 17, 10: "physical heights". I would add "physical heights (i.e. orthometric heights)"*

Added as suggested.

-*page 23, 20-25. I would skip the sentence "(ellipsoidal equipotential...over the oceans)" which could be misleading*

The sentence starting with "The defining parameters.." has been removed for clarity.

- *page 29, 15: instead of "different models quickly" write "different models" because "quickly" is written in the same line.*

Indeed, it is edited in the revised version.

- *page 32, Eq. (13): please replace "s" withe the greek letter sigma to be coherent with the statement above*

This was due to the conversion to pdf, in the revised version it is paid attention to represent it correctly.

ICGEM – 15 years of successful collection and distribution of global gravitational models, associated services and future plans

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Abstract. The International Centre for Global Earth Models (ICGEM, http://icgem.gfz-potsdam.de/) hosted at the GFZ German Research Centre for Geosciences (GFZ) is one of the five Services coordinated by the International Gravity Field Service (IGFS) of the International Association of Geodesy (IAG). The goal of the ICGEM Service is to provide the scientific community with a state of the art archive of static and temporal global gravity field models of the Earth, and develop and operate interactive calculation and visualisation services of gravity field functionals on user defined grids or at a list of particular points via its website. ICGEM offers the largest collection of global gravity field models, including those from the 1960s to the 1990s, as well as the most recent ones that have been developed using data from dedicated satellite gravity missions, CHAMP, GRACE, and GOCE, advanced processing methodologies and additional data sources such as satellite altimetry and terrestrial gravity. The global gravity field models have been collected from different institutions at international level and after a validation process made publicly available in a standardized format with DOI numbers assigned through GFZ Data Services. The development and maintenance of such a unique platform is crucial for the scientific community in geodesy, geophysics, oceanography, and climate research. ~~The services of ICGEM have motivated researchers worldwide to grant access to their gravity field models and also provide them an access to variety of other gravity field models and their products.~~ In this article, we present the development history and future plans of ICGEM and its current products and essential services. We present the ~~concept of the~~ICGEM's data by means of Earth's static, temporal, and topographic gravity field models as ~~provided in the lists of ICGEM as~~ well as the gravity field models of other celestial bodies together with examples produced by the ICGEM's calculation and 3D visualisation services and give an insight how the ICGEM Service can additionally contribute to the needs of research and society.

1 Introduction

The determination of the Earth's gravity field is one of the main tasks of geodesy. With the highly accurate satellite measurements as result of today's advancing technology, it is now possible to represent the Earth's global gravity field and its variations with better spatial and temporal resolutions compared to the first generation global gravity field models derived in the 1960s to 1990s. Global gravity field models provide information about the Earth's shape, its interior and fluid envelope and mass ~~variations~~ change which give hints to climate related changes in the Earth system. The computation of gravity field functionals (e.g. geoid undulations, gravity anomalies) from the model representation is therefore not only relevant for geodesy, but also for other geosciences, such as geophysics, glaciology, hydrology, oceanography, and climatology.

Some application examples in which the precise knowledge of the Earth's gravity field is fundamental are: (1) To establish a global vertical datum of global reference systems (Sideris and Fotopoulos, 2012), (2) to monitor mass distributions that are indicators of climate related changes (Tapley et al., 2004, Schmidt et al., 2006), (3) to simulate the perturbing forces on space vehicles and predict orbits in aeronautics and astronautics (Chao, 2005), (4) to explore the interior structure and geological evolution of our Earth (Wieczorek, 2015), and (5) to explore minerals or fossil fuels and to examine geophysical models developed using gravity inversion (Oldenburg et al., 1998~~; Bosch and McGaugney, 2001~~). For most of the above mentioned examples, representation of the Earth's global gravity field in terms of mathematical models is an indispensable need. For such models having plenty of vital applications, it is necessary to develop strategies for: (1) Using the most recent datasets and ~~technologies~~ analysis techniques in the field of gravity field determination ~~(Floberghagen et al., 2011; Flechtner et al., 2014)~~, (2) processing the raw data in different forms and making the validated models publicly available in citable form ~~(Barthelmes, 2014; Drewes, 2016)~~, and (3) developing sophisticated calculation and visualisation tools that are useful for both experts, young scientists, students, and for the general public (Barthelmes, 2013, ~~Barthelmes,~~ 2014;~~;~~ Barthelmes and Köhler, 2012, and Barthelmes et al., 2017 ~~Drewes, 2016; Toth, 2018~~).

There are various complementary data resources used for the development of high quality global gravity field models. For example, advanced satellite ~~observations~~ measurements or derived quantities are one of them and they can be in the form of satellite orbital perturbations derived from GNSS measurements, microwave/laser range rate measurements between two satellites, satellite laser ranging (SLR) observations from the Earth's surface to the near Earth satellites, and finally gravity gradients and non-gravitational accelerations measured on-board spacecraft. Recent satellites contributing ~~to the~~ tremendously to the improvements in global gravity field modelling are the dedicated gravity missions CHAMP (Reigber et al., 2002), GRACE (Tapley et al., 2004), GRACE Follow-On (Flechtner et al., 2014; Flechtner et al., 2016), GOCE (Drinkwater et al., 2003; Rummel et al. 2011); and SLR satellites such as LAGEOS 1 and LAGEOS 2; as well as the fleet of altimetry satellites such as Topex/Poseison and Jason 1 and 2. Other fundamental datasets used in the development of global gravity field models are terrestrial gravity measurements ~~collected on moving platforms (e.g. airborne and shipborne) and finally actual terrestrial gravity measurements collected on the Earth's surface~~ including the ones collected on moving platforms. Besides the gravity measurements, high resolution digital elevation models (DEMs) complement the global gravity field models for mapping detailed features of the gravity field and in the areas with missing real gravity measurements such as Antarctica.

Static and temporal global gravity field models are developed based on different mathematical approaches. These approaches are designed to take the advantage of each of the above mentioned measurement technique with the overarching goal of mapping the Earth's gravity field with its smallest details possible and monitor its temporal variations. Different institutions and agencies study and improve these techniques and develop gravity field models for different applications and produce regular updates when new measurements become available from satellites and terrestrial measurements. The International Centre for Global Earth Models (ICGEM) contributes to the collection and validation of these models and~~to~~ make them freely available online ~~and provides~~ with additional interactive calculation and visualisation services. Therefore, it has naturally become the ~~meeting point~~meeting platform for both the model developers and the users of the global gravity field models.

ICGEM is one of the five Services coordinated by the International Gravity Field Service (IGFS) (http://igfs.topo.auth.gr) of the International Association of Geodesy (IAG, http://www.iag-aig.org). The IAG is the global scientific organization in the field of geodesy which promotes scientific cooperation and research in geodesy and contributes to it through its various research bodies. The roots of the IAG can be traced back to the 19^{th} century. Today it is one of the largest organizations in geodetic and geophysical research, especially thanks to the extensive services it provides. The IAG is a member of the International Union of Geodesy and Geophysics (IUGG, http://www.iugg.org) which itself is a member of the International Science Council (ISC, https://council.science). Within the same hierarchy, the IGFS as an IAG Service is a unified "umbrella", which: (1) coordinates the collection, validation, archiving and dissemination of gravity field related data, (2) coordinates courses, information materials and ~~outreach to the~~ general public outreach related to the Earth's gravity field, (3) unifies gravity products for the needs of the Global Geodetic Observing System (GGOS, www.ggos.org). ~~The Services of the IGFS and corresponding responsible institutions are shown in Figure 1.~~

~~Figure 1: The IGFS Services and hosting institutions.~~

The five Services of IGFS are: The International Centre for Global Earth Models (ICGEM), the Bureau Gravimetrique International (BGI), the International Service for the Geoid (ISG), the International Geodynamics and Earth Tide Systems (IGETS), and the International Digital Elevation Model Service (IDEMS) (http://www.iag-aig.org/index.php?tpl=cat&id_c=11). These ~~five S~~services exchange information via the IGFS and collaborate in ~~for~~ the future plans of geodetic and gravity field related activities, such as GGOS which aims to advance our understanding of the dynamic Earth system by quantifying the changes of our planet in space and time (www.ggos.org).

Within this well developed and maintained services, ~~T~~the 15 year old ICGEM Service has been collecting and archiving almost all of the existing static global gravity field models available worldwide. During the last few years, due to requests of users and model developers, ICGEM started to collect also temporal gravity field models and ~~also~~ provide links to the original ~~contributors~~model developers' resources. Since its establishment, ICGEM has structured itself based on users' needs and nowadays provides the following services:

- Collecting and long term archiving of existing static global gravity field models, solutions from dedicated shorter time periods (e.g. monthly GRACE models), and recently topographic gravity field models, and making them available on the web in a standardized format (Barthelmes and Förste, 2011),
- Since late 2015, the above service has been extended with the possibility of assigning Digital Object Identifiers (DOI) to the models, i.e. to the datasets of coefficients, enabling the citation of the models.
- A web interface to calculate gravity field functionals from the spherical harmonic models on freely selectable grids and user defined point coordinates,
- A 3D interactive visualisation service for the gravity field functionals (geoid undulations and gravity anomalies) using static and time variable gravity field models,
- Quality checks of the models via comparisons with other models in the spectral domain and also with respect to GNSS/levelling derived geoid undulations at benchmark points collected for different countries,
- The visualisation of surface spherical harmonics as tutorial,
- The theory and formulas of the calculation service documented in GFZ's Scientific Technical Report STR09/02 (Barthelmes, 2013),
- Manuals and tutorials for global gravity field modelling and usage of the service (Barthelmes, 2014), and finally
- The ICGEM web-based gravity field discussion forum.

~~The tasks of the other four Services are the following (http://www.iag-aig.org/index.php?tpl=cat&id_c=11):~~

~~- The Bureau Gravimetrique International (BGI) collects all terrestrial measurements and pertinent information worldwide related to the Earth gravity field; compiles, stores, and redistributes them based on requests.~~

~~- The International Service for the Geoid (ISG) collects worldwide geoid data, conducts research and collects and distributes software for geoid determination, and organises Geoid schools.~~

~~- The International Geodynamics and Earth Tide Systems (IGETS) provides a service to monitor temporal variations of the Earth gravity field through long-term records from ground gravimeters and other geodynamic sensors via the database run by GFZ.~~

~~- Finally, the International Digital Elevation Model Service (IDEMS) distributes the data and information about Digital Elevation Models, relevant software and related datasets which are publicly available.~~

~~The five Services exchange information via the IGFS and collaborate in the future plans of geodetic and gravity field related activities, such as GGOS which aims to advance our understanding of the dynamic Earth system by quantifying the changes of our planet in space and time (www.ggos.org).~~

With this ~~paper~~article, we aim to inform ICGEM's current and potential new users about the content and the services that the ICGEM provides and share ~~the~~ future aspects of the Service that aims to bridge the ~~future~~ plans of the ICGEM Service with the users' needs. We describe ~~different~~ various types of gravity ~~global gravity~~ field models archived in the Service, ~~and~~

provide examples of their use for different purposes via ICGEM's interactive calculation and 3D visualisation tools and give a summary of the documents available on the Service such as tutorials for undergraduate and graduate students.

The manuscript is organised as follows. We provide an overview of the general and scientific background ~~as well as the~~and the future plans of the ICGEM Service and its data content in Section 2~~ together with the details of different gravity field models provided by ICGEM~~. Details and examples of ICGEM's new features and various services such as the Calculation and 3D Visualisation, as well as the DOI Services ~~with examples~~ are given in Section 3~~ with their extensive examples~~. Documentation of the Services and details on the web programming of the new website, which has been implemented in May 2017~~6~~, are ~~given~~ provided in Section 4 and 5, respectively. Finally, in Section 6 and 7, we provide a summary and information on the ~~and plans for future developments and aspects of the ICGEM Service~~data availability~~, respectively~~. The sections are written independently which enables the reader to directly refer to the relevant section without reading the previous parts nor the entire paper.

2 The background of the ICGEM Service

2.1 History, Status, and Future Plans of ICGEM

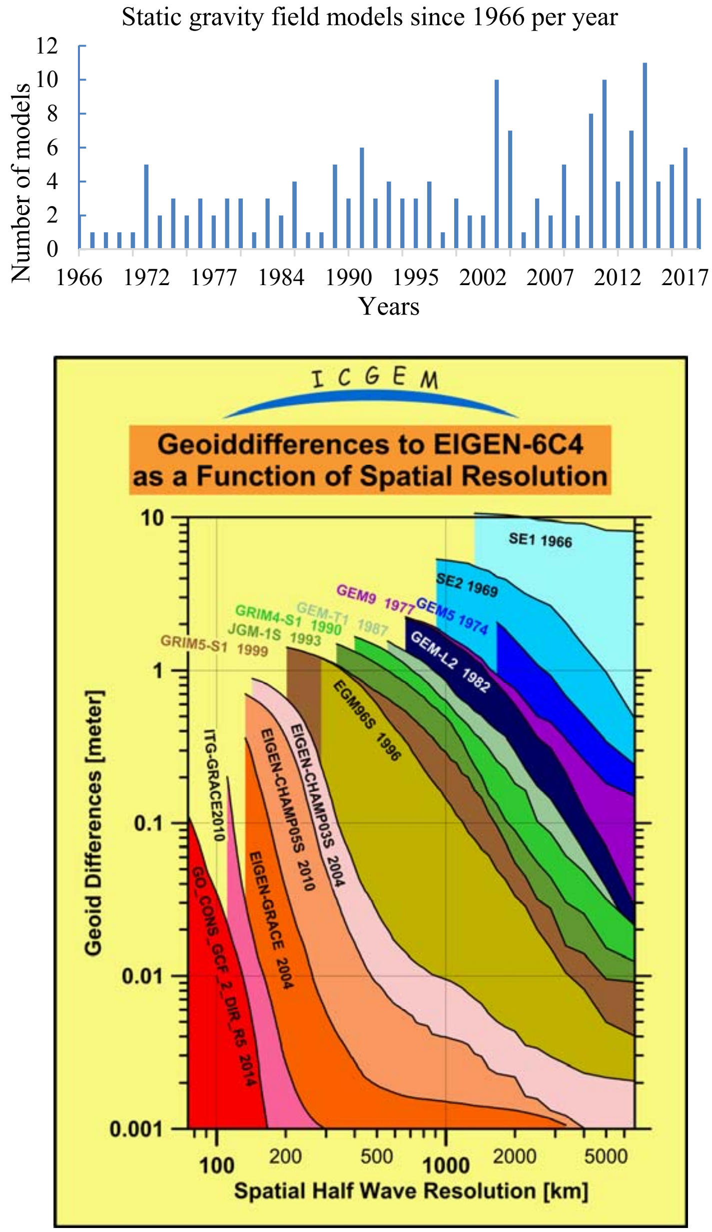
In the second half of the 1990s, the demand for a single access point to the collection and distribution of gravity field models and associated services arose from an interdisciplinary scientific community (1997 IAGA resolution No 1, http://www.iaga-aiga.org/index.php?id=res1-97) that included geodesists, geophysicists, oceanographers and climate scientists. With the IGFS's initiation in 2003 and the hosting and financial support of GFZ, the ICGEM Service was established in the same year. The ICGEM Service was initially established to collect static global gravity field models under one umbrella and provide easy access to the models via its website without any required user registration. Different models developed based on different combination of datasets, serve for variety of different purposes. The old models are collected to be included in the archive, whereas the newer models are used in the modelling of the Earth's gravity field with its finest details and its temporal variations due to different reasons, e.g. mass redistributions due to climate change. The interest in the development and application of the static as well as the temporal gravity field models has increased significantly with the launch of the dedicated gravity field satellite missions such as CHAMP, GRACE, and GOCE. As a consequence, the ICGEM Service has become a unique platform for the largest and most complete collection of the static and temporal gravity field models.

The number of static gravity field models developed by various institutions since the 1960s with respect to time is shown in Fig.~~ure~~ 1~~2~~a. The launch of the dedicated gravity satellite missions stimulated the studies in global gravity field determination as indicated by the increased number of the models. The details of the features resolved by some of the selected satellite only models in the spatial domain are shown in Fig.~~ure~~ ~~2~~1b. Each new satellite only model shows improvement due to the high quality data retrieval. For example, the uncertainties in the geoid signal have been reduced from tens of meters to ~10 cm, whereas the spatial details that can be resolved from the satellite only global models have been improved from thousands of km to ~~about~~ ~120 km. It is important to recall that the CHAMP mission was a break through mission and increased the details provided by the global gravity field models drastically in the spatial domain from about 1500 to 300 km. One of the first models with CHAMP contribution has become famous as the “Potsdam Gravity Potato” (personal communication, Reigber and Schwintzer, 2002).

By January 2019, the ICGEM Service provides access to 168 static gravity field models ~~(listed in Appendix 2)~~, more than 20 temporal gravity field models (including different releases from same institutions between the years 2002 and 2016) ~~(listed in Appendix 3)~~, 18 topographic gravity field models ~~(listed in Appendix 4)~~ and finally models for three other celestial objects (~~,~~ 6 ~~models~~ for Mars, 18 ~~models~~ for the Moon and 2 ~~models~~ for Venus). The ICGEM Service plans to continue its long-term services w~~W~~ith ~~the~~ new releases of better quality static and temporal gravity field model contributions from the recently launched GFZ and NASA mission GRACE-FO (Flechtner et al., 2014) and ongoing reprocessing efforts of GOCE (Siemes, 2018) and GRACE mission data (Dahle et al., 2018; Save et al., 2018; Yuan, 2018) ~~we expect to receive new releases of better quality static and temporal gravity field models in the following year~~ ~~s.~~ as well as ~~the~~ contributions from the New Generation Gravity Missions. Considering the number of visits of the ICGEM Website during the last few years, it has become obvious that the ICGEM Service has been recognised as a highly demanded service by the community and used very actively worldwide. The distribution of visits of the ICGEM ~~service~~ Service ~~users~~ by continents and the corresponding numbers between May 2018 and December 2018 are shown in ~~Figure~~ Fig. 2~~3~~.

~~The ICGEM plans to continue its long term services in the future with the contributions from the reprocessed GOCE and GRACE data, the GRACE-FO mission as well as New Generation Gravity Missions.~~ In the near future, the old G3 Browser, which showed the time variation of gravity field at any desired point or pre-defined basin, will be available again with improved features developed for both advanced researchers and educational purposes. A specific web interface will be made available for the user to calculate and visualise ~~the~~ time series of mass variations. The results again will be available both in .png and. ASCII formats. Moreover, new services, such as the provision of time series of the changes of the gravity field of the Earth due to the flattening retrieved from SLR measurements from different institutions and agencies, ~~and also~~ the offer ~~offering~~ of the calculation of horizontal gravity gradients in the ICGEM Calculation Service, and developing strategies for sharing the external datasets used in the evaluation (e.g. GNSS/levelling derived geoid undulations) are ~~some o~~among~~f~~ our future plans.

To realise the above mentioned future plans, ~~Accordingly,~~ development of a new modernised and more flexible ICGEM W~~w~~ebsite ~~for future developments~~ was necessary which ~~indeed~~ was realised and made available by GFZ in May 2017~~8~~ (see also Section 5). A scheme of the current website structure of the ICGEM Service is presented in ~~Figure~~ Fig. 4~~3~~. ~~The list of the models, calculation and visualisation services and other services are accessible via the menu listed on the homepage (http://icgem.gfz-potsdam.de) as shown in Fig.ure 43.~~



a)

b)

Figure 1: a) Number of ~~the~~ static gravity field models released per year ~~released~~ since 1966. Note the increased number of models due to the launch of the dedicated satellite gravity missions (CHAMP, GRACE and GOCE) after 2003 and 2011. b) The history of the improvement of the spatial resolution and the accuracy of the satellite only gravity field models. Signal amplitude difference over the years w.r.t. one of the latest combined global gravity field models, EIGEN-6C4 is shown (http://icgem.gfz-potsdam.de/History.png). Note that the EIGEN-6C4 is not the truth but a better approximation to the real gravity field, because it is a combination of data retrieved from ~~dedicated~~ satellite missions, ~~and includes~~ terrestrial measurements, and altimetry-derived gravity field information. The uncertainties of the geoid signal have been reduced together with improved spatial resolution. See also the large improvement between the EGM96S and EIGEN-CHAMP03 due to the contribution of the CHAMP measurements.

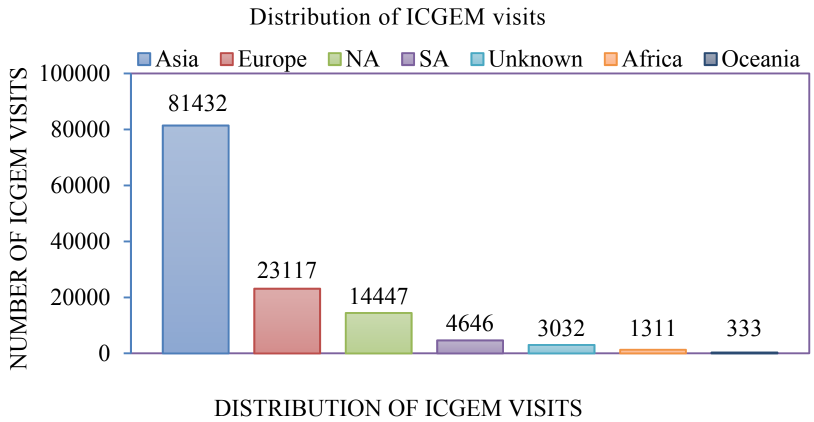


Figure 2: Distribution of ICGEM ~~use~~ visits over continents between May 2018 and December 2018. NA is for North America, SA is for South America and Unknown is for anonymous entries.

2.2 Scientific background and ICGEM's Data

The global gravity field model of the Earth is a mathematical model which describes the potential of the gravity field of the Earth in the 3 dimensional space. The terms gravity field and gravitational field are commonly mixed or used interchangeably. Therefore, we will start with the basic definition of the two terms for the sake of clarity in the rest of the paper. In geodesy, there is a clear difference between the two terms. Gravitational potential, V is formed by the summation of pure gravitational forces of the masses of the Earth; whereas, gravity field potential, W is the sum of the potential of the Earth's gravitational attraction, V and potential of the centrifugal force due to Earth rotation.

Within this concept, a global model of the Earth's gravity field is a mathematical function which approximates the real gravity field potential and allows to compute physical quantities related to the gravity field, i.e. the gravity field functionals at any position in the 3 dimensional space. A gravity field model should therefore contain both, a model of the gravitational potential and a model of the centrifugal potential. Because the modelling of the centrifugal potential is well known and can be done very accurately (Hofmann-Wellenhof and Moritz, 2006), the relevant and challenging part of a gravity field model is the modelling of the gravitational field. Therefore, the term gravity field model is also very often used in the sense of gravitational field model. ~~Through this article, we use the term "gravity field" since it has been commonly used in the past by the "gravity field" community.~~In this article, the model coefficients are representative for the gravitational field and gravity field is used when the centrifugal potential is included in the computation of the gravity field functionals.

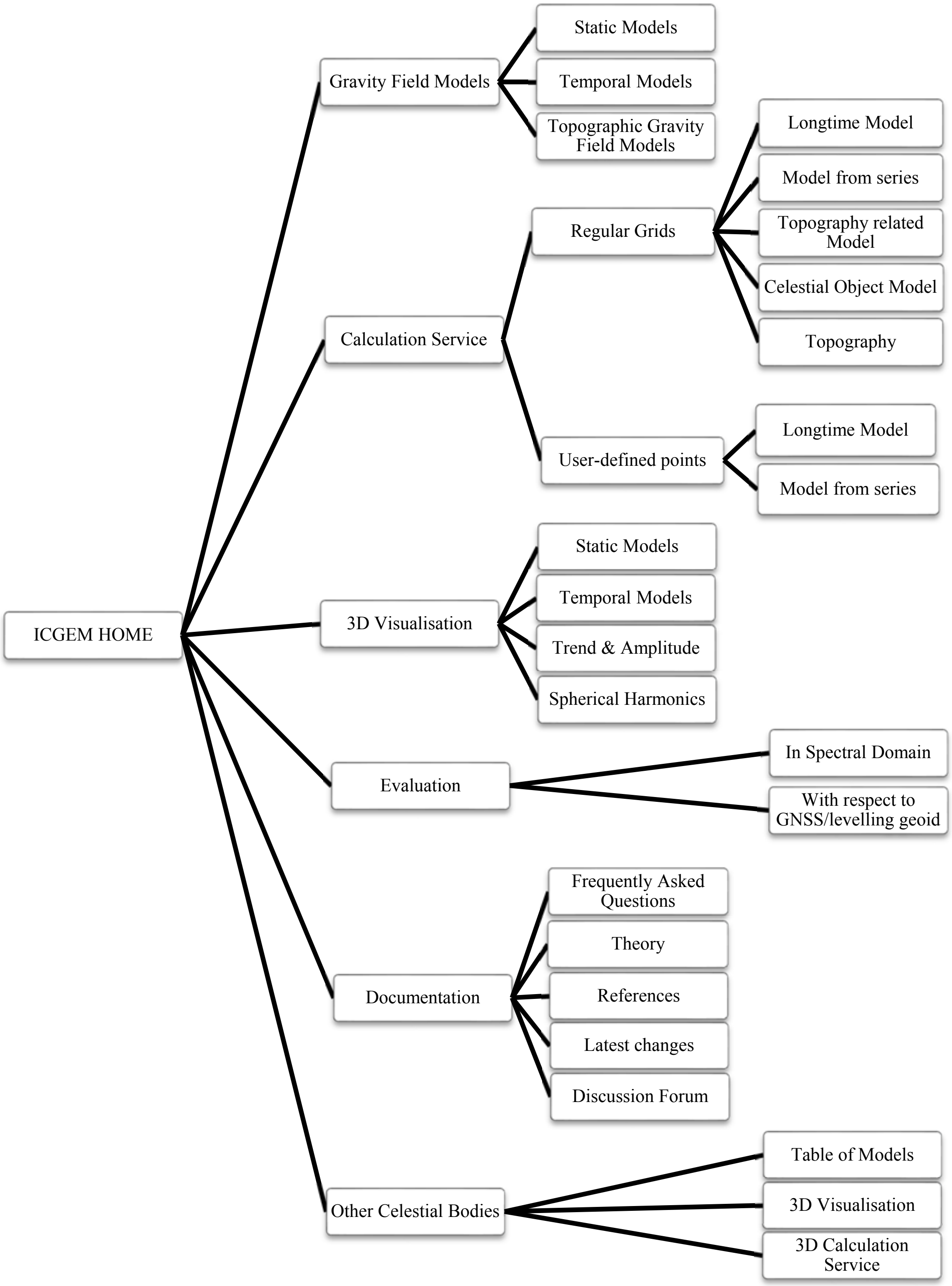


Figure 3: The homepage structure of the new ICGEM service website.

Due to mass redistribution on, inside and outside the Earth caused by different reasons, the gravity field changes with respect to time. Although these temporal changes are very small and/or very slow, they can be measured (e.g. using GRACE mission data) and modelled up to a certain spatial and temporal resolution (Wahr et al., 1998; Wahr et al., 2004; Schmidt et al., 2006). ICGEM provides access also to these temporal gravity field models.

~~In this paper we will remind the reader that the notation of the~~

~~According to Newton's law of gravitation, two point masses m_1 and m_2 separated by a distance of l, attract each other with a force:~~

$$\cancel{F = G\frac{m_1 m_2}{l^2},} \qquad \text{~~Eq. (1)~~}$$

~~where G is the gravitational constant. Although m_1 and m_2 attract each other symmetrically, it is convenient to call one of them attracting mass and the other one attracted mass. For simplicity, setting the attracted mass equal to unity, the formulation is transformed into:~~

$$\cancel{\vec{F} = G\frac{m}{l^2}\frac{\vec{l}}{l},} \qquad \text{~~Eq. (2)~~}$$

~~m being the attracting mass and the force indicated as a vector. It is the expression of the force applied by the attracting mass m onto a unit mass at a point distanced by l. Here the potential of gravitation for the two mass points can be introduced, which is a scalar function:~~

$$\cancel{V = G\frac{m}{l},} \qquad \text{~~Eq. (3)~~}$$

~~with $\nabla V = \vec{F}$ where the ∇ is the nabla operator and ∇V is the gradient of the gravitational potential.~~

~~The gravitational potential of a system is V and consisting of infinite number of infinitely small volume elements $dv(x,y,z)$ with density $\rho(x,y,z)$, can be represented by:~~

$$\cancel{V(x,y,z) = G\iiint_v \frac{\rho(x',y',z')}{l^2}dv,} \qquad \text{~~Eq. (4)~~}$$

~~where the integral is computed over the entire body, ρdv is the mass element and $l = \sqrt{(x-x')^2+(y-y')^2+(z-z')^2}$.~~

~~The gravitational potential satisfies the Poisson's equation:~~

~~$\nabla^2 V = -4\pi G\rho$, Eq. (5)~~

~~where ∇^2 is called the Laplace operator which is a differential operator given by the divergence of the gradient of ∇ (Heiskanen and Moritz, 1967). Geodesy describes the gravitational potential only in empty space, outside the masses, and estimates a mathematical function that approximates the potential. Outside the masses, where the density ρ is zero, the gravitational potential satisfies the Laplace condition:~~

~~$\nabla^2 V = 0$. Eq. (6)~~

~~With this condition satisfied, V is a harmonic function in empty space.~~

Models approximating the real (true) gravity field can be developed based on different mathematical representations, e.g. ellipsoidal harmonics, spherical radial basis functions, or spherical harmonic wavelets which are all harmonic outside the masses (outer Earth). In practice, solid spherical harmonics are the ones widely used to represent the gravitational potential (or geopotential) globally which excludes the centrifugal potential. Solid spherical harmonics are an orthogonal set of solutions to the Laplace equation represented in a system of spherical coordinates (Heiskanen and Moritz, 1969; Hofmann-Wellenhof & Moritz, 2006).

The datasets available via the ICGEM Service are the spherical harmonic coefficients, which together with the spherical harmonic functions, approximate the real gravitational potential of the Earth and/or its variations. The spherical harmonic (or Stokes') coefficients represent the global structure and irregularities of the geopotential field in the spectral domain (Heiskanen and Moritz, 1967; Moritz, 1980; Hofmann-Wellenhof and Moritz, 2006; Barthelmes, 2013) and the formulation of the relationship between the spatial and spectral domain of the geopotential is expressed as:

$$V(r,\varphi,\lambda) = \frac{GM}{r}\sum_{l=0}^{l_{\max}}\sum_{m=0}^{l}\left(\frac{R}{r}\right)^{l}\bar{P}_{lm}(\sin\varphi)\left(\bar{C}_{lm}\cos m\lambda + \bar{S}_{nm}\sin m\lambda\right), \quad \textbf{Eq. (1)}$$

where V is the Gravitational potential, r,φ,λ correspond to the spherical geocentric coordinates of computation point (radius, latitude and longitude, respectively),

R is a (mathematically arbitrary) reference radius (in geodesy usually the mean semi-major axis of Earth is used),

GM is the Gravitational constant times the mass of the Earth,

l, m are degree and order of spherical harmonic, respectively,

$l_{\max}$ is the maximum degree (and order) of the model expansion,

$\bar{P}_{lm,}$ are fully normalized Legendre polynomials of degree l and order m ,

$\bar{C}_{lm,}\bar{S}_{lm,}$ are fully normalized Stokes' coefficients.

Spherical harmonics are calculated using spherical coordinates and the normalisation is defined such that ~~represents when~~ the average square value of the normalised harmonics integrated over the sphere is equal to unity (Heiskanen and Moritz, 1967): ~~and it is represented by:~~

$$\frac{1}{4\pi}\int_{\lambda=0}^{2\pi}\int_{\varphi=-\pi/2}^{\pi/2}\left[\bar{P}_{lm}\sin\varphi\cos m\lambda\right]^{2}\cos\varphi d\varphi d\lambda=1. \qquad \textbf{Eq. (2)}$$

The very low degree and order spherical harmonic functions can be physically defined and easily illustrated. For example, the $\bar{C}_{00}$ describes the mass of the Earth by scaling the value of GM, the whole mass of the Earth times the Newtonian constant. Therefore its value is close to 1. The degree 1 spherical harmonic coefficients, $\bar{C}_{10},\bar{C}_{11,}$ and $\bar{S}_{10}$ are related to the coordinates of the geocentre and if the coordinate system's origin coincides with the geocentre, they are equal to zero. The coefficients $\bar{C}_{21}$ and $\bar{S}_{21}$ are related to the mean rotational pole position. A tutorial on the representation of the spherical harmonics is available on the ICGEM website (http://icgem.gfz-potsdam.de/vis3d/tutorial) and an example of three different degree and order spherical harmonics are shown in Fig.~~ure~~ 4~~5~~.

Mathematical representation of a ~~gravity~~ gravitational field model using summation of spherical harmonics is displayed in Fig.~~ure~~ ~~6~~5. Sectorial, zonal, and tesseral spherical harmonic functions multiplied by the corresponding coefficient values are used to develop ~~gravity~~ gravitational field model of the Earth expanded up to degree l and order m . The spherical harmonic degree expansion corresponds approximately to the spatial resolution of $\lambda_{degree}=\frac{180^{\circ}}{l}$ or $\lambda_{km}=\frac{20000km}{l}$, where 20000 20000 km is the half wavelength of the equatorial length and l is the spherical harmonic degree. A spherical harmonic model of the ~~gravity~~ gravitational field up to maximum degree $l_{\max}$ consists of $\left(l_{\max}+1\right)^{2}$ coefficients (see also ~~Figure~~ Fig. ~~6~~5).

The terms $\bar{C}_{lm}$ and $\bar{S}_{lm,}$, and their variations are the fundamental data of the ICGEM Service that are retrieved from real gravity measurements and satellite observations and derived quantities as well as forward modelling using high resolution digital elevation models. Moreover, these coefficients are used in the calculation of the gravity field functionals directly.

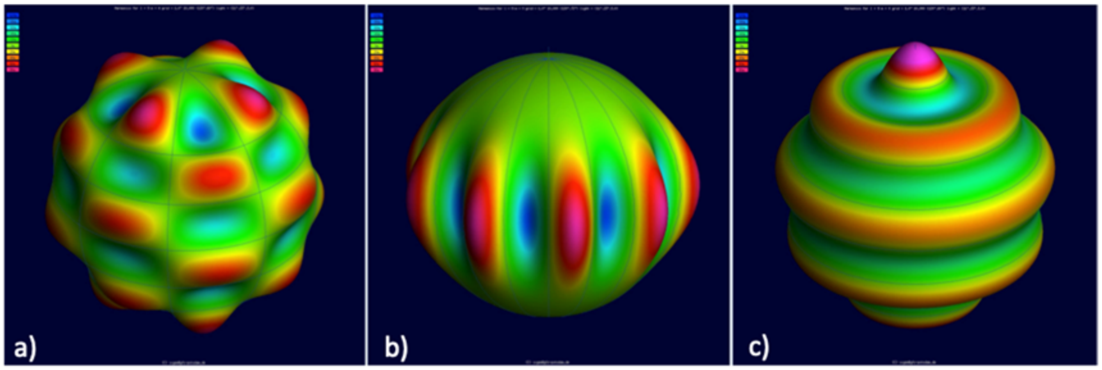


Figure 4: 3D Visualisation of spherical harmonics as tutorial. The images show one specific surface spherical harmonic of degree *l* and order *m* such as a) tesseral (*l*=9, *m*=4) b) sectorial (*l*=9, *m*=9) c) zonal (*l*=9, *m*=0) spherical harmonics.

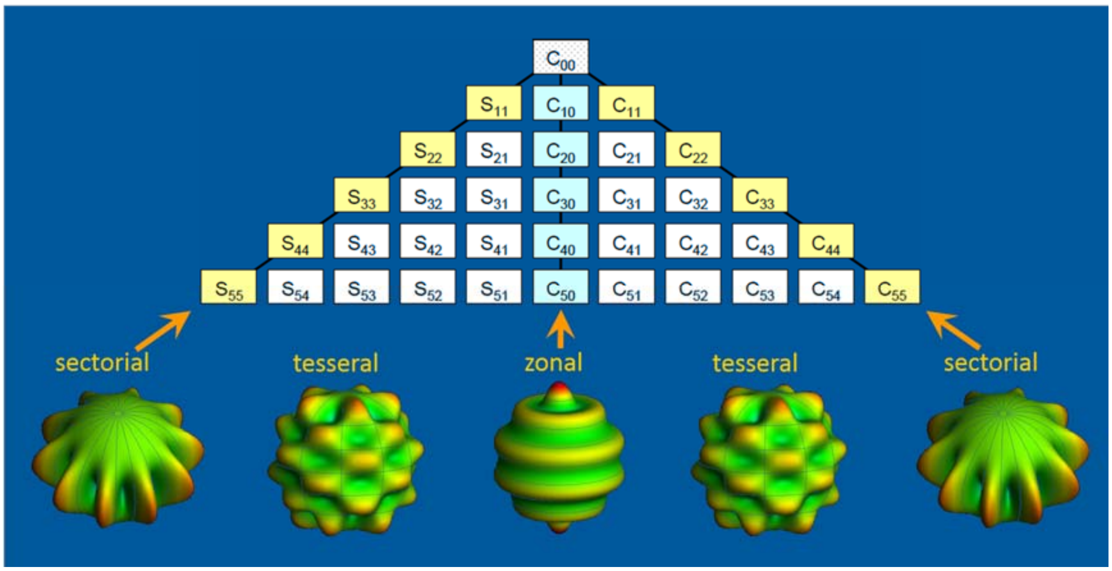


Figure 5: Mathematical representation of gravitational~~y~~ field potential using sectorial, tesseral and zonal spherical harmonics. A spherical approximation of the gravitational~~y~~ field up to maximum degree of l_{max} consists of $(l_{max}+1)^2$ coefficients~~ (credit Barthelmes, F.)~~.

At this point, it is worth mentioning about the mathematically defined normal potential which helps to approximate the real gravity potential for practical reasons. For many purposes, it is useful and sufficient to approximate the figure of the Earth by a reference ellipsoid. This is defined as the ellipsoid of revolution which fits the geoid, i.e. equipotential surface that in average approximates the mean sea surface ~~the undisturbed sea surface of the Earth and its fictitious continuations below the continents, as good as possible~~ (i.e. in the sense of least squares fit). The normal potential together with the geometrical ellipsoid establish the Geodetic Reference System, e.g. WGS84 or GRS80 (Moritz, 1980; Mularie, 2000). Like the gravity potential W, the normal potential U also consists of a gravitational potential and centrifugal potential. The attracting part of the normal potential can also be represented in terms of spherical harmonics. Due to the rotational symmetry, the expansion of ellipsoidal normal potential contains only the terms for $m=0$ and degree l = even. In most cases, the coefficients of $\bar{C}_{00}^{U}, \bar{C}_{20}^{U}, \bar{C}_{40}^{U}, \bar{C}_{60}^{U}$, and $\bar{C}_{80}^{U}$ are used in the calculation of the normal potential, where the superscript U indicates the normal potential. Using the normal potential, the real gravity field potential can be split into two parts, the normal potential and the disturbing potential as expressed below:

$$W(r,\varphi,\lambda)=U(r,\varphi)+T(r,\varphi,\lambda). \qquad \textbf{Eq. (3)}$$

If we subtract the Stokes' coefficients ($\bar{C}_{00}^{U}, \bar{C}_{20}^{U}, \ldots, \bar{C}_{80}^{U}$) of an ellipsoidal normal potential, $U(r,\varphi)$ from the gravity potential, the disturbing potential $T(r,\varphi,\lambda)$ can also be mathematically represented in terms of spherical harmonics, $\bar{C}^{'}=\bar{C}-\bar{C}^{U}$.

The disturbing potential is a 3d function ~~and valid~~ in space and it can be represented by:

$$T(r,\varphi,\lambda)=\frac{GM}{r}\sum_{l=0}^{l_{\max}}\sum_{m=0}^{l}\left(\frac{R}{r}\right)^{l}\bar{P}_{lm}(\sin\varphi)\left(\bar{C}_{lm}^{'}\cos m\lambda+\bar{S}_{lm}^{'}\sin m\lambda\right). \qquad \textbf{Eq. (4)}$$

The two fundamental gravity field functionals used in geosciences very often are geoid undulation and gravity disturbances which in practice can be approximately calculated using the disturbing potential, whereas the exact calculation of gravity disturbances is possible using W and U directly. It is worth recalling that the geoid undulation is the distance between the particular equipotential surface (geoidal surface) and the surface of the reference ellipsoid (conventional ellipsoid of revolution). The gravity disturbance on the other hand is the difference of the magnitude of the gradient of the Earth's potential (the gravity) and the magnitude of the gradient of the normal potential (the normal gravity) at the same point (e.g. Earth's surface), $\delta g(r,\varphi,\lambda)=\left|\nabla W(r,\varphi,\lambda)\right|-\left|\nabla U(r,\varphi)\right|$.

In continental areas or over land, apart from some regions (e.g. Death Sea area), the geoid is located inside the masses, whereas the gravity potential W is only harmonic outside the mases. Therefore, in order to calculate the geoid undulation from the potential W, a correction due to the masses ~~over~~ above the geoid has to be applied which could be done by using a representation of the topography in terms of spherical harmonics, $\bar{C}_{lm}^{topo}$ and $\bar{S}_{lm}^{topo}$. Using the model spherical harmonic coefficients from potential and topography, the geoid can be expressed as first approximation by:

$$N(\varphi,\lambda)\approx\frac{GM}{r_e\gamma(r_e,\varphi)(}\sum_{l=0}^{l_{\max}}\left(\frac{R}{r_e}\right)^l\sum_{m=0}^{l}\bar{P}_{lm}(\sin\varphi)\left(\bar{C}'_{lm}\cos m\lambda+\bar{S}'_{lm}\sin m\lambda\right)$$

$$-\frac{2\pi G\rho}{\gamma(r_e,\varphi)}\left[R\sum_{l=0}^{l_{\max}}\sum_{m=0}^{l}\bar{P}_{lm}(\sin\varphi)\left(\bar{C}^{topo}_{lm}\cos m\lambda+\bar{S}^{topo}_{lm}\sin m\lambda\right)\right]^2 \quad , \qquad \textbf{Eq. (5)}$$

whereas the gravity disturbance can be approximated by its radial component:

$$\delta g(r,\varphi,\lambda)\approx\frac{GM}{r^2}\left[\sum_{l=0}^{l_{\max}}\left(\frac{R}{r}\right)^l(l+1)\sum_{m=0}^{l}\bar{P}_{lm}(\sin\varphi)\left(\bar{C}'_{lm}\cos m\lambda+\bar{S}'_{lm}\sin m\lambda\right)\right]. \qquad \textbf{Eq. ~~(~~ (6)}$$

In the following section, we will give examples of different functionals and their relevant applications. For the details of the formulations of exact calculations and approximations and insight to the other functionals, the reader is referred to Barthelmes, 2013.

2.2.1 Static global gravity field models of the Earth

As mentioned above, the ICGEM Service was established 15 years ago to mainly collect all available static global gravity field models from different institutions under one umbrella and make these models freely available to the public. Therefore, this feature is the fundamental component of the service and special attention is paid to maintain the complete list of static global gravity field models with a possibility to assign DOI number upon model developer(s)'s request. The three main complementary data sources to compute gravity field models are satellite based ~~and~~ measurements, terrestrial gravity measurements and satellite radar altimetry derived quantities. The satellite based gravity measurements cover long wavelength information of the gravity field, whereas the spatial details of the gravity field (i.e. short wavelengths or high frequencies) are collected via terrestrial, airborne and shipborne gravity measurements and radar altimetry. The altimetry records yield the sea surface height which after some corrections can be taken as mapping of the geoid over the oceans and seas (e.g. Rummel and Sanso, 1993). Consequently, high degree and order resolution static gravity field models can only be developed based on a combination of the three sources which can also be supported by high-resolution topographical models. These high-resolution static gravity field models are used for regional geoid and gravity field determination in geodesy and geophysics, as well as for geodynamic interpretation and modelling, see also Table 1.

The development of the Earth Gravitational Model 2008 (EGM2008) (Pavlis et al., 2012) was a very important milestone in terms of delivering high-resolution static global gravity field models. The spherical harmonic degree and order expansion reached up to ~~2159~~ 2190 using a combination of available gravity and topography data available worldwide. The improvement was due to the introduction of the National Geospatial-Intelligence Agency (NGA)'s worldwide terrestrial data coverage. After the release of EGM2008, different processing centres were also able to take the advantage of using the EGM2008 grids for the higher frequency components of the gravity field and to develop different "combined" high-resolution global gravity field models. ~~One~~ As an example of one of the high-resolution static global gravity field models developed by GFZ is EIGEN-6C4 (Förste et al., 2014, Förste et al., 2016b) which is also a combination of satellite and terrestrial data and expanded up to spherical harmonic degree and order 2190. EIGEN-6C4 contains data from the GOCE mission which was not yet available for EGM2008. With the latest release of EIGEN series, the spatial resolution of the "Potsdam Gravity Potato" has been ~~resolved~~ increased up to ~9 km half wavelength.

The global geoid undulations and gravity disturbances computed from EIGEN-6C4 are shown in Fig. ~~ures 7~~ 6 and ~~8~~7, respectively. Even though the Earth's interior is still a mystery, gravity can help to understand what is inside our planet. Regions inside the Earth with higher mass densities (with respect to the mean density) produce larger gravity attraction on the surface; whereas on the contrary, mass deficit causes lower gravity if measured at the same point. However, if the mass densities change anywhere Earth's interior, the geoid (equipotential surface) and consequently the surface of the Earth would not stay at the same point and they would also change. As a result, interpretation of gravity disturbances and geoid undulations (in particular globally) is more sophisticated than it is expected. In general one can say that geoidal "dales" (negative geoid undulations), as in the Indian Ocean, are the result of mass deficit in the deep mantle (Ghosh et al., 2017) and the big geoidal "bumps" (positive geoid undulations), as in the region of North Atlantic, are the result of higher mass density in the interior~~. However, the influence of density anomalies on the geoid (which describes the gravity potential) is, at first glance, not so obvious. Positive density anomalies result in positive geoid undulations "geoid bumps" (i.e. the mean sea surface which follows the geoid is positive with respect to the ellipsoid) even though the gravity attraction is stronger. If we bear in mind that all the gravity forces must be perpendicular to the geoidal surface, this becomes apparent. Also, if we "switch on" a (spherical) positive density anomaly beneath the ocean, the water flows towards the stronger attraction till the forces are perpendicular to the surface (i.e. no tangential forces are left) which is the case in the region of the North Atlantic. On the contrary, the big geoidal "dale" (negative geoid undulation) in the Indian Ocean is the result of mass deficit underneath the Earth (Ghosh et al., 2017).~~ In that sense, the use of gravity field models to supplement the geophysical and geological models enhance our understanding of the Earth's dynamics.

The studies on the development of high-resolution global gravity field continue with the reprocessed GOCE and GRACE data. Moreover, National Geodetic Survey (NGS) has collected plenty of new terrestrial data in the US (e.g. GRAV-D project) (Li et al., 2016) and worldwide; and it is expected that the new EGM model from NGA will be available in 2020. An experimental model as the precursor study for the upcoming EGM2020, namely XGM2016 has already been released in 2016 with the degree and order expansion of 719 (Pail et al., 2018). It is expected that the EGM2020 will have a spatial resolution of about 9km or better.

A lower degree expansion of a gravity field model simply means a lower resolution in the spatial domain. The refined features of the gravity field are only visible using the high degree and order coefficients. Figure 8 shows four examples of different degree expansions, 50, 150, 250 and 500 of EIGEN-6C4 gravity anomalies corresponding to about 400, 133, 80 and 40 km half wavelength spatial resolution, respectively. It becomes obvious that the features are refined in spatial domain more and more not only over the land but also over the oceans as the model is expanded up to higher degree and order. Accordingly, the ultimate goal would be the development of high-resolution and high-quality static gravity field model taking advantage of different datasets available.

As mentioned in the introductory section, gravity field models are important inputs in several research fields. In geodesy, they are most commonly used for the GNSS levelling. Together with a high-quality and high-resolution geoid model, ellipsoidal heights (geometric heights) measured using GNSS sensors can provide physical heights (i.e. orthometric heights) very efficiently. In the past, the physical heights were measured via spirit levelling (or other levelling methods) which has been limited to the road ways and widely accessible areas only. Other application areas of static gravity field models together with temporal and topographic gravity field models are summarized in Table 1.

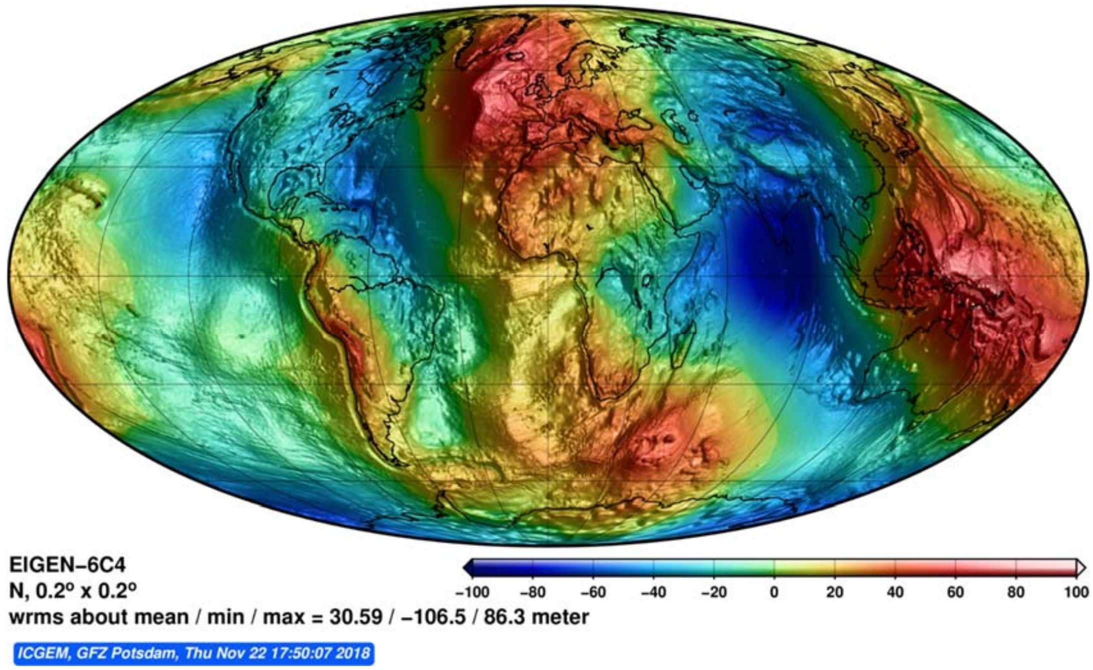


Figure 6: Geoid undulation computed from EIGEN-6C4 combined gravity field model expanded up to degree and order 2190.

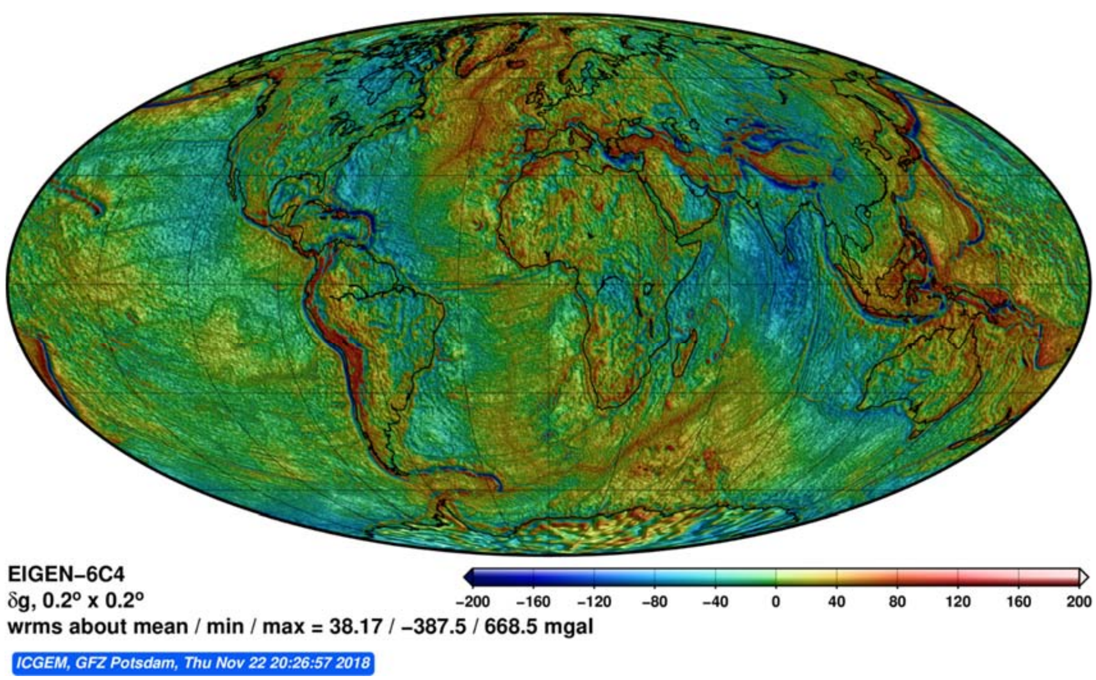


Figure 7: Gravity disturbance computed on the Earth surface from EIGEN-6C4 combined gravity field model expanded up to degree and order 2190.

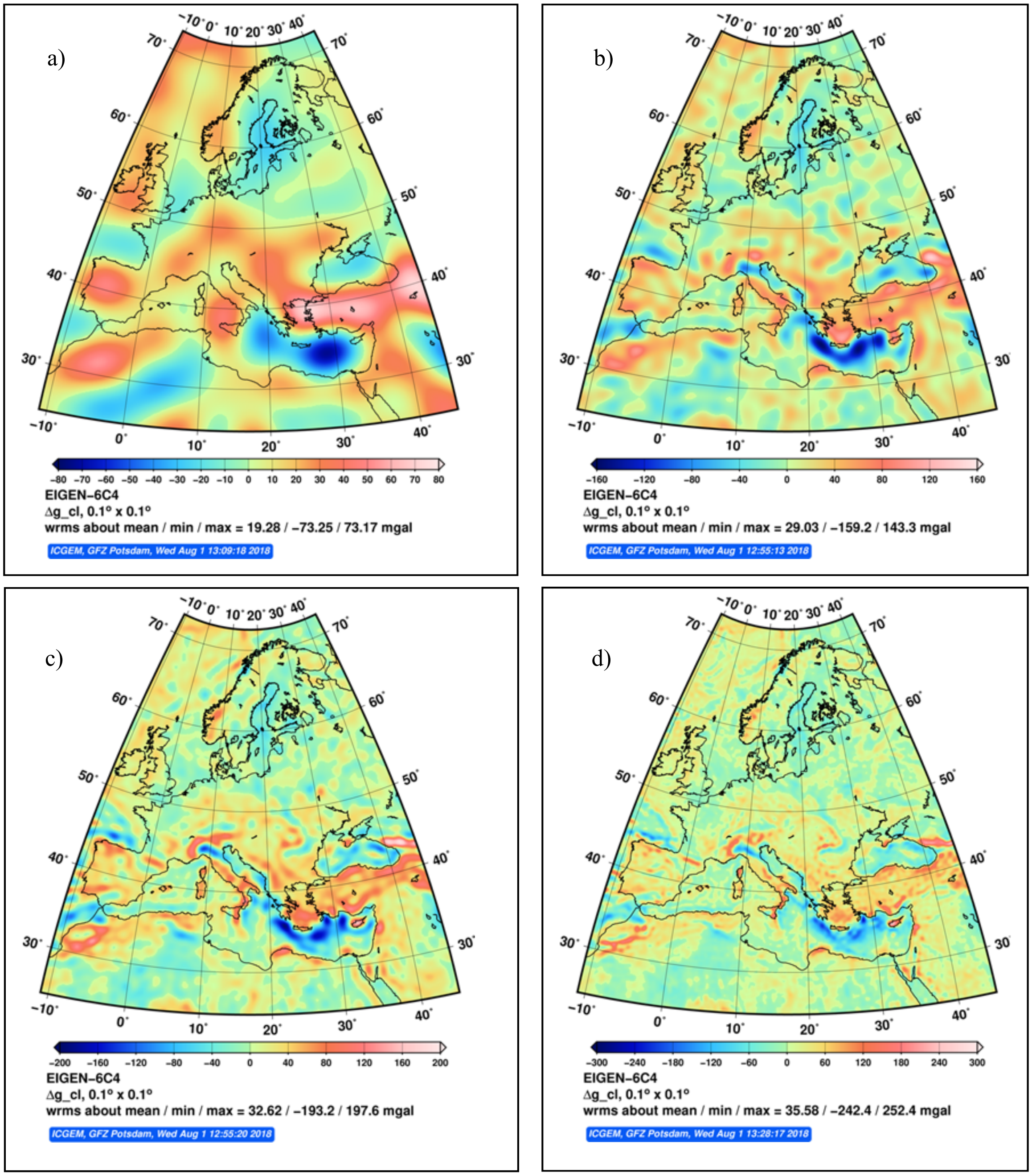


Figure 8: Geographical distribution of gravity anomalies in mGal with different spectral (l_{max}) and spatial resolution (half wavelength $\lambda_{min}/2$) of EIGEN-6C4. Spherical harmonic degree expansions for the four examples are as follows: a) 50 b) 150 c) 250 d) 500 which correspond to 400, ~133, 80 and 40 km half wavelength spatial resolution, respectively. See the refined features and better spatial localisation as the model expansion increases. For instance, topographical features such as mountains are well resolved in Figure ~~9d~~8d, whereas they are not precisely located in Figure ~~9a~~8a. The transmission borders of higher and lower anomalies in Alps and Mediterranean Sea are better resolved in Figure ~~9d~~8d, whereas it is not possible to distinguish and locate them precisely in Figure ~~9a~~8a. Note the different colour scales which have not been changed and kept as retrieved from ICGEM.

2.2.2 Temporal global gravity field models

Using the models derived from input data of dedicated time periods, it is possible to monitor the temporal changes in the gravity field. The spatial coverage of the shorter period observations is not as dense as ~~in the~~for longer periods. Therefore, the spatial resolution of temporal gravity field models ~~-~~(~ 300 km for monthly solutions) is lower than those of the static gravity field models (~ 9km). However, on the contrary to the static gravity field models, a mean over a short time provides a higher resolution in the time domain (e.g. 10 days, 1 month).

Both, the GRACE and now GRACE-FO missions are fundamental in observing the variation of the global gravity field. There are three official data analysing centres for GRACE and GRACE-FO data, namely GFZ, JPL (Jet Propulsion Laboratory) and UTCSR (University of Texas Center for Space Research), which calculate temporal global gravity field models within the missions Science Data System. Even though the software packages of the three analysis centres are independent; they use the same Level 1 data (raw measurements from the satellite that are converted into engineering units, Level 1A) and edited and down-converted data (Level-1B) as input, nearly identical processing standards and background models to generate the GRACE/GRACE-FO Level 2 products (e.g. spherical harmonic coefficients for monthly periods). Same processing standards (Bettadpur 2012, Dahle, 2012; and Watkins and Yuan, 2014) mean common properties of the data processing (e.g. removing solid Earth tides or non-tidal atmospheric and oceanic effects from measurements). After the well-known effects of other geophysical phenomena (e.g. air pressure, tides) are removed, the residuals are mainly expected to represent the water mass redistributions over a certain time period and/or ~~or~~ geophysical signals of the solid Earth such as the mass distributions due to big earthquakes or GIA effect. However, mathematical methods including instrument parameterisations applied in designing measurement equations or Level-1B data editing and weighting vary among the three centres and this results in slightly different model coefficients. For the visualisation of the GFZ Level-2 solutions and access to use-ready gridded Level-3 data, the reader is referred to the Gravity Information Service (GravIS) platform (http://gravis.gfz-potsdam.de/home).

The three data analysing centres release unconstrained solutions which means that no data besides GRACE measurements are applied nor any regularization (sometimes called stabilization) is used in the solution. After the solutions are retrieved, the lower degree (C_{20}) component of the temporal gravity field from GRACE/GRACE-FO is replaced with higher accuracy values derived from the SLR measurements. The disadvantage of these unconstrained models is the fact that the high-degree coefficients have large errors (e.g. from aliasing of tidal and non-tidal mass variations or errors in the satellite-to-satellite tracking) and they are not recommended to be used directly (i.e. without filtering). On the other hand, users are free to develop their own filters or apply the commonly used DDK filters (Kusche et al., 2009), which are also offered in the ICGEM Calculation Service.

Temporal gravity field models developed by different institutions and agencies ~~are summarized in Appendix 3~~can be found in http://icgem.gfz-potsdam.de/series (see also Fig. 3). Even though the initial models are derived based on the monthly coverage of GRACE observations; recently, daily models computed using the state of art techniques are published via the ICGEM Service (Mayer-Gürr et al., 2018). Moreover, combinations of different measurements from different satellites, such as ~~(~~SLR, ~~normal matrices from 9 satellites and position data for~~ CHAMP and GRACE~~)~~ are used to derive monthly solutions (Weigelt et al., 2013) and also included in the ICGEM monthly series database~~ as well~~.

Each temporal gravity model has different characteristics and may help retrieving different information depending on its data content and the application area it is used for. For instance, monthly models are very useful and important in monitoring the variations in the terrestrial hydrological cycle (Schmidt et al., 2006), ice melting (Velicogna, 2009), sea level change (Cazenave et al., 2009) and to help investigating climate change related variations in the Earth system (Wahr et al., 2004), whereas daily solutions have the potential to be used to monitor short term scale variations such as flood events and they contribute assessing natural hazards as proven with the successful outcomes of the EGSIEM project (Gouweleeuw et al., 2018). The results are generally presented in terms of equivalent water height (EWH) or water column (Wahr et al., 1998, Wahr, 2007). Some examples on the temporal gravity field models are shown in Section 3.

2.2.3 Topographic global gravity field models

Topographic global gravity field models are one of the most recent products that are included in the ICGEM Service. They represent the gravitational potential generated by the attraction of the Earth's topographic masses and enrich the possible applications of the geopotential models in geodesy and geophysics (Hirt and Rexer, 2015; Grombein et al., 2016; Hirt et al., 2016; Rexer et al., 2016). Different than the satellite based or combined gravity field models, gravity from these models is computed based on very high resolution digital elevation models which describe the shape of the Earth and model of mass densities inside the topography; therefore, they are not based on real gravity measurements.

This type of models are also called synthetic gravity models or forward models. Topographic masses used in the forward modelling include not only all solid Earth topography (rock, sand, basalts, etc.) but also ocean and lake water and ice sheets. These models can help retrieving very high frequency components of the global gravity field, interpret and validate real gravity measurements and global gravity field models, and help filling the gaps in which the actual gravity measurements are limited or not available, as it is the case in EGM2008 (Pavlis et al., 2012). More importantly, they can be used to subtract the topographical gravity signal from the gravity measurements and model computed gravity data; and make any other gravity signal visible that are related to the inner Earth. Therefore, use of these models is becoming more important in all kind of geophysical applications. An example of topographic model computed gravity anomalies in the Antarctica region together with the EGM2008 ~~disturbances~~ gravity anomalies in the same area are shown in ~~Figure~~ Fig. ~~10.~~9 Note the resolved features in topographic model dV_ELL_Earth2014_plusGRS80 (Rexer et al., 2016) due to the availability of the high-resolution topography data in the area. The typical applications for using these models are given in Table 1 and ~~and~~ a list of currently available topographic gravity field models ~~on the ICGEM website is provided in Appendix 4~~can be found in http://icgem.gfz-potsdam.de/tom_reltopo (see also Fig. 3).

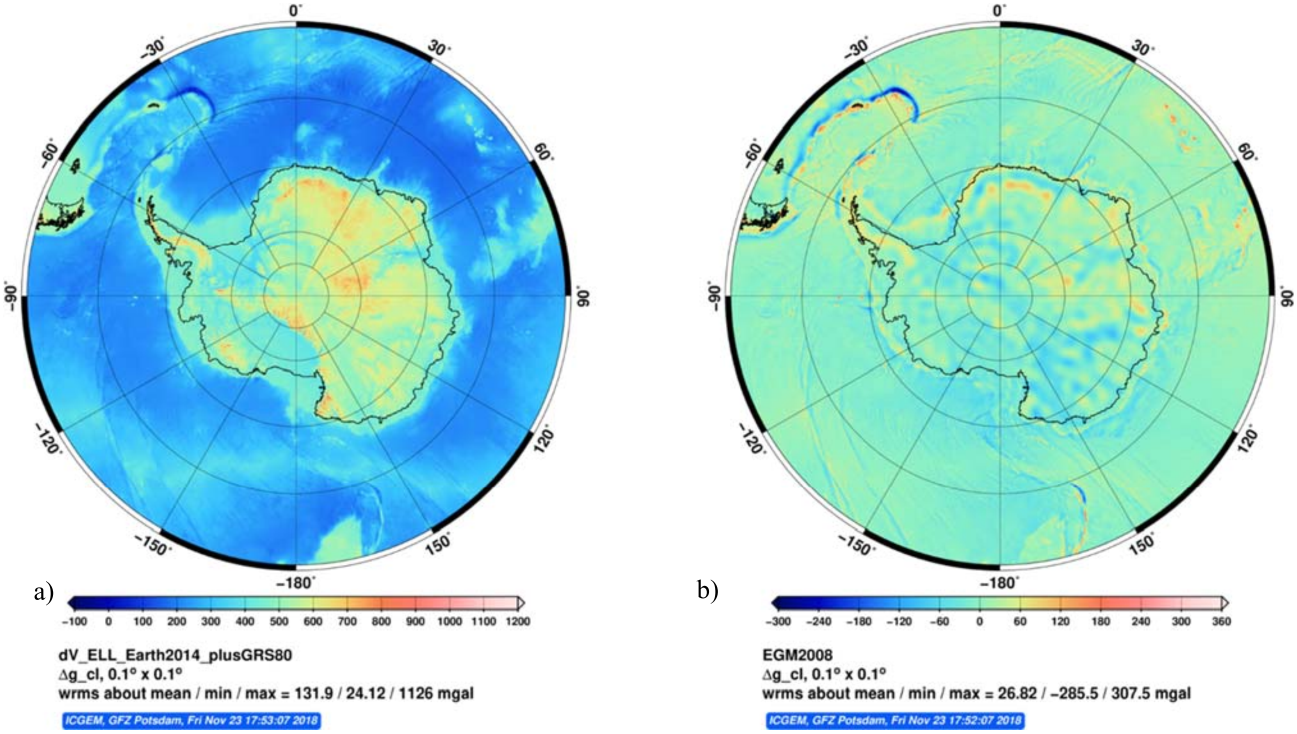


Figure 9: The classical gravity anomalies which are also known as free air gravity anomalies computed on the Earth's surface based on a) topographic model dV_ELL_Earth2014_plusGRS80 and b) EGM2008 using models highest degree/order available, 2190. It is clearly seen that the features in Antarctica are better resolved in a. Note that the scale is ~~left~~ kept as is for individual cases on purpose since the ~~current~~ present forms ~~shape~~ of the figures are what exactly the ICGEM Calculation Service provides.

Table 1: The application areas of the Global Gravity Field Models. Note that the variations refer to the "mass change".

Application of gravity field models		
Static Gravity Field Models	**Temporal Gravity Field Models**	**Topographic Gravity Field Models**
Geodesy • Regional geoid modelling (using remove-compute-restore technique) • Definition of a unified~~que~~ vertical datum and height modernization • Satellite orbit determination	Geodesy • Monitoring the changes in the static gravity field model • Monitoring the changes in the regional geoid model	• Modelling high-resolution gravity field assuming the highest spatial resolution features are mainly produced by topography • Modelling the omission error of the gravity field models • Evaluation of satellite-based gravity field models using external independent data • Reducing terrain and topographic gravity to smooth gravity measurements • Reducing topographic gravity to retrieve gravity signals of other sources • Modelling Bouguer gravity anomaly
Oceanography • Monitoring sea level variation • Reference to sea surface topography • Derivation of geostrophic ocean surface currents	Hydrology • Monitoring inter-annual, seasonal and sub seasonal water mass variations • Monitoring ground water variations • Monitoring ice melting	
Geophysics • Monitoring mass and density distribution~~,~~ • Monitoring isostasy and~~,~~ mantle processes	Atmosphere • Monitoring inter-annual, seasonal variations Geophysics • Monitoring ~~GIA~~Glacial Isostatic Adjustment • Detection of co- and post- seismic mass redistribution	

2.2.4 Models of other celestial bodies

Gravity field models for other celestial bodies, the Moon, Venus and Mars are by-products of the ICGEM Service. They are provided due to the interest of the model developers and users. These models have the same mathematical representation, i.e. expansion of spherical harmonic series, as the static gravity field models of the Earth. Therefore, it is ~~easy~~ convenient to include also these models in the ICGEM calculation and visualisation services.

These models are also developed based on similar observations of the gravity field of the body. For instance, spacecraft to spacecraft tracking observations from the Gravity Recovery and Interior Laboratory (GRAIL) have been used to develop the most detailed ~~a~~ gravitational field of the Moon so far (Zuber et al., 2013).

3 Services of ICGEM

3.1 Calculation Service

By the time that the ICGEM Service was established, it was naturally installed together with the calculation and visualisation services. Due to the interest of scientists and students worldwide, the ICGEM team ~~have~~ has developed a web interface to calculate gravity field functionals (e.g. geoid undulation, height anomaly, gravity anomaly) from the spherical harmonic representations of the Earth's global gravity field on freely selectable grids with respect to a reference system of user's preference. This service is the only online service worldwide available that computes variety of gravity field functionals with the GMT plots (Wessel et al., 2013) provided for grid values and the option to download the computed values. During the 15 years, interested researchers and students have used the ICGEM service extensively for calculating gridded gravity field functionals (see ~~Figure~~ Fig. ~~11~~10). Calculated results are not only provided in ASCII format but also visualised using the Generic Mapping Tools (GMT) software (Wessel and Smith, 1998; Wessel et al., 2013) with the basic statistics provided. An example can be found in Fig. 11.

Starting from December 2018, the ICGEM Service introduced the calculation of gravity field functionals also at the user defined list of points which was a request from the users. The list of the particular points can be prepared by the user in one of the allowed formats and the calculations are performed directly at those particular points. Different heights for different points can be introduced in the point calculation which is different to the grid calculation where the height is assumed same for all the grid points and consequently delivers results faster. For the point calculations, after the user uploads the text file of the set of data points in a predefined format (see Fig. 12), the points are displayed on the map. The example in Fig. 12 shows the GNSS/levelling benchmark points in Europe which also are used in the geoid comparisons in the model evaluations.

~~The point calculation service was developed based on the request from the users as well. he list of the functionals has also been expanded during the years based on requests and t heir descriptions are given in Table 2. The equations referred in Table 2 are given in Barthelmes, 2013 in detail. Calculated results are not only provided in ASCII format but also visualised using the Generic Mapping Tools (GMT) software (Wessel and Smith, 1998; Wessel et al., 2013) with the basic statistics provided. An example can be found in Figure 12.~~

~~For the point calculations, after the user uploads the text file of the set of data points in a predefined format, the points are displayed on the map. The example in Figure 13 shows the GNSS/levelling benchmark points in Europe which also are used in the geoid comparisons in the model evaluations.~~

Some of the gravity field functionals are calculated based on a particular reference system in 3D while some others depend on 2D position only. During the years, the list of the functionals has also been expanded based on requests. For the 3D functionals, the ICGEM calculation service provides different options for the reference system such as the commonly used ones as WGS84 (World Geodetic System 1984) and GRS80 (Geodetic Reference System 1980). In addition, it provides users the option to define their own reference system by providing the radius (semi-major axis), GM, flattening ratio (f), and angular velocity of the rotation (ω). Considering the researchers working on different regions of the world based on different normal ellipsoid reference systems, this feature is very helpful and eliminates the time the user needs for the transformation between the reference systems. The descriptions of the gravity field functionals computed via the Calculation Service are given in Table 2 and the equations referred are given in Barthelmes, 2013 in detail.

Another component in the calculation of the gravity field functionals is the systematic effect that is due to the reference tide system regarding the flattening of the Earth. These are important for the definition of the geoid. Three different tide systems, namely tide-free, zero-tide and mean-tide systems (Lemoine et al., 1998), can be selected via the given options on the calculation page. It is worth reminding that in the:

- *Tide-free system,* the direct and indirect effects of the Sun and the Moon are removed.
- *Zero-tide system,* the permanent direct effects of the Sun and Moon are removed but the indirect effect related to the elastic deformation of the Earth is retained.
- *Mean-tide system,* no permanent tide effect is removed.

Geoidal surface is generally given in terms of geoid undulations or geoid heights with respect to a reference system. The reference system consists of a best approximating geometric rotational ellipsoid (normal ellipsoid) and an associated best approximating ellipsoidal normal potential U. ~~Moreover, t~~ The normal potential is defined in such a way that its value on the normal ellipsoid is $U =$ constant $= U_0$ and approximates the real value W_0 as good as it is known (at the time when this reference system is defined). Hence, the reference system also defines the value $W_0 = U_0$. It is worth noting that an improvement of the numerical estimation of W_0 value is still under discussion and requires up to date information of small changes of gravity field potential (e.g. due to sea level rise).

Following up the above discussion, zero degree term arises when W_0 is chosen/calculated different than U_0 and/or when GM values between the geopotential model and reference ellipsoid are different. Therefore, this term needs to be taken into account to calculate the geoid undulation correctly with respect to a known reference ellipsoidal surface (see also questions 16, 17 and 18 in http://icgem.gfz-potsdam.de/icgem_faq.pdf).

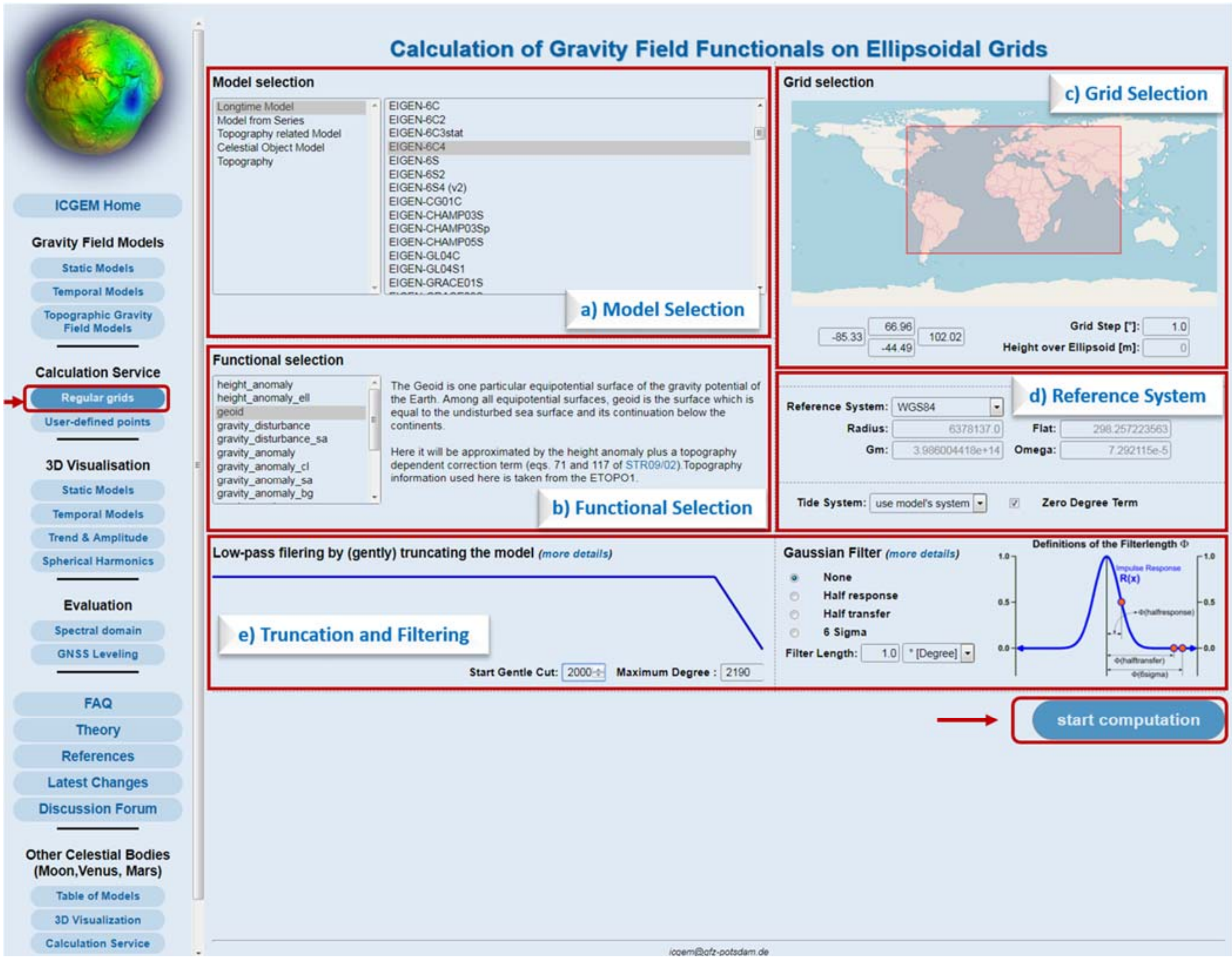


Figure 10: Snapshot of the C~~c~~alculation S~~s~~ervice interface. The calculation settings allow the user to choose (a) the model of preference from the list of global gravity field models, (b~~a~~)~~,~~ the functional of interest with a short definition provided and link to the equations detailed in the technical report, (c~~b~~)~~,~~ the boundaries of the area and the grid interval, (d~~c~~)~~,~~ reference and tide system, and (e~~d~~)~~, and~~ truncation degree and filtering ~~(e)~~ before starting the computation. The grid area can also be selected using the red rectangle in (c) by simply changing its ~~borders~~ boundaries or entering the coordinates manually. Moreover, grid interval can be entered in terms of degrees.

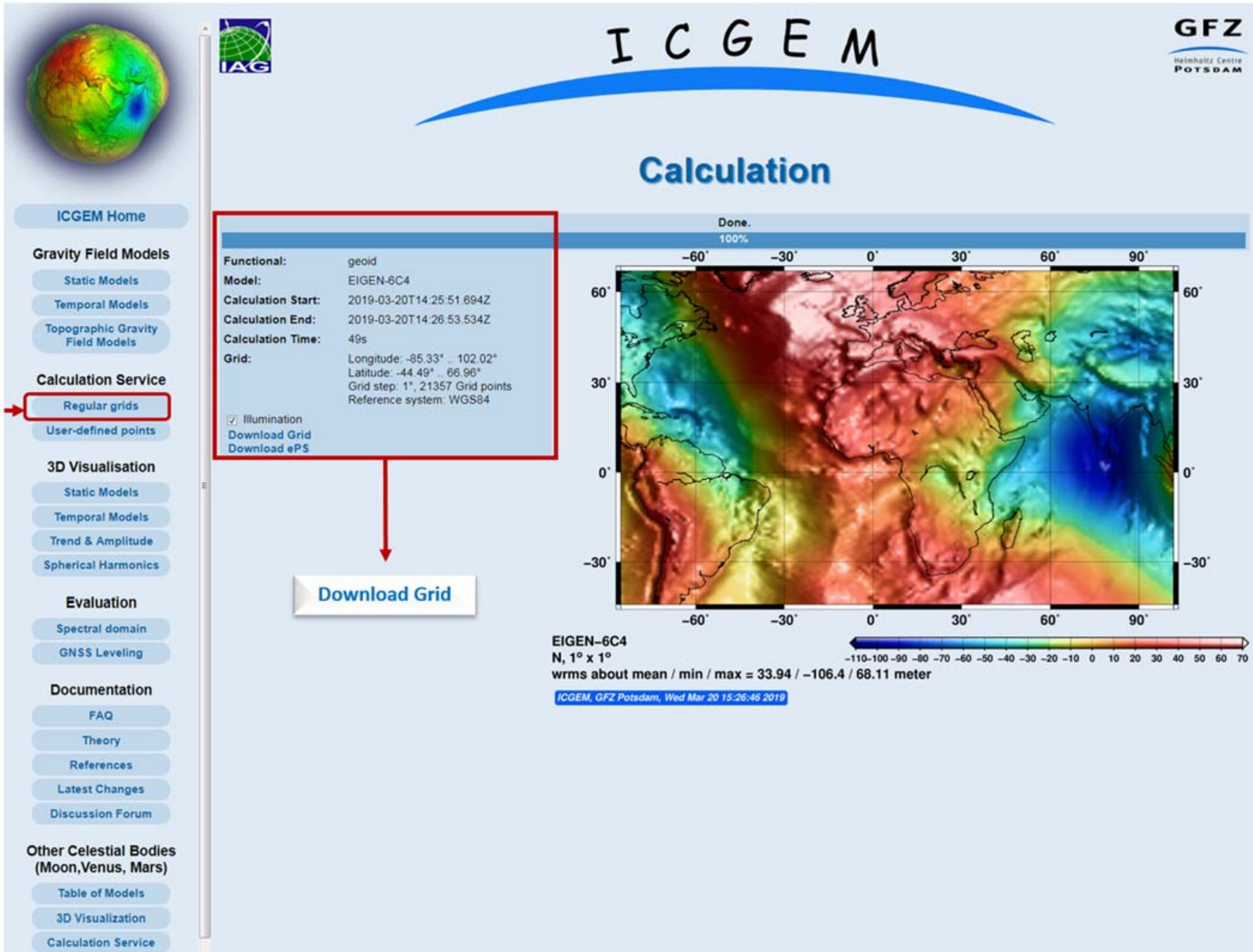


Figure 11: Snapshot of C~~c~~alculation S~~s~~ervice interface with the results from the input settings entered in Fig. 10, provided in numerical and map view. The figure and grid values can be downloaded from the same page and the figure can be illuminated for better visibility of the features.

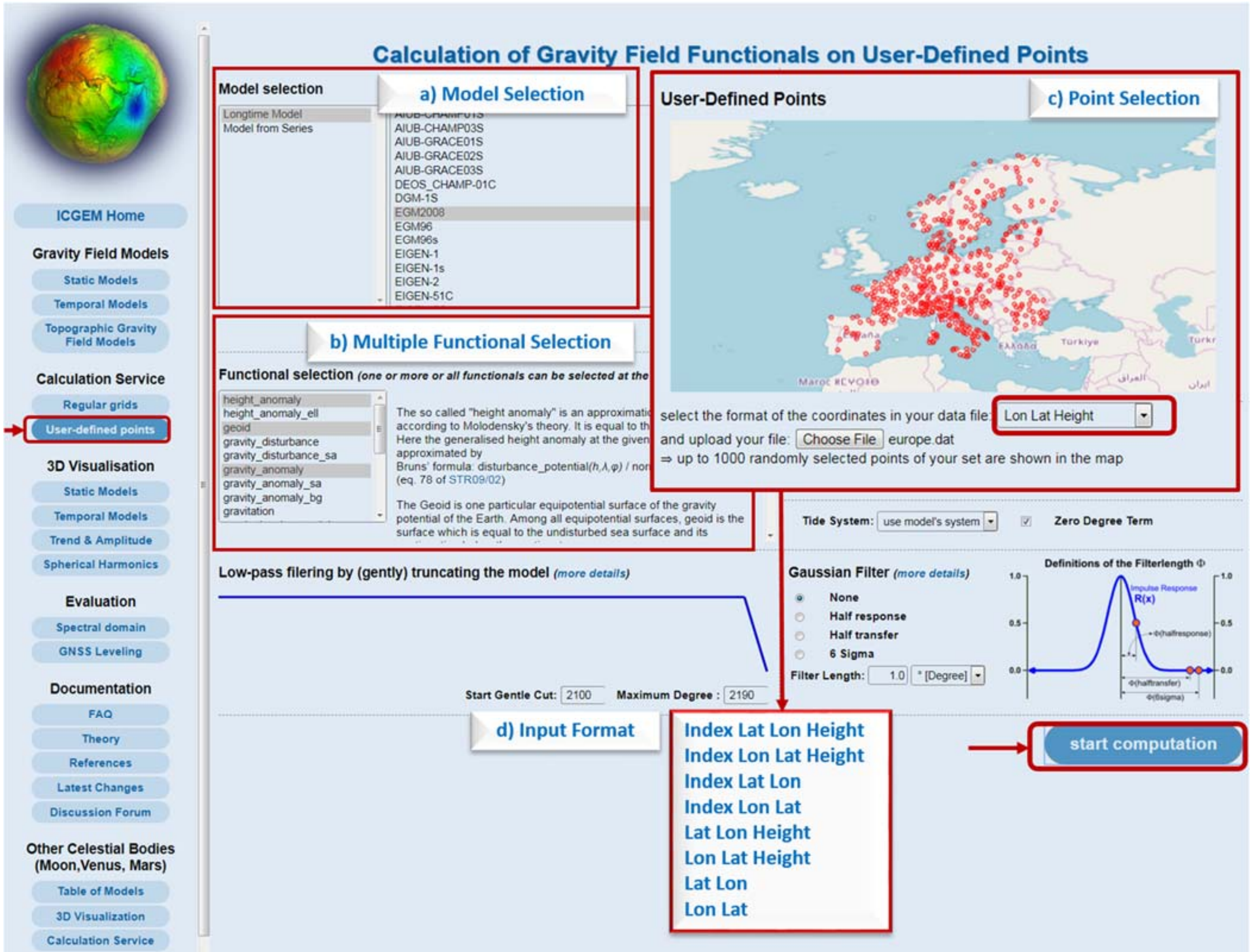


Figure 12: Snapshot of the point value C~~c~~alculation S~~s~~ervice on ICGEM, (a) the model selection, (b) functional selection (choosing multiple functionals or all is possible), (c) input file selection and mapping the location of user-defined points, and (d) input file format as .txt file. The example shows the GNSS/levelling benchmark points in Europe that are used also in the ICGEM static model evaluation. ~~The user can choose one, multiple or all the functionals at the same time to compute at those points.~~

Table 2: The list of gravity field functionals available on the calculation service for grid and point calculations. The detailed description and definitions of the gravity field functionals are given in detail in Barthelmes (2013). The equation numbers (eqs.) refer to the same document.

Gravity field functional	**Definition** **See also Barthelmes, F., (2013).**	**Static model**	**Temporal model**	**Top. model**	**Celestial model**
height_anomaly	It is an approximation to geoid height according to Molodensky's theory, defined on the Earth's surface (eqs. 81 and 119) where the height (elevation) used in the calculation is taken from etopo1m ~~automatically~~.	x	x	x	-
height_anomaly_ell	It is the generalized pseudo height anomaly which is defined on the ellipsoid; therefore, the h value used in the calculation is set to zero.	x	x	x	x
geoid	It is a particular equipotential surface of the gravity potential of the Earth that ~~, which~~ is equal to the undisturbed sea surface and its continuation below the continents. Here it is approximated by the height anomaly plus a topography dependent correction term (eqs. 71, 117).	x	x	x	-
gravity_disturbance	~~The gravity~~ It is ~~disturbance is~~ defined as the magnitude of the gradient of the potential at a given point on the Earth's surface minus the magnitude of the gradient of the normal ~~—~~potential at the same point ~~.~~ (eqs. 87, 121 − 124).	x	x	x	-
gravity_disturbance_sa	It is calculated by spherical approximation on h=0 or above at an arbitrary height over the ellipsoid, h>0.	x	x	x	x
gravity_anomaly	~~The gravity anomaly~~It is defined (according to Molodensky's theory) ~~is defined~~ as the magnitude of the gradient of the potential on the Earth's surface minus the magnitude of the gradient of the normal potential on the Telluroid (eqs. 101 and 121 − 124).	x	x	x	-
gravity_anomaly_cl	The classical gravity anomaly is defined as the magnitude of the gradient of the downward continued potential on the geoid minus the magnitude of the gradient of the normal potential on the ellipsoid (eqs. 93, 121 − 124). This type of gravity anomalies are also known as free-air gravity anomaly.	x	x	x	-
gravity_anomaly_sa	The gravity anomaly calculated by spherical approximation (eqs. 100 or 104, 126). Unlike the classical gravity anomaly, the Molodensky gravity anomaly and the spherical approximation can be generalised to 3D space, hence here it can be calculated on h=0 or above the ellipsoid, h>0.	x	x	-	-
gravity_anomaly_bg	The (simple) Bouguer gravity anomaly is defined by the classical gravity anomaly minus the attraction of the Bouguer plate. Here it is calculated by the spherical approximation of the classical gravity anomaly minus $2\pi G\rho H$ (eqs. 107, 126). The topographic heights $H(\lambda,\varphi)$ are calculated from the spherical harmonic model of etopo1m up to the same maximum degree as the gravity field model. For $H \geq 0$ (rock) $\rightarrow \rho = 2670$ kg/m3, and for $H<0$(water) $\rightarrow \rho=(2670-1025)$ kg/m3 is used. The density contrast between ice and rock is not been taken into account.	x	x	-	-
gravity_earth	The gravity is defined as the magnitude of the gradient of the potential (including the centrifugal potential) at a given point. Here it will be calculated on the Earth's surface (eqs. 7, 121 − 124).	x	x	x	-
gravity_ell	The magnitude of the gradient of the potential (including the centrifugal potential) calculated on/above the ellipsoid ~~including the centrifugal potential~~ (eqs. 7, 121−124).	x	x	x	-
potential_ell	The potential of the gravity field of the Earth without the centrifugal potential (gravitational field). Here it can be calculated on/above the ellipsoid (eq. 108).	x	x	x	x
gravitation_ell	The magnitude of the gradient of the potential calculated on or above the ellipsoid without the centrifugal potential (eqs. 7, 122).	x	x	x	x
second_r_derivative (vertical gravity gradient)	The second derivative of the disturbance potential in radial direction calculated on/above the ellipsoid.	x	x	x	x
water_column	The variable thickness of a fictitious water layer which is distributed over the reference ellipsoid and produce the disturbance potential or the geoid undulations. ~~For calculating~~To calculate "water_column" from a gravity field model, Earth's ~~the~~ elastic deformation ~~of the Earth~~ due to the load of the water layer is considered.	x	x	-	-
vertical_deflection_abs	~~This is the m~~Magnitude of the deflection of the vertical. It is the angle between the vector of gravity and the vector of normal gravity both at the	x	x	-	-

	same point (h,λ,φ).				
vertical_deflection_ew	~~This is the east-west component of the deflection of the vertical.~~ It is the east-west component of the angle between the vector of gravity and the vector of normal gravity both at the same point (h,λ,φ).	x	x	-	-
vertical_deflection_ns	~~This is the north-south component of the deflection of the vertical.~~ It is the north-south component of the angle between the vector of gravity and the vector of normal gravity both at the same point (h,λ,φ).	x	x	-	-

3.2 3D Visualisation Service

An online interactive V~~v~~isualisation S~~s~~ervice of the static gravity field models (geoid undulations and gravity anomalies), temporal models (geoid undulation and equivalent water column), trend and annual amplitude of GRACE gravity time variations, and spherical harmonics as illuminated projection on a freely rotatable sphere are available on the ICGEM Service. The V~~v~~isualisation S~~s~~ervice was established to provide the users ~~and researchers~~ a sophisticated visual representation of the gravity field related products and it was the first of its kind at the time it was available to the general public with its well-known name "Potsdam Gravity Potato". It has become a service which is very useful for quick look analyses of the functionals globally and also for tutorial purposes of different educational levels (http://icgem.gfz-potsdam.de/vis3d/longtime). Users of this service can select the functional, the model, the grid interval and the spherical harmonic degree expansion of the model to see the results on the 3D visualisation. Moreover, rotation tool can be used to locate different regions of the globe and the selected image can be exported via the export tool. An example of geoid undulation and gravity anomalies is shown in Fig. ~~14~~13.

Static model visualis~~z~~ation enables also the demonstration of the differences between two models with a selected grid interval and spherical harmonic degree expansion. Zooming in and out functions are available which makes this tool very useful for also advanced users to ~~quickly~~ investigate particular regions of interest based on different models~~ quickly~~. Using the 3D visualisation service, as an example, the substantial differences between the new experimental geopotential model XGM2016 of the upcoming Earth Gravitational Model 2020 (EGM2020) and the older EGM2008 model are displayed for Antarctica and Himalaya regions (Fig. ~~15~~14). As shown in Fig. ~~15a~~14~~a~~, the differences are mostly due to the 'terrestrial' update in Antarctica which are due to the updates of the 'non-data' or 'synthetic' values used in the EGM2008. Similar differences are also shown for the Himalaya regions in Fig. 15b.

3D Visualisation of temporal gravity field models displays computation of geoid undulation and equivalent water height (EWH) from different daily and monthly series with an option of using ~~un~~filtered or unfiltered model coefficients. The visualisation tool can also be used for animation purposes for different monthly series~~,~~, January 2009 and May 2009, filtered using DDK1 filter are displayed in Fig. ~~16a~~ 15a and ~~16b~~15b. The differences between the two figures represent the mass changes. The visualisation of the trend and annual amplitude of GRACE measurements that are collected between 2002 and 2015 are also available as shown in Fig. ~~16c~~ 15c and Fig. ~~16d~~15d, respectively. Clearly visible in these representations is the ice melting trend over Greenland, Glacial Isostatic Adjustment (GIA) effect in Alaska and Hudson Bay area, and the annual mass variation in the Amazon region which have been some of the priority research topics during the last few years.

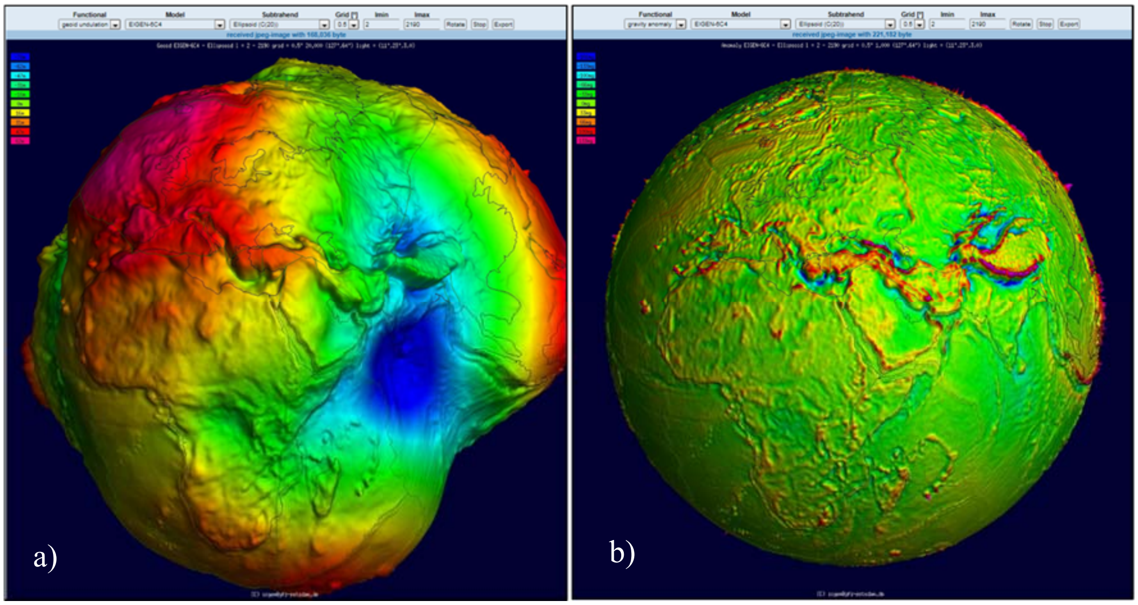


Figure 13: Examples of V~~v~~isualisation S~~s~~ervice for a) geoid undulation and b) gravity anomaly computed from a high resolution combined static gravity field model.

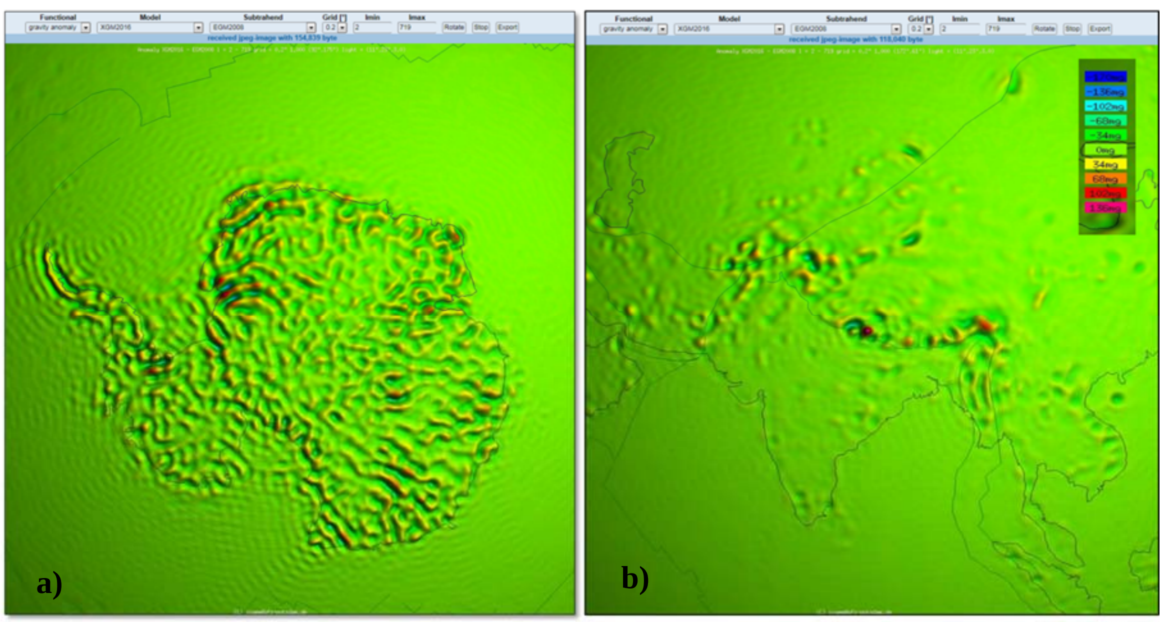


Figure 14: Examples of V~~v~~isualisation S~~s~~ervice for the gravity anomaly differences computed from XGM2016 and EGM2018 up to degree and order 719 for the a) Antarctica and b) Himalaya regions. The EGM2008 relied exclusively on ITG-Grace03s (Mayer-

Gürr, 2007) expanded up to d/o 120 to fill Antarctica with synthetic values; whereas, in XGM2016 (Pail et al., 2018), these synthetic values were derived from GOCO05s (Mayer-Gürr et al., 2015) and from forward modelling of ice and rock thicknesses from the Earth2014 Digital Terrain Model (Hirt and Rexer, 2015).

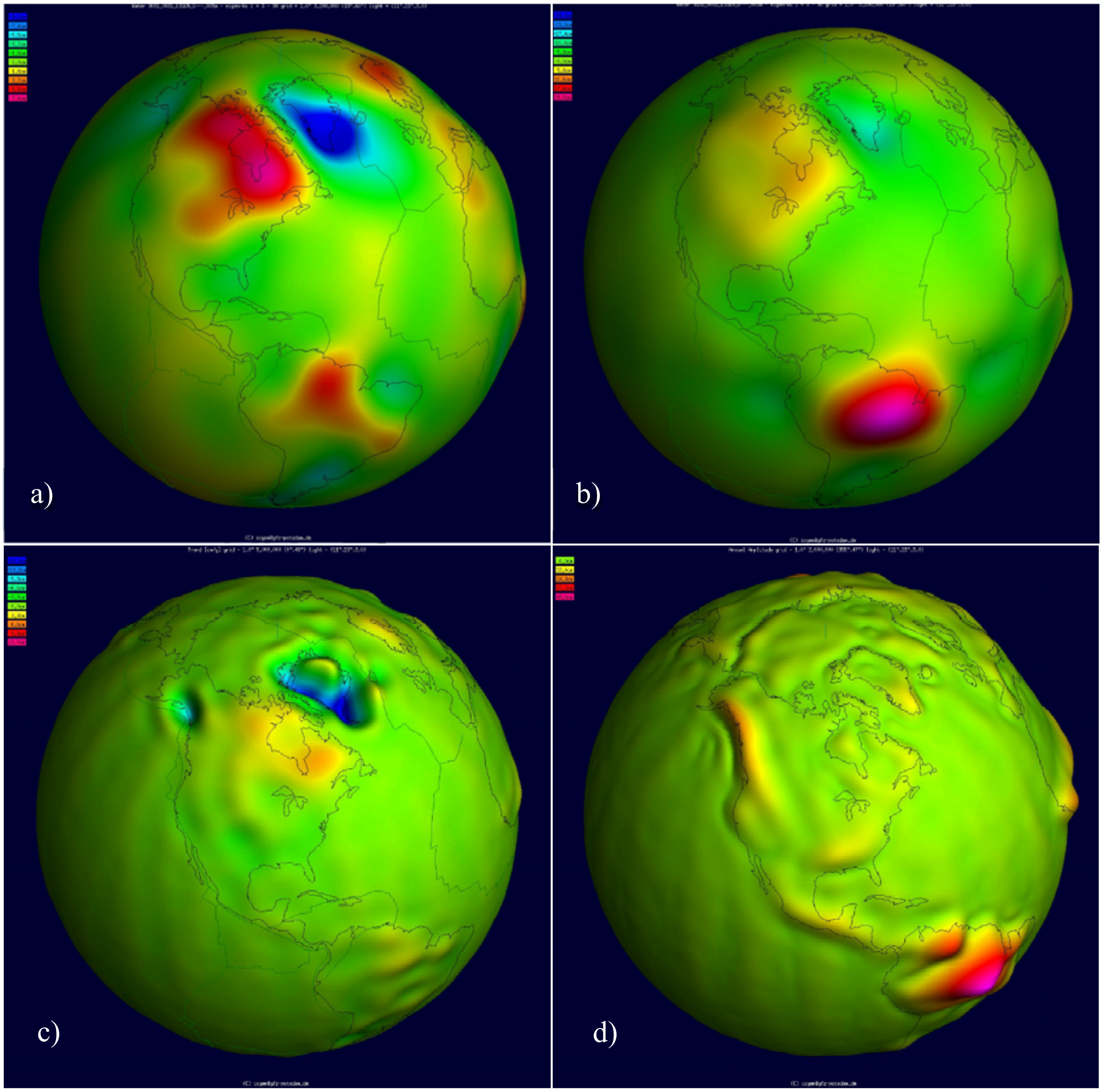


Figure 15: Snapshot of V~~v~~isualisation S~~s~~ervice for temporal models a) EWH in January 2009 b) EWH in May 2009, note that the EWH difference between the two months represents the mass ~~distributions~~change, c) trend, note the strong effect due to the GIA in Hudson Bay area, Canada and Alaska and ice melting in Greenland d) annual amplitude, where the large signal amplitude in the Amazon region is noticeable.

3.3 Evaluation of global gravity field models

With its additional evaluation service, ICGEM goes beyond the collection and distribution of the gravity field models. Before being published as part of the ICGEM Service, each new global model is investigated to ensure that its content is worthy to be published in the service. There are two techniques covered in the ICGEM evaluation procedure: 1) comparisons w.r.t. other (already identified as reliable) global models in the spectral domain using signal degree amplitudes 2) comparison of the model calculated geoid undulations w.r.t. set of GNSS/levelling derived geoid undulations for different regions of the Earth.

3.3.1 Model evaluation with respect to other models in the spectral domain

One of the most commonly used techniques in the assessment of global gravity field models is the cumulatively looking at the signal and noise amplitudes per degree and signal and noise amplitudes. The signal can be computed using the spherical harmonic coefficients whereas the noise can be computed using the associated errors. In the ICGEM evaluation procedure, we use the signal degree amplitudes, σ_l of functional of the disturbing potential $T(r,\varphi,\lambda)$ at the Earth's surface but not the error degree amplitude, since not all of the models include the same type of error. Some of the models include formal errors whereas the other ones include calibrated errors. The signal degree amplitudes of the models can be computed by:

$$\sigma_l = \sqrt{\sum_{m=0}^{l}\left(\bar{C}'^{\,2}_{lm} + \bar{S}'^{\,2}_{lm}\right)}, \qquad \textbf{Eq. (7)}$$

in terms of unit less coefficients. The outcomes refer to the internal accuracy of the global model in terms of geoid height, gravity anomaly or other functionals. The error degree variance can also be computed using the spherical harmonics associated error coefficients using the same formula (Eq. 7). The outcomes of this analysis do not necessarily represent the model characteristics or signal to noise ratio of a particular area or a region but represent the model characteristics globally. In our comparisons, we particularly use geoid heights signal amplitudes per degree which can be computed via:

$$\sigma_l(N) = R\sigma_l, \qquad \text{Eq. (8)}$$

in terms of meter. An example of the comparison of two recent static global gravity field models, satellite only model GOCO05S (Mayer- Gürr et al., 2015) and combined model EIGEN-6C4 (Förste et al., 2014), is shown in Fig. 16.

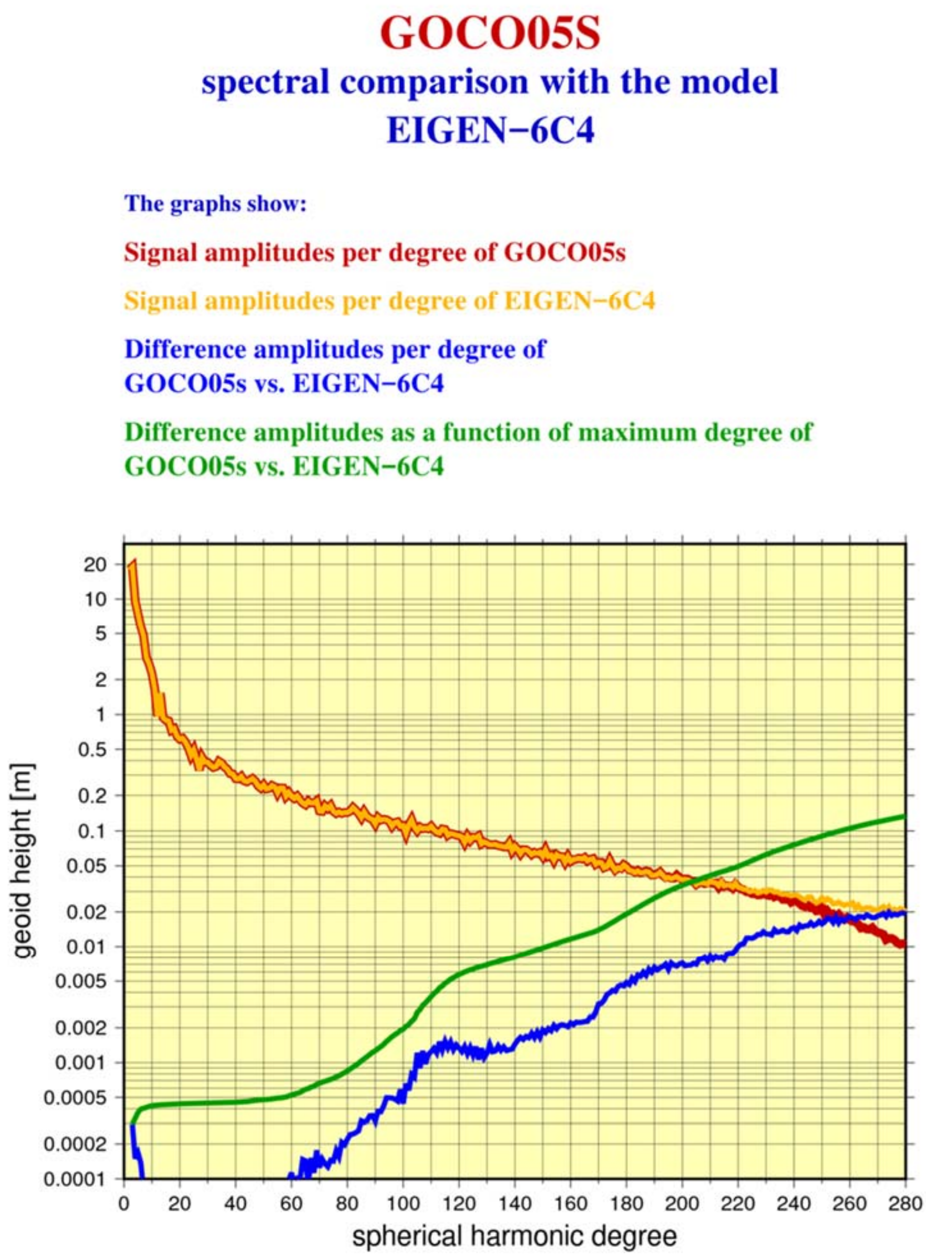


Figure 16: Spectral comparison of two static global gravity field models, GOCO05S and EIGEN-6C4. Note that the comparisons are performed for each degree separately. GOCO05S is a satellite only model, whereas the EIGEN6C4 is a combined model that uses both the satellite and terrestrial measurements. The blue curve represents the difference in the amplitude of the GOCO05S and EIGEN-6C4 combined static gravity field models per degree, whereas the green line represents the cumulative difference amplitudes ~~as a function of the maximum degree~~ of the two models as a function of maximum degree. See the increasing difference as the degree increases due to the contribution of the terrestrial gravity data to EIGEN-6C4.

3.3.2 Model evaluation with respect to GNSS/levelling derived geoid undulations

Another way of assessing a global gravity field model is to compare the model outputs with respect to independent external sources. For instance, it is very common to compare the model computed geoid undulations with GNSS/levelling derived geoid undulations (Gruber T., 2009; Gruber et al, 2011; Huang and Veronnaeu, 2015; Ince et al., 2012; Kotsakis et al, 2009). Traditionally, geoid undulations have been derived from the ellipsoidal and orthometric heights that are measured using GNSS sensors and via levelling which is limited to the levelling benchmark points. This kind of evaluation is also valid for other gravity field functionals, such as gravity anomalies or deflections of vertical where the model computed values are compared with the terrestrial measurements. The advantage of this method is that it is suitable to assess the model outcomes in a regional level or at a particular area but the assessments are only as good as the quality of the external datasets used in the validation. ICGEM has collected some series of GNSS/levelling datasets from different countries. These countries are Australia, Brazil, Canada, Japan and the USA. Moreover, a series of data points from Europe is also included in the comparisons. More information on the GNSS/levelling data points provided in Table 3.

In contrast to the global gravity field models, these data are not freely available. Their availability is limited to the legal restrictions or the observers' own interest. Due to the relevance of these external data sets for the model evaluation, ICGEM will address this issue and develop strategies in improving the availability of these data for the general public and for the benefit of the global community.

In general, the GNSS/levelling measurements are collected over decades. Besides the epoch differences among the measurements, different GNSS or GPS equipment are used and different length of observations, and observing procedures are followed which cause the estimation accuracy of the ellipsoidal heights (h) to vary. The GNSS/levelling derived geoid undulations can be computed via

$$N = h - H \,, \qquad \textbf{Eq. (9)}$$

which are erroneous. These errors are not taken into account in our assessments and obviously the comparison results will only be as good as the quality of both resources, global gravity field model and GNSS/levelling derived geoid undulations. ~~Moreover, to perform realistic and informative comparisons, one needs to consider the omission error that is caused by the truncation of the global solutions. To ensure fair comparisons~~In principle, this evaluation is much more sophisticated than what is currently covered by the ICGEM Service (Gruber, T. 2009; Gruber et al., 2011, Ince et al., 2011). T~~t~~he GNSS/levelling derived geoid undulations should also be reduced to the same spectral content of the gravimetric geoids, which is ~~also~~ not taken into account in our quick check assessments since the ~~purpose of this service~~aim of this procedure is to provide relative comparisons among the models w.r.t. the same set of GNSS/levelling data. Comparison results are given in the evaluation section of the service and results for the recent models are shown in Fig.~~ure~~ 17~~8~~. Interested scientists are invited to share their GNSS/levelling datasets with ICGEM to improve and extend the evaluation procedure.

Table 3: Information on the GNSS/levelling benchmark points ICGEM collected during the years and corresponding authors/institutions.

	Australia	Brazil	Canada	Europe	Japan	USA
# of points	201	1112	2691	1047	816	6169
Corresponding author	G. Johnston	D. Blitzkow, A. Cristina, O. Cancoro de Matos	M. Veronneau, February 2003	Ihde et al., 2002	Tokuro Kodama,	Milbert, 1998
Corresponding Institution	Geoscience Australia	CENEGEO, the data belongs to the LTG/USP and the (IBGE)	NRCan		Geospatial Information Authority of Japan	

CENEGEO: Centro de Estudos de Geodesia; IBGE: Brazilian Institute of Geography and Statistics; LTG/ USP: Laboratory of Topography and Geodesy/University of Sao Paulo; NRCan: Natural Resources Canada

The table is interactively re-sortable for all columns by clicking in the header cells.

Nr	Model	Nmax	Australia (201 points)	Brazil (1112 points)	Canada (2691 points)	Europe (1047 points)	Japan (816 points)	USA (6169 points)	All (12036 points)
168	**Tongji-Grace02k**	180	0.432 m	0.592 m	0.475 m	0.587 m	0.661 m	0.525 m	0.5357 m
167	**SGG-UGM-1**	2,159	0.217 m	0.446 m	0.13 m	0.121 m	0.076 m	0.245 m	0.2353 m
166	**GOSG01S**	220	0.359 m	0.518 m	0.373 m	0.426 m	0.526 m	0.442 m	0.4392 m
165	**IGGT_R1**	240	0.317 m	0.513 m	0.348 m	0.387 m	0.483 m	0.412 m	0.4111 m
164	**IfE_GOCE05s**	250	0.337 m	0.512 m	0.329 m	0.385 m	0.48 m	0.414 m	0.4081 m
163	**GO_CONS_GCF_2_SPW_R5**	330	0.33 m	0.511 m	0.299 m	0.346 m	0.442 m	0.396 m	0.3873 m
162	**GAO2012**	360	0.293 m	0.531 m	0.309 m	0.453 m	0.759 m	0.366 m	0.4177 m
161	**XGM2016**	719	0.218 m	0.44 m	0.151 m	0.14 m	0.125 m	0.263 m	0.2489 m
160	**Tongji-Grace02s**	180	0.452 m	0.605 m	0.478 m	0.596 m	0.669 m	0.53 m	0.5417 m
159	**NULP-02s**	250	0.351 m	0.512 m	0.375 m	0.413 m	0.508 m	0.427 m	0.4284 m
158	**HUST-Grace2016s**	160	0.489 m	0.658 m	0.594 m	0.69 m	0.837 m	0.596 m	0.6273 m
157	**ITU_GRACE16**	180	1.778 m	6.645 m	1.591 m	1.307 m	0.976 m	2.741 m	2.9603 m
157	**ITU_GRACE16 (upto130)**	130	0.515 m	0.747 m	0.676 m	0.871 m	1.093 m	0.692 m	0.7419 m
156	**ITU_GGC16**	280	0.335 m	0.505 m	0.31 m	0.343 m	0.45 m	0.398 m	0.39 m
155	**EIGEN-6S4 (v2)**	300	0.327 m	0.507 m	0.298 m	0.345 m	0.447 m	0.405 m	0.3915 m
154	**GOCO05c**	720	0.221 m	0.445 m	0.154 m	0.138 m	0.217 m	0.262 m	0.2541 m
153	**GGM05C**	360	0.239 m	0.461 m	0.213 m	0.225 m	0.282 m	0.321 m	0.3055 m
152	**GECO**	2,190	0.216 m	0.451 m	0.131 m	0.123 m	0.08 m	0.246 m	0.2371 m
151	**GGM05G (upto210)**	210	0.357 m	0.521 m	0.374 m	0.454 m	0.543 m	0.448 m	0.4461 m
151	**GGM05G**	240	0.326 m	0.502 m	0.342 m	0.384 m	0.487 m	0.407 m	0.4065 m
150	**GOCO05s**	280	0.335 m	0.505 m	0.308 m	0.344 m	0.45 m	0.399 m	0.3904 m
149	**GO_CONS_GCF_2_SPW_R4**	280	0.322 m	0.508 m	0.33 m	0.375 m	0.473 m	0.406 m	0.4023 m
148	**EIGEN-6C4**	2,190	0.212 m	0.446 m	0.126 m	0.121 m	0.079 m	0.247 m	0.2361 m
147	**ITSG-Grace2014s**	200	1.175 m	1.273 m	0.871 m	0.962 m	0.932 m	1.095 m	1.0468 m
146	**ITSG-Grace2014k**	200	0.433 m	0.611 m	0.419 m	0.582 m	0.651 m	0.542 m	0.5347 m
145	**GO_CONS_GCF_2_TIM_R5**	280	0.336 m	0.505 m	0.31 m	0.343 m	0.45 m	0.398 m	0.39 m
144	**GO_CONS_GCF_2_DIR_R5**	300	0.327 m	0.507 m	0.299 m	0.345 m	0.447 m	0.405 m	0.3915 m

Figure 17: RMS of the mean differences between the model computed geoid undulations and the GNSS/levelling derived geoid undulations. The comparison results are shown for the most recent models and retrieved from http://icgem.gfz-potsdam.de/tom_gpslev. **Note that the comparisons should be realised among different type of models, e.g. combined model up to similar degrees, satellite-only models up to similar degrees. One can the change the order of the models using the Nmax column.**

3.5 DOI Service

For more than a decade, the need for and value of open data have been expressed in major science society position statements, foundation initiatives, and in statements and directives from governments and funding agencies worldwide. The citable data publication with assigned digital object identifiers (DOI) can be regarded as best practice for addressing these requirements. Ideally, the data are technically described and provided with standardised metadata, including the licence for reuse that are readable for humans and machines. Today, datasets with assigned DOI are fully citable research products that can and should be included in reference lists of research articles (Data Citation Synthesis Group 2014, Hanson et al., 2015).

Following the bottom-up structure of ICGEM, the DOI Service was developed as a request by the user community. Global gravity field models are often shared through ICGEM months or even years before they are described in scientific research articles. The publication of static and temporal models with a DOI makes them citable and provides credit for the originators already with their publication via the ICGEM Service. The DOI Service of ICGEM was developed in cooperation with GFZ Data Services, the domain repository for the geosciences hosted by GFZ (http://dataservices.gfz-potsdam.de/~~portal/~~). To reduce the heterogeneity in the data documentation for static global gravity field models, ~~we have developed~~ standardised metadata templates for describing the models were developed that include~~and~~ cross-references between the model data ~~with~~ and research articles, data reports with detailed model description and other text or data publications (see Fig. 18). At the moment, all models with assigned DOIs are published under the Creative Commons Attribution 4.0 International Licence (CC BY 4.0).

For DOI-referenced models, data access is ~~also~~ provided via specific, ICGEM branded, DOI Landing Pages (~~as shown in~~ see Fig. ~~19~~18)~~,~~ at~~the~~ GFZ Data Services ~~catalogue or~~ and via the ICGEM Website (see Fig. ~~20~~19). In addition~~, on the DOI Landing Pages~~ ~~we provide~~ direct links to the ICGEM Visualisation and Calculation Services for the specific model are provided in the DOI Landing Pages. The citation of the model and the licence ~~(we recommend to use Creative Commons Attribution 4.0 International CC BY 4.0)~~ is also included in the header of the data files themselves.

Since its implementation in late 2015, we have assigned DOIs to 17 static and 3 temporal series, mostly timely related to their first publication via ICGEM. As DOI-referenced~~s~~ datasets are required to remain unchanged, for the case of ~~a~~ one model update we have developed a DOI versioning service with direct links between the two versions and a version history explaining the differences (e.g. Förste et al., 2016a and b). GFZ Data Services provide their DOI landing pages and metadata for each dataset in machine-readable form (schema.org and XML, respectively), following DataCite 4.0 and ISO19115 metadata standards. ~~and is equipped with an Application Programing Interface (OAI-PMH) that allows automatic m~~Metadata ~~exchange~~can be harvested via an Application Programing Interface (OAI-PMH). ~~Consequently~~As a result, metadata from ICGEM models is also findable in the catalogues of e.g. DataCite (http://search.datacite.org/), B2Find (http://b2find.eudat.eu/) and the newly released Google Dataset Search engine (https://toolbox.google.com/datasetsearch).

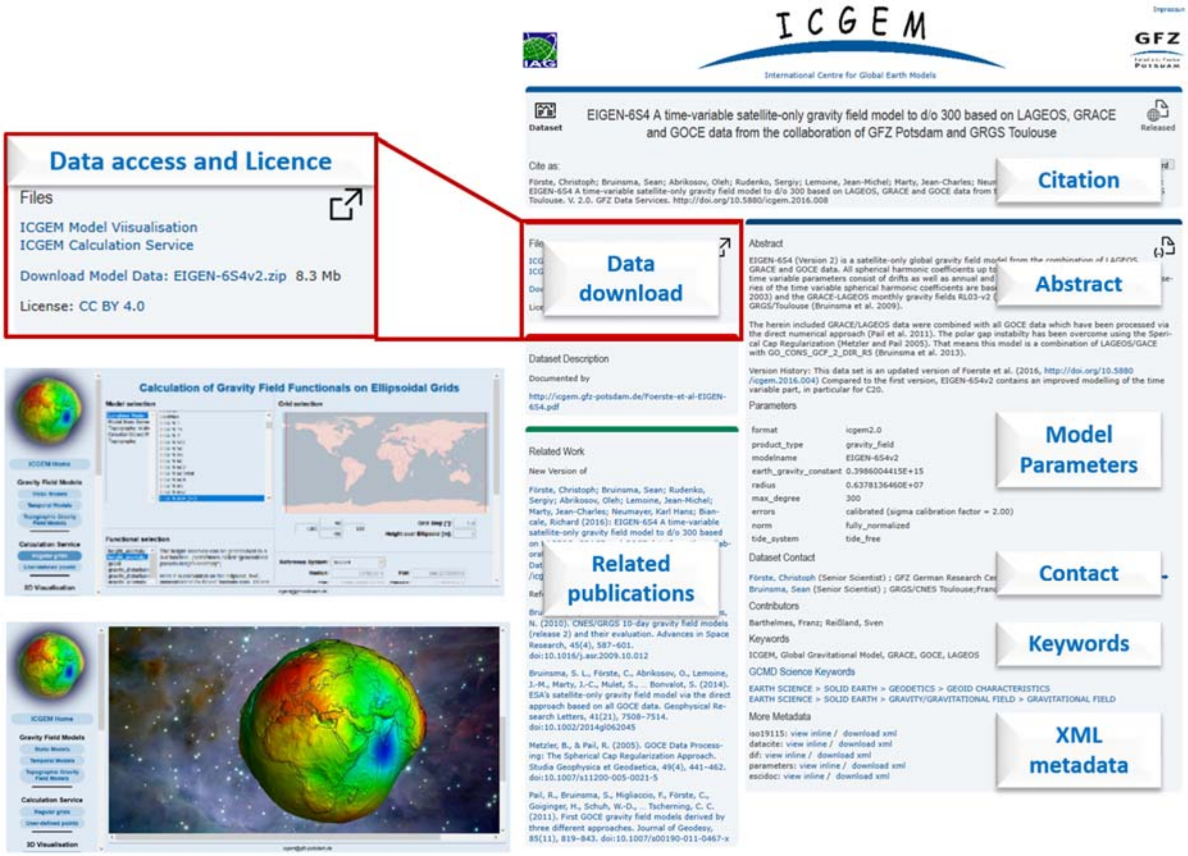


Figure 18: Example for and features of an ICGEM DOI Landing Page (EIGEN-6S4, http://doi.org/10.5880/icgem.2016.008). The DOI Landing Page to the right is the visualisation of the metadata for data discovery that is collected for the DOI assignment. In addition to the links to the data, it includes the citation information, a data description (abstract), a table of model parameters, contact information, keywords and links to related publications. The metadata is also provided in machine-readable XML format. The key elements of the DOI metadata is also included in the header of the data files (model coefficients). The left part of the figure is a close-up of the data download section. GFZ Data Services stores a copy of the model data and provides direct links to the ICGEM Visualisation and Calculation Services with the pre-selection of the actual model.

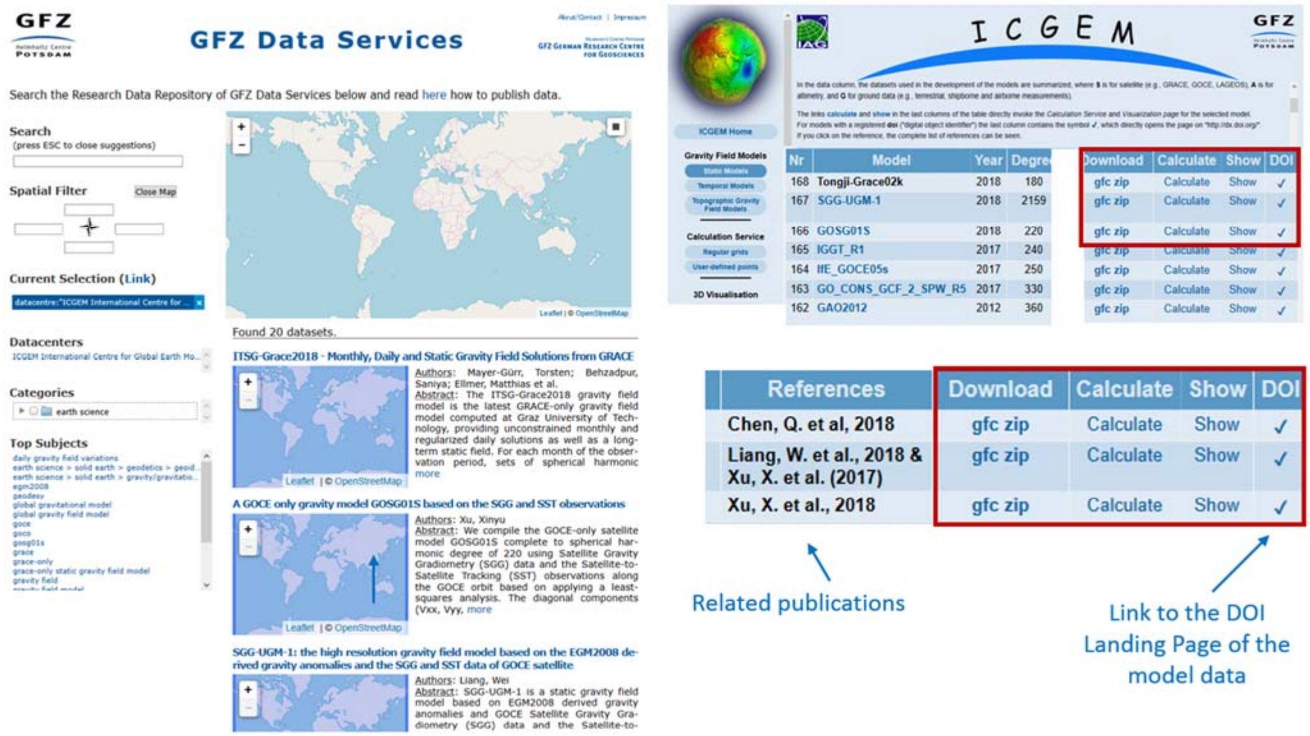


Figure 19: Illustration of the two different possibilities to access the DOI-referenced ICGEM models: via the Catalogue of GFZ Data Services (left) and the ICGEM Website (right). GFZ Data Services have created a specific data centre for the ICGEM Service (http://dataservices.gfz-potsdam.de/portal/?fq=datacentre_facet:%22DOIDB.ICGEM%20-%20ICGEM%20International%20Centre%20for%20Global%20Earth%20Models%22). On the ICGEM Website (to the right, table of models), each ICGEM model with assigned DOI is linked to the DOI Landing page via the mark in the DOI column.

4 Documentation

The documentation section of the ICGEM Service consists of five subsections: Frequently asked questions, theory, references, latest changes, and discussion forum. The ICGEM team responds to users' questions as soon as possible in the discussion forum. During the last few years, there were common questions from advanced users, researchers and students that are fundamental to do thorough analyses in different application areas~~s~~. The ICGEM team has collected frequently asked questions (FAQs) and provided this collection with answers as a pdf document. The questions are answered to meet the needs of both users from different scientific disciplines and experts in the field of physical geodesy. The FAQs list is regularly updated when new questions accumulate. The last version of the FAQs can be accessed via http://icgem.gfz-potsdam.de/faq.

Although the theory of the global gravity field modelling and the calculations of gravity field functionals are not presented in this paper, it is most fundamental to the development of the ICGEM Service and a detailed documentation is reported in Barthelmes, 2013. This scientific technical report includes the potential theory and approximations that are used in the global gravity field modelling.

ICGEM does not only collect gravitational model, but also pays attention on the full documentation of the models. New model releases, new documentation, conference and symposium presentations can be found in the ICGEM Home page and in the list of latest changes. Moreover, f~~F~~or the convenience of the users, all relevant sources are listed in ~~this~~ the references ~~list~~. This will ensure that the service and its components are available at the same place.

Moreover, the ICGEM Service provides a gravity field discussion forum (http://icgem.gfz-potsdam.de/guestbook) which provides users with a platform to communicate with the ICGEM team and other scientists working on similar topics. Apart from fulfilling the requirements of the service, this platform has also been used as a tool for educational purposes in which undergraduate or graduate students communicate with the ICGEM team directly. Since the interaction between the users and ICGEM team members has evolved and included extensive communications including e-mails, the definition of the old 'guest book' was redefined and has been modified into the forum in 2016 which better represents the current status of the platform.

The new version of the forum should give the users the opportunity to discuss any topic related to gravity field among themselves or answer each other's question and probably share data in the future. In the following years, we propose to establish sub-sections for different topics and expand the discussion forum to be unique in this field. Anyone without any registration requirement should still be able to write comments in the forum which will be publicly available after approval of the ICGEM team.

5 Web Programming

The original ICGEM website was established in 2003 and was based on plain HTML, Java Applets and Perl scripts. In 2016 and 2017, several components of the website received an upgrade. The webpages are generated with the Python based framework CherryPy and Jinja2 templates. A MongoDB serves as database backend (see Fig.~~ure~~ 20~~1~~ for an overview of the Web programming scheme). In addition, the 3D Visualis~~z~~ation received minor changes and the user interface of the Calculation Service has been re-designed. The programs used in the calculation are the same as providing identical results and make use of the database to display the status of individual calculations.

***Visualisation Service*:** The Visualis~~z~~ation Service received minor updates primarily to ease the maintenance. The information of all models is kept in the MongoDB database. To visualis~~z~~e a specific model in user's browser, the ICGEM server creates a scene, dynamically applies changes to this scene and returns the resulting picture for display. Changes to the scene could be the rotation of the visualis~~z~~ed model or changes of parameters.

Table(s) of Models: This page simply requests all the model information from the MongoDB and displays it in a table, if a user wants to download a model, the model file is requested from the Model storage.

Discussion Forum: Posts from users are saved in the MongoDB and those approved by the ICGEM team are displayed on the page.

Calculation Service (Browser): When the user clicks on “Start Calculation”, the browser sends the calculation settings to the server. The calculation settings are stored in the MongoDB database and the user is redirected to the calculation status page. The calculation progress is periodically updated from the MongoDB database. When the calculation is done, the results are displayed and download links are shown.

Calculation Service: The Calculation Service is a dedicated program on the server that requests new calculations from the MongoDB. For new calculations a calculation process is started and progress is stored in the MongoDB, to be requested by the calculation status page. After the calculation is done, the resulting grid is converted to an image. The number of concurrent calculation processes is limited, so a new calculation will have to wait until a slot is free.

Evaluation (Browser): For each model, the GNSS/levelling information is saved in the MongoDB. For the spectral domain evaluation, additionally, the images of the evaluation results are loaded and displayed.

Evaluation Service: In the MongoDB one model is selected as reference model, all other models have an attribute indicating which model was used for the evaluation. The Evaluation Service runs in regular intervals and requests the evaluation status of all models from the database. Models, which were not evaluated with the current reference model, will be automatically re-evaluated. When a new model is added, it will automatically be evaluated within some minutes. If the reference model changes, all models will be reevaluated.

Static Sites: The Static Sites like the FAQ and Theory are only a Jinja2 template and do not need any information from the MongoDB.

The overall architecture of the ICGEM website and its services is visualized in Fig.~~ure~~ 2~~1~~0. Pivotal component is the MongoDB database. On the one hand, this database is used to feed forms with information about models or discussion posts and to link to file storages, and on the other hand, the MongoDB database decouples most of the server components from the users internet browser. Therefore, long-lasting model calculations can be bookmarked for later inspection of the results. Because of its dynamic behavior, the Visualization Service requires direct communication with the users internet browser and the MongoDB database is not used to exchange information.

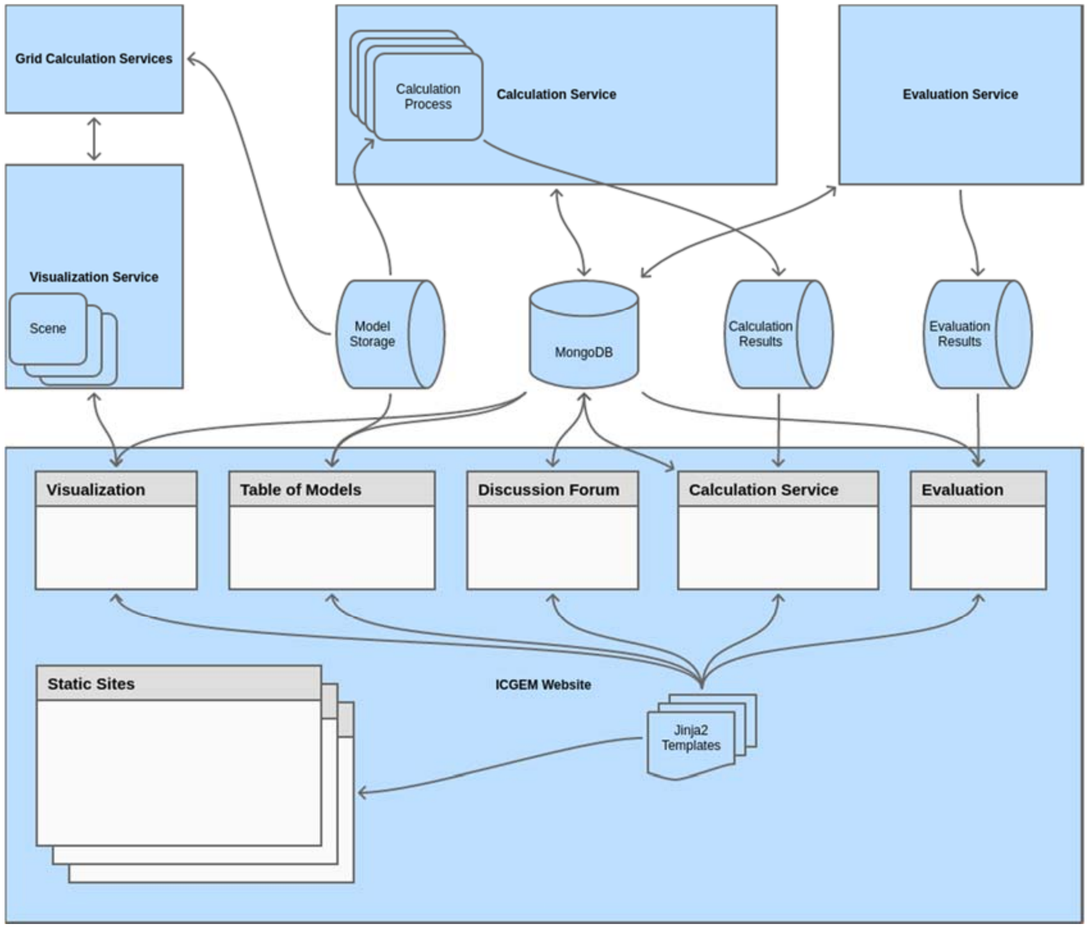


Figure 20: Illustration of the scheme of the ICGEM Website in terms of its web programming. Arrows indicate the direction of data flows. Cylinders are the default symbol for Databases and sideway cylinders are used for file-based data stores. Model Storage is file based, the Calculation Results are the calculated Grid files and the images converted from them. Evaluation Results are only the generated images on the Spectral domain page, the values in the GNSS/levelling page derive from the MongoDB. At the bottom of the scheme, every grey-white rectangle represents a subpage on the Website. Similar pages, like the different Visualization pages or the Tables of Models, are presented together, and we included only the static pages, that are more interesting from a technical perspective.

6 Conclusions ~~and Future Aspects~~

The ICGEM Service is a worldwide used service, which continues to maintain its content and develop new features based on users' needs and requests since its establishment. Over the years, ICGEM has become the unique platform for providing comprehensive access to static, temporal, and topographic gravity field models and their documentation as well as to the online calculation and visualisation services of the gravity field functionals.

~~In the near future, the old~~Apart from adding the G3 Browser back, which showed the time variation of gravity field at any desired point or pre-defined basin, ~~will be available again with improved features developed for both advanced researchers and educational purposes. A specific web interface will be made available for the user to calculate and visualise the time series of mass variations. The results again will be available both in .png and. ASCII formats.~~

~~T~~the other contribution will focus on the collection and provision of the C_{20} coefficient time series from different institutions. This feature has been requested by advanced users who indicated that there is a need to collect these values from all developers in a common platform enabling access for the scientists and use for different purposes.

The discussion forum will be divided into sub sections and formatted for the user to communicate the other users as well as the ICGEM team and find answers to possible questions. If requested by the users, data sharing such as terrestrial gravity measurements and GNSS/levelling derived geoid undulations and exchange can also be developed under the ICGEM web settings safely. Moreover, creation of an e-mail subscription list for the delivery of monthly updates to the interested users is under discussion. These are possible options and opportunities to share the science and its products.

7 Data availability

The website of ICGEM with all model data, documentation and services as described in this article is available via http://icgem.gfz-potsdam.de/. In addition, all gravity models with assigned DOI are also accessible via GFZ Data Services catalogue (http://dataservices.gfz-potsdam.de/portal/?fq=datacentre_facet:%22DOIDB.ICGEM%20-%20ICGEM%20International%20Centre%20for%20Global%20Earth%20Models%22). As the purpose of this article is the description of the ICGEM Service with all its features, including the DOI Service, we do not provide an additional DOI to all model data but refer the users to directly access the data via the ICGEM Website or GFZ Data Services.

Author contributions: ESI is responsible for the maintenance and the development of the ICGEM Service as of January 2018, prepared and coordinated the manuscript, FB developed the software and tools used in the ICGEM Service and contributed in the preparation and review of the manuscript, SR is responsible for the maintenance of the Service together with ESI, does the web programming of the ICGEM Service and contributed to the preparation of Section 5, KE developed the DOI Services and is responsible for the DOI assignment for the models in the Service, prepared subsection 3.5 and reviewed the paper and suggested improvements, CF reviewed the paper in general and suggested improvements, FF reviewed the paper especially section 2.2.2 and suggested improvements, HS reviewed the IAG Service and IUGG relevant parts and suggested improvements.

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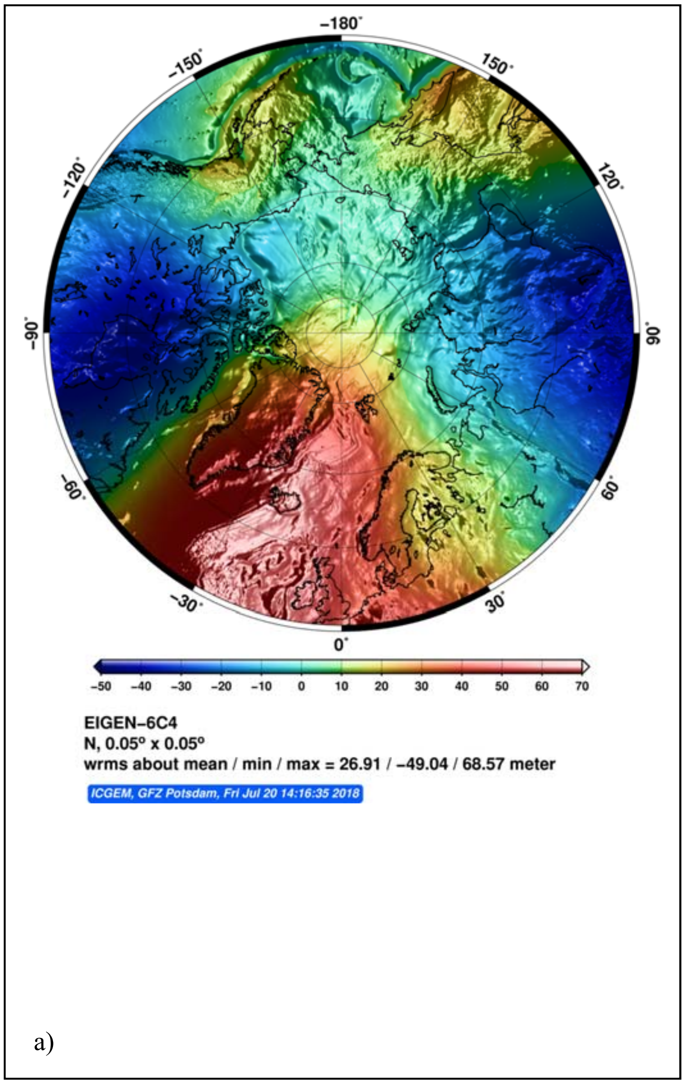
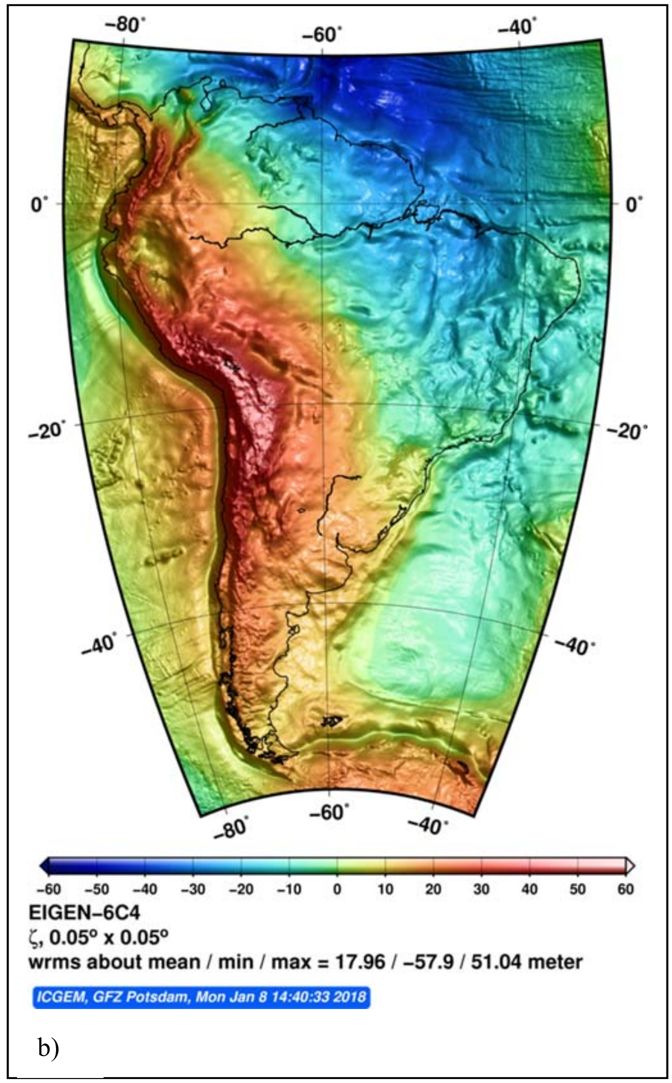
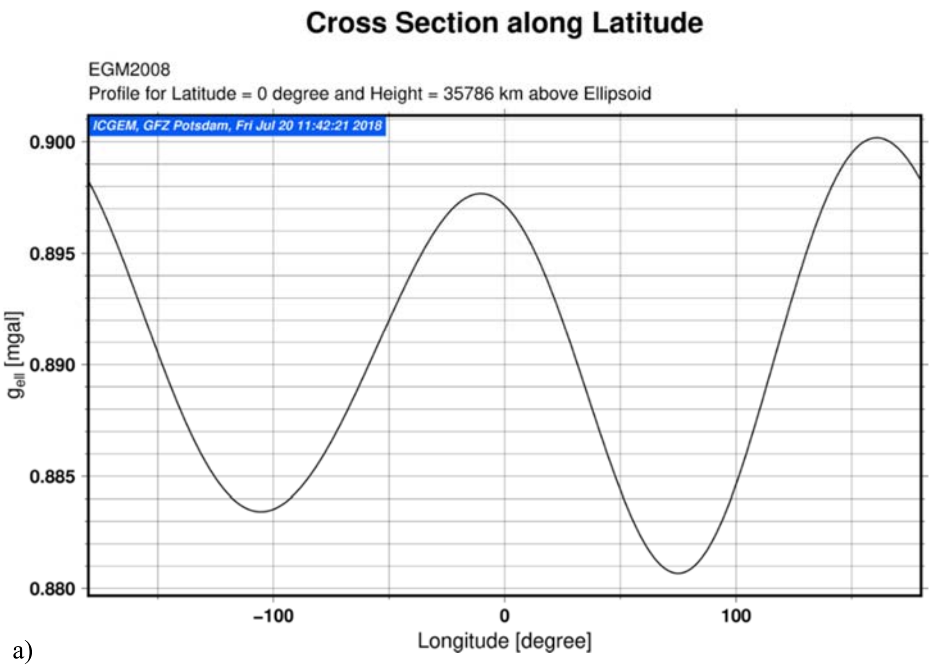
Appendix 1: Other features of the calculation service

A- Different projections are introduced in the background script which uses GMT version 5.0. The figures are adjusted based on the calculation area. The below figures show geoid undulations and height anomalies in a) North Hemisphere above latitude 50 degrees b) South America.

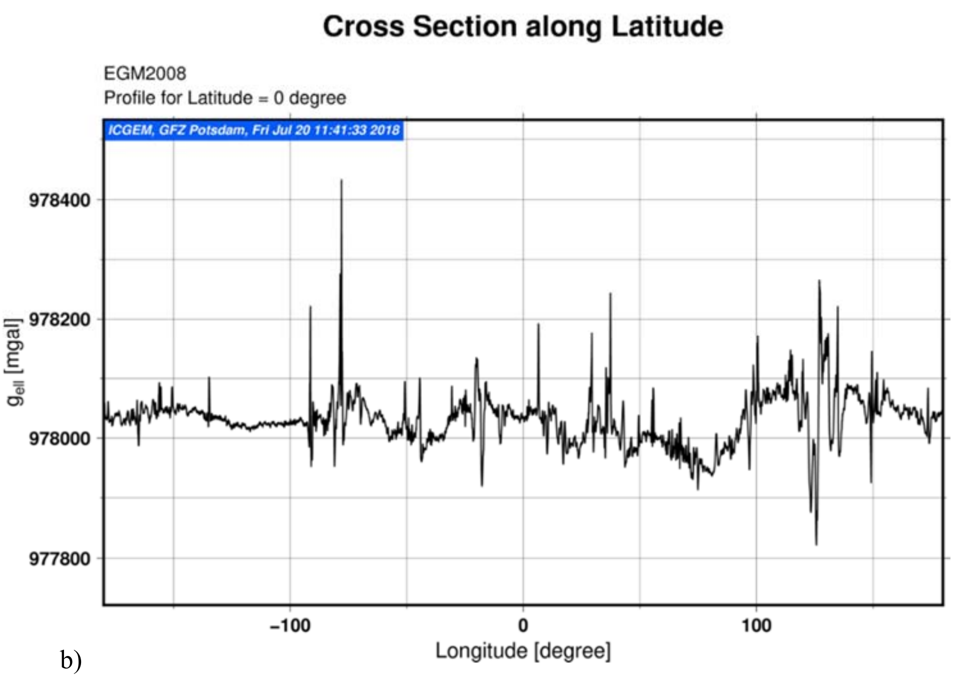




B- Cross section calculation of gravity field functionals along latitude. The below figures show cross section along latitude of a) gravity of a potential geostationary satellite at an altitude of approximately 36000 km b) gravity on the earth surface along the equator.

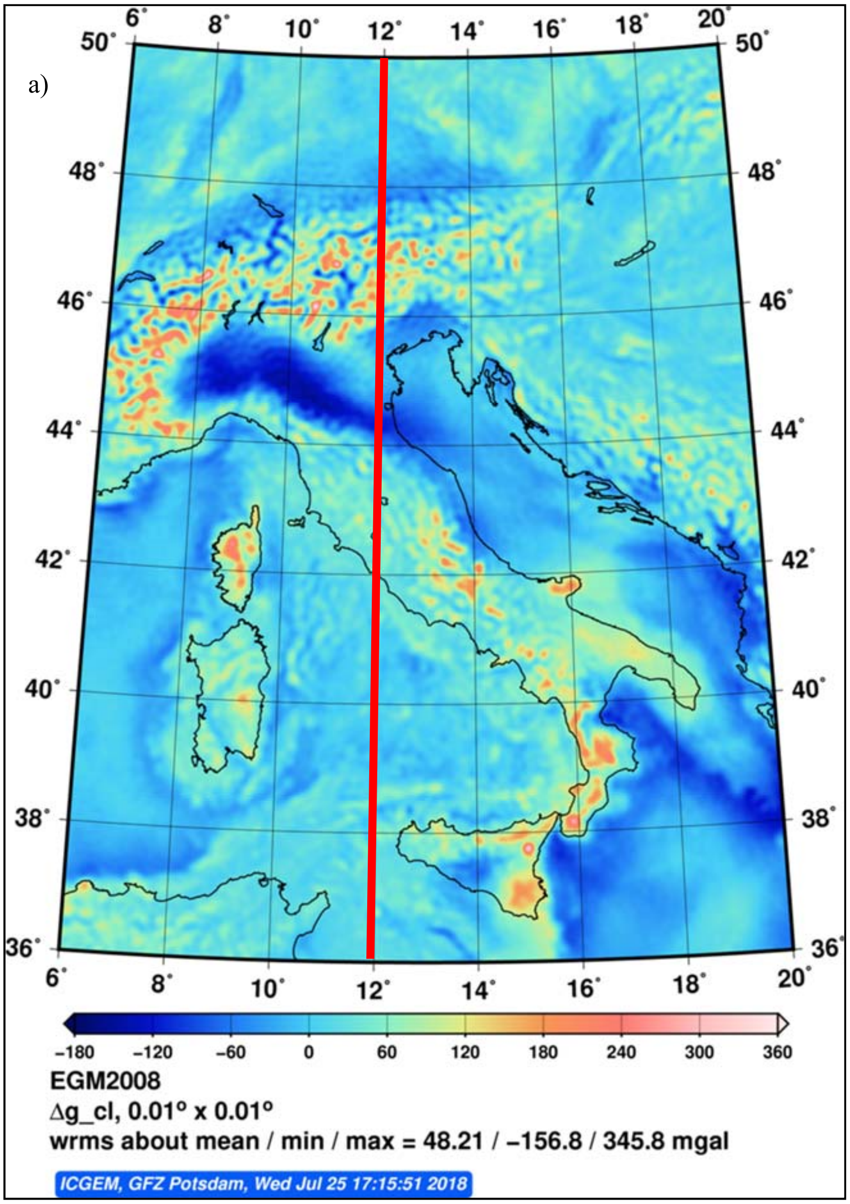


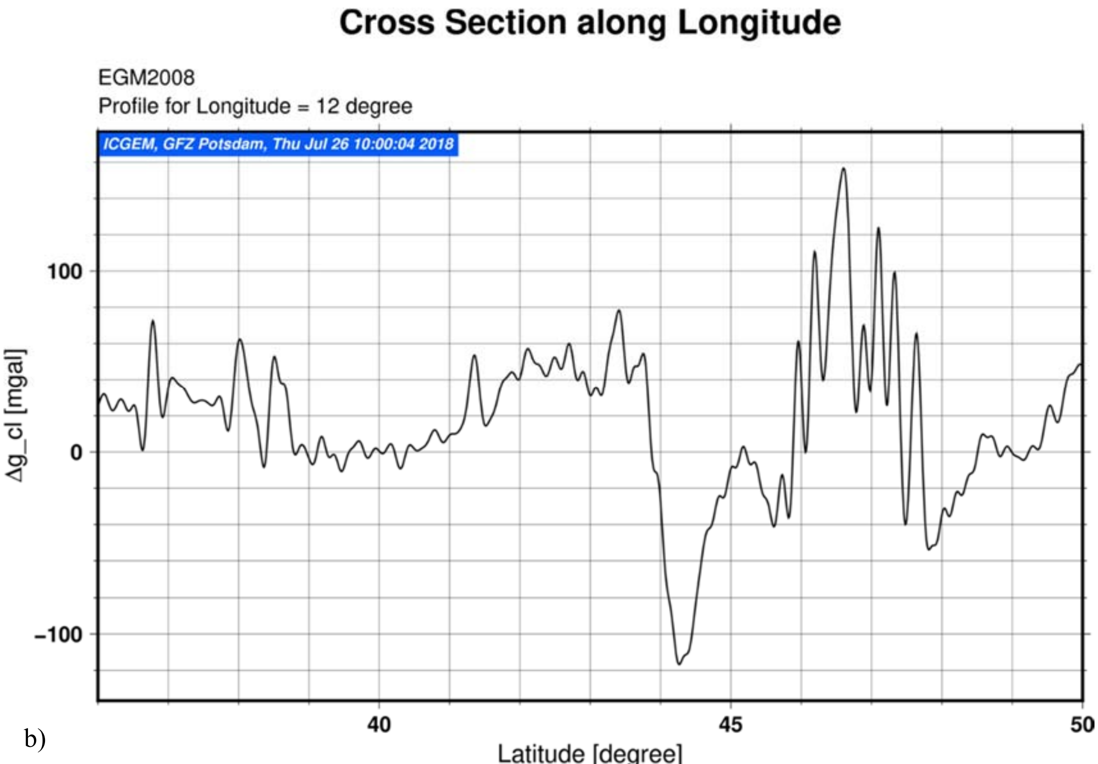
a)



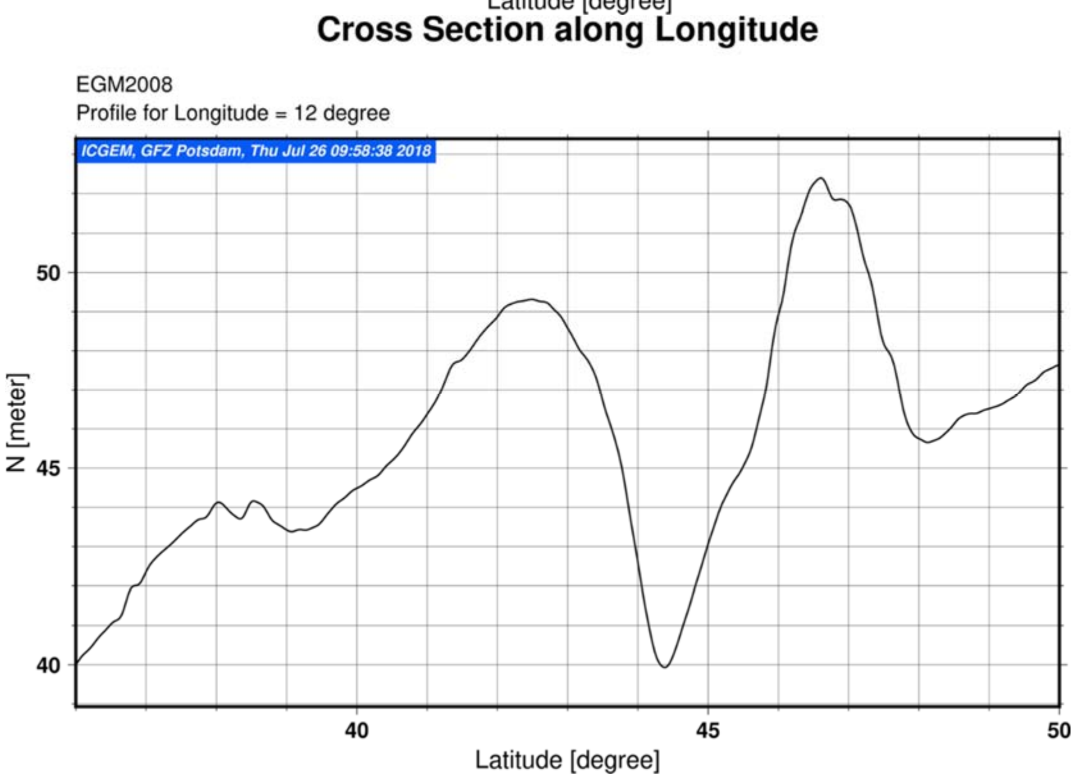
b)

C- Cross section calculation of the gravity field functionals along longitude. The figures below show a) Classical gravity anomalies at grid points where the red line indicated the cross section along longitude b) Cross section classical gravity anomalies along longitude c) Cross section geoid undulations along longitude




Cross Section along Longitude
EGM2008
Profile for Longitude = 12 degree
ICGEM, GFZ Potsdam, Thu Jul 26 10:00:04 2018
Δg_cl [mgal]
100
0
−100
40
45
50
Latitude [degree]

b)


Cross Section along Longitude
EGM2008
Profile for Longitude = 12 degree
ICGEM, GFZ Potsdam, Thu Jul 26 09:58:38 2018
N [meter]
50
45
40
40
45
50
Latitude [degree]

c)

D- Visualisation of other celestial bodies. Figures below show geoid undulations of a) Moon b) Mars c) Venus