AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2019GL082521

Key Points:
- Global 3 arc-second SRTM topography has been accurately converted to implied topographic gravity effects at ~28 billion locations over most land areas
- Ninety-meter detailed gravimetric terrain correction grid reflecting the gravitational attraction of Earth's topographic masses is publicly available
- New model directly applicable to reduce gravimetric surveys to Bouguer gravity over land areas between −60° and 85° geographical latitude

Supporting Information:
- Supporting Information S1

Correspondence to:
C. Hirt,
c.hirt@tum.de

Citation:
Hirt, C., Yang, M., Kuhn, M., Bucha, B., Kurzmann, A., & Pail, R. (2019). SRTM2gravity: An ultrahigh resolution global model of gravimetric terrain corrections. *Geophysical Research Letters*, *46*, 4618–4627. https://doi.org/10.1029/2019GL082521

Received 19 FEB 2019
Accepted 8 APR 2019
Accepted article online 16 APR 2019
Published online 6 MAY 2019

SRTM2gravity: An Ultrahigh Resolution Global Model of Gravimetric Terrain Corrections

Christian Hirt[1,2], Meng Yang[1], Michael Kuhn[3], Blažej Bucha[4], Andre Kurzmann[5], and Roland Pail[1]

[1]Institute for Astronomical and Physical Geodesy (IAPG), Technical University Munich, Munich, Germany, [2]Institute for Advanced Study (IAS), Technical University Munich, Garching, Germany, [3]School of Earth and Planetary Sciences and Western Australian Geodesy Group, Curtin University, Perth, Western Australia, Australia, [4]Department of Theoretical Geodesy, Slovak University of Technology in Bratislava, Bratislava, Slovak Republic, [5]Leibniz-Rechenzentrum (LRZ) der Bayerischen Akademie der Wissenschaften, Garching, Germany

Abstract We present a new global model of spherical gravimetric terrain corrections that take into account the gravitational attraction of Earth's global topographic masses at 3″ (~90 m) spatial resolution. The conversion of Shuttle Radar Topography Mission-based digital elevation data to implied gravity effects relies on the global evaluation of Newton's law of gravitation, which represents a computational challenge for 3″ global topography data. We tackled this task by combining spatial and spectral gravity forward modeling techniques at the 0.2-mGal accuracy level and used advanced computational resources in parallel to complete the 1 million CPU-hour-long computation within ~2 months. Key outcome is a 3″ map of topographic gravity effects reflecting the total gravitational attraction of Earth's global topography at ~28 billion computation points. The data, freely available for use in science, teaching, and industry, are immediately applicable as new in situ terrain correction to reduce gravimetric surveys around the globe.

Plain Language Summary Measurement and study of the gravitational force (the *g* value) is essential for geoscientists concerned with, for example, mineral prospection and investigation of Earth's gravitational field. Most applications require the analyst to remove the gravitational signal caused by the surrounding and remote terrain (mountains and valleys) from the *g* value at the location of the measurement. This task involves tedious numerical computations when high-resolution terrain data sets, for example, from the Shuttle Radar Topography Mission, are used. Utilizing improved computational methods and 1 million computation hours on a supercomputer, a globally 90-m-detailed map has been created that shows the subtle influence of the terrain on g measurements at ~28 billion measurement sites around the globe. This first-of-its-kind map, released into the public domain, is expected to simplify the daily work of geoscientists in research and industry concerned with gravity interpretation and to clear the path for next-generation global gravity maps with extreme detail.

1. Introduction

Gravity field observations are essential for investigating the structure of Earth's gravitational field. The shape and anomalies of the gravity field carry important clues on the mass composition and geological evolution (e.g., Blakeley, 1996; Fowler, 2005). Before a gravimetric survey can be interpreted for anomalous signals, the effect of the topographic masses on the gravity measurements must be calculated and reduced. This is also denoted topographic mass reduction (Jacoby & Smilde, 2009) or gravimetric terrain correction (Featherstone & Kirby, 2002; Li & Sideris, 1994). The gravity effect associated with the topographic masses is obtained through evaluation of Newton's law of gravitation. While classical terrain corrections rely on approximations such as planarization and neglect of topographic masses beyond some fixed integration radius, for example, 167 km (e.g., Hammer, 1939; Nowell, 1999), contemporary approaches are often based on more accurate spherical approximation and model all of Earth's topographic masses around the globe and with increasingly higher resolution (e.g., Balmino et al., 2012; Kuhn et al., 2009). The spatial resolution of terrain correction computations is important to better resolve and detect small-scale or near-surface mass-density anomalies, for example, in the context of geophysical exploration.

In modern terrain correction computations, detailed digital elevation models (DEMs) are commonly used as representation of the topographic masses. High-resolution gravimetric terrain correction grids have been computed over local (e.g., Cella, 2015; Tsoulis, 2001) and even continental areas (Featherstone & Kirby, 2002; Kuhn et al., 2009) at a resolution commensurate with the DEM (e.g., ~50 to ~270 m). Global grids of gravimetric terrain corrections have been developed too, notably in the context of UNESCO's World Gravity Map project (Balmino et al., 2012; Bonvalot et al., 2012). However, a ~2- to ~4-km resolution level —as in case of the World Gravity Map—is usually not sufficient to accurately reduce ground gravimetric observations that capture the gravitational attraction of the surrounding local masses too. Thus far, a global map of highly detailed gravimetric terrain corrections that would take into account the global topography to finest detail is not available. This might be related to the significant computational challenges encountered when attempting to evaluate Newton's integral down to the DEM resolution globally (Hirt et al., 2013).

Here we present the first ultrahigh resolution model of gravimetric terrain corrections that uniquely unites local detail resolution with global coverage. We have converted global 90-m DEM data, primarily based on the Shuttle Radar Topography Mission (SRTM), to implied topographic gravity effects. The outcome, denoted SRTM2gravity, is a modern gravimetric terrain correction model that reflects the gravitational attraction of Earth's global topographic masses at any of the ~28 billion computation points covering all of Earth's land areas within −60° to 85° geographic latitude at 90-m resolution. The SRTM2gravity model contains implicitly the effect of the Bouguer shell (the linear term) and all gravity terrain effects residual to the Bouguer shell (e.g., surrounding valleys and mountains). It therefore reflects the total gravity signal generated by the global topographic masses. The SRTM2gravity model relies on improved global DEM data representing the bare ground (section 2) and a validated combination of mature spectral and spatial techniques for efficient evaluation of Newton's integral (section 3). We provide two products, one reflecting the total gravitational attraction of the global topography and the other capturing the high-frequency topographic gravity signal only (section 4.1). Application examples including the in situ reduction of gravimetric surveys around the globe and construction of extremely detailed gravity maps are given (section 4.2), limitations are summarized (section 4.3), and conclusions are drawn (section 5).

2. Data

Key input data are the 3 arc-second (3″) resolution global v1.0.1 MERIT (Multi-Error-Removed Improved-Terrain) DEM data set by Yamazaki et al. (2017). The MERIT DEM primarily relies on SRTM version 2.1 data within ±60° latitude and uses AW3D DEM data (ALOS/PRISM) North of 60° latitude. For the filling of SRTM voids (unobserved areas), DEM data collected and maintained by Viewfinder Panoramas was used. Together with a constant mass density of 2,670 kg/m^3, MERIT is our representation for Earth's topographic masses. In contrast to other global DEM products, radar error sources (speckle noise, stripes, and biases) as well as the tree canopy signal have been reduced in MERIT (see Yamazaki et al., 2017 for details). As a result, MERIT elevations represent—in good approximation—the bare ground and thus improve the representation of topographic masses, which is an important conceptional benefit for the purpose of our work. The lower bound of the MERIT topography model is the geoid (mean sea level).

In previous studies using earlier SRTM data releases (e.g., Hirt et al., 2014), the need to carefully inspect and correct the topography data for outliers prior to the forward modeling has become clear. For this study, efforts were therefore made to develop artifact screening techniques (Hirt, 2018) for detection of steps, spikes, pits, and other unwanted features in the topography model. Based on the terrain gradient threshold of 5 m/m (i.e., a 5-m elevation change per 1-m horizontal distance), a total of 123 locations with elevation outliers were detected in the MERIT v1.0.1 data set and removed through interpolation (Hirt, 2018). Though the number of detected artifacts is comparatively small, we consider the DEM screening and artifact removal important, because elevation outliers may propagate into a wider region of surrounding gravity values. The cleaned 3″ MERIT DEM is free of spurious artifacts and represents the detailed topographic mass model (Figure 1a) for the gravity forward modeling.

SRTM2gravity uses the MERIT-DEM as only input data set, so does not include the topographic masses of Antarctica, nor the ice-density contrast of Greenland. These simplifications produce very long-wavelength signals on the order of few mGal over non-ice-covered areas (Kuhn & Hirt, 2016). A correction is possible, for example, using forward models representing the ice-density effect of Greenland (Tenzer et al., 2010) and topography/ice masses of Antarctica (Rexer et al., 2016). The MERIT-DEM represents the surface of water bodies (oceans or lakes) and the surface of ice masses where present. Note that no attempt was

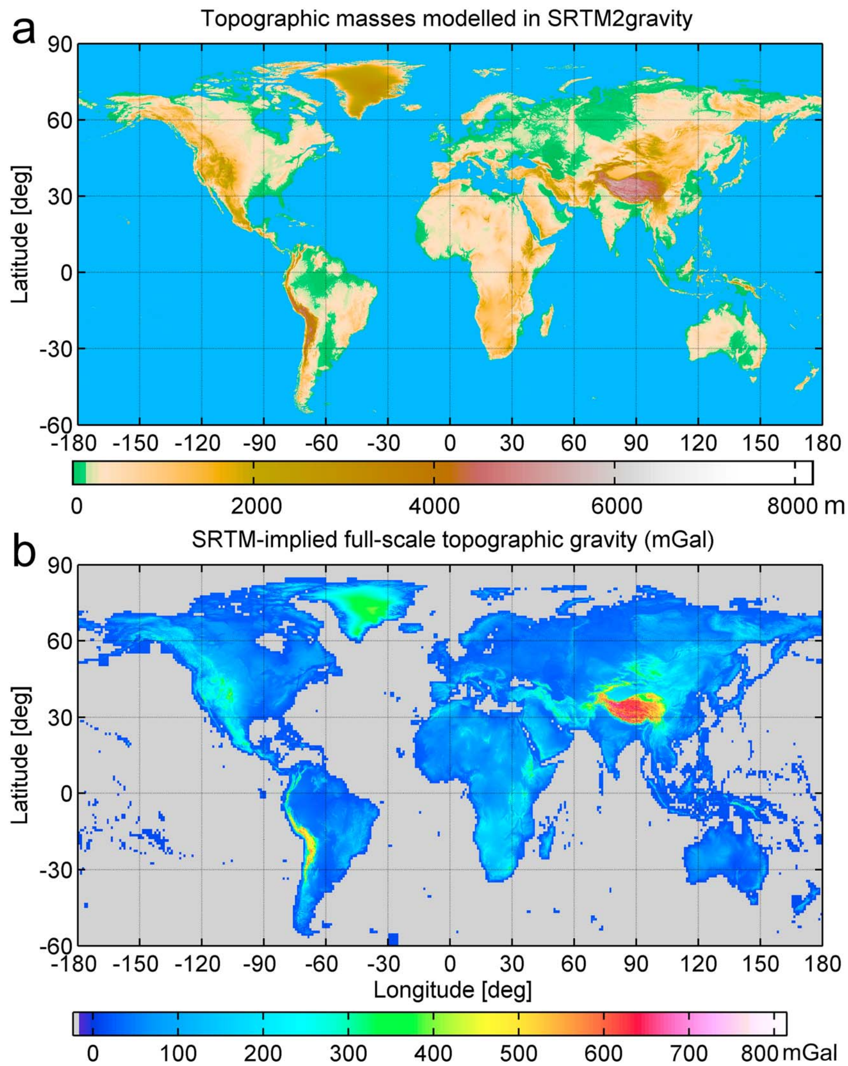

Figure 1. (a) Global topographic masses (elevations in meters) modeled in SRTM2gravity; (b) topography-implied full-scale gravity signal (in mGal) and model availability. Data shown at 1-arc-min resolution in both panels.

made to model other mass bodies or mass-density anomalies such as ocean or lake water or sediments. Users having detailed models of such mass bodies at hand can forward-model and refine the terrain corrections from the SRTM2gravity model.

3. Methods and Computations

The principal difficulty for global yet high-resolution terrain correction modeling is the computational effort associated with evaluation of Newton's integral. The effort increases linearly with (i) the number of computation points and (ii) the number of mass elements the topography model is divided into. At 90-m spatial resolution, the MERIT-DEM contains ~28 billion elevation points across all land areas within −60° and 85° latitude, requiring—in principle—~$(28 \times 10^9)^2$ evaluations of single-mass elements. Using cascading grid resolutions, starting from 3″ in the vicinity of the computation point to much coarser resolutions for remote topographic masses, is permitted to accelerate the computations (e.g., Forsberg, 1984), while keeping approximation errors small (e.g., Hirt & Kuhn, 2014). Nonetheless, with this optimized configuration (cf. Electronic Supplementary Materials [ESM]) the conversion of the entire MERIT-DEM to gravity effects would still require ~15 million CPU hours (CPUh) to obtain μGal level precision. Using much coarser grid resolutions would further reduce the computation time, however, at the expense of increasing approximation errors.

An alternative highly efficient strategy was developed, tested, and applied for the SRTM2gravity challenge, considerably reducing the overall computation time to the level of ~1 million CPUh. Our computational approach (cf. ESM) combines spectral-domain and spatial-domain techniques for efficient evaluation of Newton's integral. Key element of the combination technique is the use of a spherical harmonic (SH) reference topographic surface, which is here expanded up to degree 2,160. Under some approximations (cf. Hirt et al., 2019; Rexer et al., 2018; also see ESM sections S1 and S3), it facilitates the separate modeling of long-wavelength (here more than 10 km) and short-wavelength (less than 10 km) topographic gravity signals, based on the following procedure:

1. The 3″ MERIT topographic surface was accurately expanded into a set of SH coefficients to degree 2,160. We performed an ultrahigh degree SH analysis up to degree 43,200 to mitigate downsampling errors on the estimated coefficients (Hirt et al., 2019). The reference surface is rigorously self-consistent with the 3″ MERIT topographic surface.
2. For modeling the long-wavelength gravity signal implied by the degree 2,160 SH topography, spectral-domain techniques as described in, for example, Chao and Rubincam (1989) and Hirt and Kuhn (2014) were used. These expand the topographic potential into integer powers of the topography, and gravity effects are subsequently obtained via accurate SH synthesis of the topographic potential coefficients at the 3″ MERIT topographic surface (e.g., Bucha & Janák, 2014; Hirt, 2012).
3. The MERIT-implied gravity signal residual to the degree 2,160 reference topography was computed in the spatial domain via local numerical integration. A residual terrain model (RTM; Forsberg, 1984) was formed as difference between the 3″ MERIT and the reference topography and converted to high-frequency gravity effects by evaluating Newton's integral locally. For this task, the RTM was subdivided into primitive mass elements—polyhedra, prisms, and tesseroids (e.g., Heck & Seitz, 2007; Tsoulis, 2012)—and the gravitational effect of each mass element was calculated and added up. Where 3″ MERIT elevations were smaller than the reference topographic elevations, a harmonic correction was applied following the approach by Forsberg and Tscherning (1981).

The total gravitational effect of the 3″ MERIT topographic mass model is the sum of results from steps 2 and 3. To improve the spectral separation between both components, and to be able to reach sub-mGal modeling accuracy, also very high-frequency signals generated by the degree 2,160 topography at scales of ~10 km down to ~2 km were explicitly modeled and considered (Hirt et al., 2016; Rexer et al., 2018; also see ESM section S1.3).

As the main computational benefit of the adopted methodology, the RTM numerical integration could be restricted to a comparatively small ~40-km radius around the computation point without compromising the modeling quality (beyond the chosen integration radius, gravitational effects cancel out to a large extent because of the oscillating nature of the residual terrain). This has allowed a very significant reduction of the number of mass elements and the total computation time compared to more tedious global evaluations (radius of ~20,000 km) of Newton's integral over the 3″ MERIT DEM. For the production of the SRTM2gravity model, the SuperMUC phase 2 advanced computational resources of the Leibniz Supercomputing Centre (LRZ) of the Bavarian Acadamy of Sciences and Humanities could be used. This part of the LRZ supercomputer comprises 86,016 CPUs (type Haswell Xeon Processor E5–2697). At ~28 billion computation points,

1. the spectral gravity forward modeling including synthesis of gravity effects at the 3-D topographic surface required ~45,000 CPU-hours (4%), and
2. the RTM including the numerical integration within 40-km caps around each point required ~1,100,000 CPU hours (96% of total CPU time),

showing that the majority of CPU hours is consumed by the numerical integration, while the effort associated with spectral modeling of the long-wavelength reference signal tends to be negligible. Using up to 4,000 CPUs in parallel, the computations—which would have otherwise taken ~100 years on a single-core desktop computer—could be completed in 8 weeks (gross time). Compared to a truly global evaluation of Newton's law of gravitation at 3″ resolution, our spectral-spatial combination method has significantly reduced computation times. This comes at the expense of increased approximation errors over deeply carved mountain valleys, related to the approximate character of the harmonic correction in the RTM (cf. Sect 4.3 and ESM). Notwithstanding, a high precision of ~0.2 mGal for the SRTM2gravity conversion could be

10.1029/2019GL082521

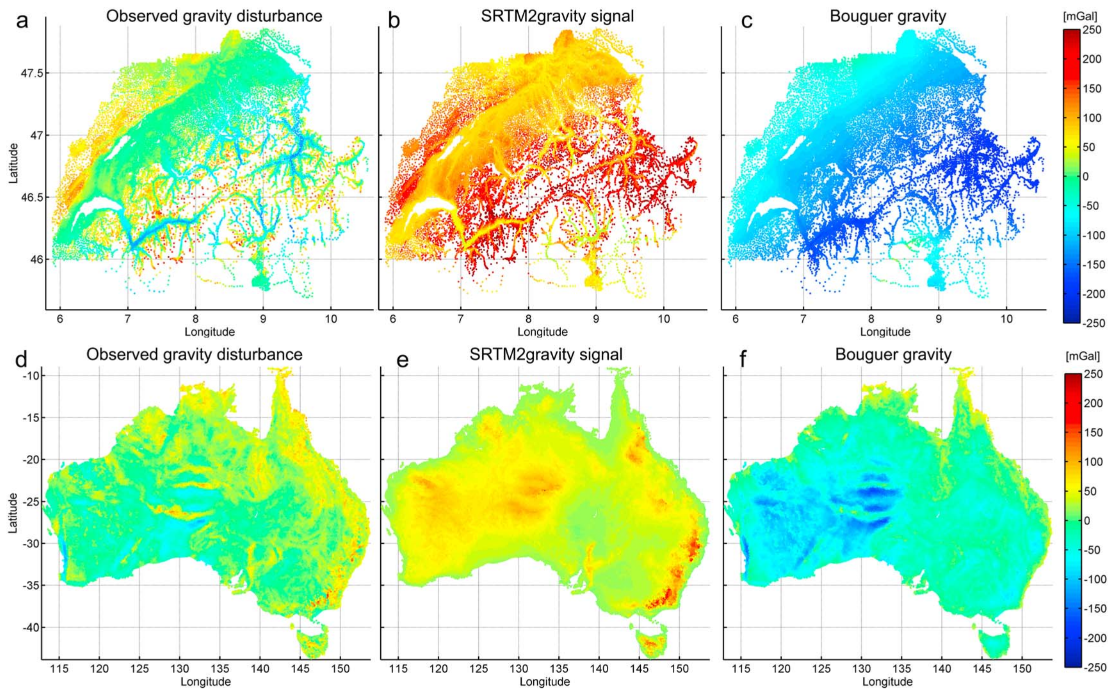

Figure 2. Top row: observed gravity, topographic gravity, and (complete) Bouguer gravity anomalies over Switzerland; bottom row: the same but over Australia. The observations shown in panels (a) and (d) are *g* values minus normal gravity, so technically gravity disturbances. The topographic gravity (panels b and e) has been interpolated from the SRTM2gravity model and represents a complete spherical terrain correction. Bouguer gravity (panels c and f) follows as difference between observation and topographic effect. Data courtesy Swisstopo, and Geoscience Australia. All units in mGal.

reached globally (cf. section 4.2). As an important conceptual benefit of the chosen method, a spectral separation between long- and short-wavelength topographic gravity signals is directly given, enhancing the applicability of the SRTM2gravity model, for example, for augmentation of global gravitational models, such as EIGEN-6C4 (Förste et al., 2015) or EGM2008 (Pavlis et al., 2012).

4. Results

4.1. SRTM2gravity Products and Applications

The first and primary outcome of the SRTM2gravity project is a 3″ resolution global grid of gravimetric terrain corrections (Figure 1b), which reflect the gravity signal produced Earth's global topography (Figure 1a), excluding the land masses of Antarctica and the Greenland ice-density contrast. It can be used as a modern kind of terrain correction to reduce the topographic gravitational effect in gravity measurements taken anywhere on Earth's land areas with the exception of Antarctica. The SRTM2gravity gravimetric terrain corrections have been calculated at 27,938,880,000 points. These extend over 19,402 1° × 1° tiles covering Earth's land areas between −60° and + 85° latitude including coastal zones (Figure 1). Over our data area, the gravimetric terrain corrections reach a total mean value of ~86.5 mGal. The variation range is from approximately −48.5 mGal (Torres del Paine, Chile) to ~825.3 mGal (Mount Everest summit; cf. Figure 1b).

It is important to note that our gravimetric terrain corrections shown in Figure 1b contain both the linear effect of the topography on gravity (also known as Bouguer shell) and the nonlinear effect (classically denoted as terrain correction in textbooks), so are identical with the (full) gravitational signal generated by Earth's global topography (Figure 1a). The SRTM2gravity gravimetric terrain corrections can thus be directly subtracted from observed gravity disturbances, without the need to separately model Bouguer plate or shell effects; see Figure 2 for examples.

As second outcome, we provide a 3″ resolution global grid of residual gravity effects, which represents high-frequency topographic gravity signals at scales from ~10 km down to ~90 m. This model component is the result of the RTM numerical integration procedure (section 3) and also takes into account very short-scale signals generated by the degree 2,160 topography to improve the band limitation of the residual gravity signals (cf. Rexer et al., 2018). Typical applications for the residual gravity effects are (a) use in the context of remove-compute-restore geoid computations to smooth gravity anomalies prior to interpolation and (b) spectral enhancement of global geopotential models (e.g., EIGEN-6C4 or EGM2008) beyond the nominal ~10-km model resolution (e.g., Hirt et al., 2013). The global root mean square (RMS) signal strength of the residual gravity effects is ~10.7 mGal and maximum signal amplitudes often exceed ~100 to ~200 mGal over rugged terrain, for example, the Himalaya Mountains. These values corroborate the significant signal amplitudes of topography-implied gravity signals at short spatial scales.

Figure 2 shows application examples for SRTM2gravity products. Using the Swiss national gravity data set, Figure 2a shows free-air gravity (technically: gravity disturbances) and Figure 2b the new gravimetric terrain corrections, which have been interpolated and subtracted from the free-air gravity to yield complete spherical Bouguer anomalies (Figure 2c). These are predominantly negative, a typical sign for isostatic compensation of the topographic masses over the European Alps. Analogously, Figures 2d–2f show the observed, topographic, and Bouguer gravity for Australia.

The application of the SRTM2gravity residual component for the spectral enhancement of global geopotential models is exemplified in Figure 3. Over a test area in the Australian Alps, Figure 3a shows residuals between observed gravity and the GGMplus model (see Hirt et al., 2013), while in Figure 3b the short-scale signals of GGMplus have been replaced with SRTM2gravity (see Table S5 from ESM for the statistics). The comparison often shows smaller residuals when SRTM2gravity is used, which is attributed here to the better spatial resolution of the forward modeling, to a reduction of canopy-related nongravity signals in the SRTM2gravity product, as well as to the improved spectral consistency of RTM. Figures 3c and 3d finally compare the short-scale component of GGMplus with SRTM2gravity, exemplifying the gain in resolution (from 220 to 90 m), and thus improved representation of short-scale gravity signals.

4.2. Validation and accuracy

We have independently validated the SRTM2gravity model through (a) global numerical integration and (b) comparisons with ground-truth gravity data (cf. ESM).

(a) Over a total of six 2° × 2° mountainous test areas around the globe (cf. ESM), global numerical integrations (=evaluation of Newton's integral in the spatial domain with 180° numerical integration radius and a 3″ resolution in the vicinity of the computation point) were performed. These calculations provide reference values for the gravimetric terrain correction—without using spectral techniques, SH reference surfaces or RTM gravity forward modeling methods—so offer an independent check of the modeling technique the SRTM2gravity products rely on (section 3). The RMS differences between SRTM2gravity values and reference values from global numerical integration were found to be smaller than 0.8 mGal over all test areas, with the RMS values ranging from 0.1 mGal (Australian Alps), 0.15 mGal (Indonesian Islands and South American Andes), ~0.5–0.6 mGal (European Alps and Canadian Rocky Mountains) to 0.75 mGal (Himalayas) as example for Earth's most rugged areas. Maximum differences at individual field points never exceeded an amplitude of 12.5 mGal over our test areas. For any area where topography is smoother than that of the Australian Alps (these are more than 90% of Earth's land areas), ~0.1-mGal accuracy can be reasonably expected.

These values are a measure for the computational accuracy, in that they show the error level that can be attributed to our SRTM2gravity conversion technique described in section 3. SRTM2gravity values should be well reproducible within this error margin with any independent and accurate forward modeling technique. It is important to bear in mind that the error level of SRTM elevation data is at the level of ~5 m (e.g., Rodriguez et al., 2006), which translates into ~0.5 mGal in the gravity domain (using a simple Bouguer plate model). In rugged terrain, individual SRTM errors can exceed 100 m (or ~10 mGal). Relative to the impact of elevation errors on the terrain corrections, the SRTM2gravity computational error level will thus play only a minor role for the quality of the terrain corrections.

(b) We have utilized the GGMplus gravity maps, which rely on SRTM-based forward modeling at spatial scales of ~10 km down to 250 m, and EGM2008 including GRACE/GOCE satellite gravity data at spatial scales down to 10 km. Ground-truth gravity was compared with two model variants, (1) GGMplus gravity (as released by Hirt et al., 2013) and (2) EGM2008, refined with GRACE/GOCE satellite gravity (as in Hirt et al., 2013) and augmented with the 90-m resolution SRTM2gravity short-scale component. Over our test

10.1029/2019GL082521

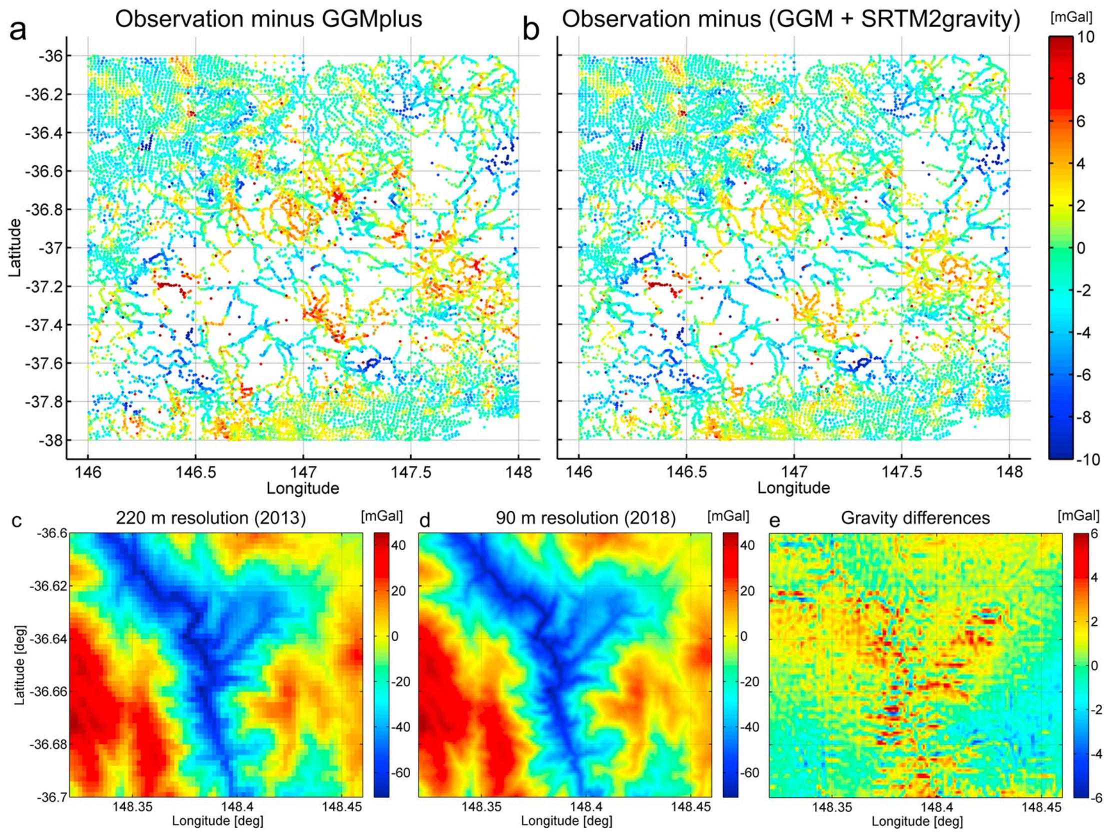

Figure 3. Top row: residuals between gravity observations and modeled gravity over the Australian Alps. (a) model = GGMplus; (b) model = GGMplus with the short-scale component replaced by SRTM2gravity. The top row gives an example of smaller gravity residuals as result of using SRTM2gravity data. Bottom row: comparison of the spatial detail modelled by GGMplus (Hirt et al., 2013; panel c) and SRTM2gravity (panel d) and their differences (panel e) over a 10 × 10 km area of the Australian Alps. The bottom row shows the short-scale gravity model constituents and their differences (mGal) at spatial scales less than 10 km. With the 90-m resolution level (center) many short scale terrain features are better represented in the gravimetric terrain corrections.

areas Bavaria, Switzerland, Australia, and Slovakia, the ground-truth gravity data sets suggest a comparable or better agreement (mostly over mountainous regions) when the new SRTM2gravity model is used as source for short-scale gravity constituents (see Table S5 from ESM for the statistics). This outcome can be attributed to the higher spatial detail resolution (90 m instead of 220 m), the use of bare-ground elevations, and refined forward modeling techniques (cf. Rexer et al., 2018).

4.3. Limitations

SRTM2gravity is a pure topography-implied gravity field model. Due to its very nature, it does not contain any observed gravity values. At short spatial scales, our model is an approximation of the real gravity field, but not an exact description of what can be measured with gravimetric techniques.

While due attempts have been made to remove spurious artifacts from the topographic input model, we cannot exclude the presence of further smaller artifacts in the topography data (e.g., steps or spikes with terrain gradients less than 5 m/m) and, in turn, in the forward-modeled gravity.

SRTM2gravity models the topographic gravity effect only and relies on the constant mass-density assumption. Mass-density anomalies (relative to the reference density of 2,670 kg/m^3) and the topographic masses of Antarctica have not been modeled. Examples of unmodeled density anomalies include, but are not limited to, the density contrasts associated with (a) lake water, (b) ocean water, (c) ice sheets, and (d) sediments. Users with mass density models at hand can forward model and improve the SRTM2gravity terrain correction grids. The mentioned restrictions especially apply to Greenland and to coastlines around the world. An extension of the modeling to Antarctica and the inclusion of ice sheets, ocean, and lake bathymetry in detailed 3″ resolution forward modeling is desirable and considered an important future task.

Over extremely narrow and deep mountain valleys (e.g., 2-km height difference w.r.t. surrounding summits), SRTM2gravity approximation errors will be largest. This is a consequence of the harmonic correction approach applied in the RTM gravity forward modeling. Approximation errors can reach few mGal up to ~12 mGal for kilometer-deep narrowly carved mountain valleys, as encountered, for example, in parts of the Himalayas, Rocky Mountains, or European Alps. This effect, included in the RMS accuracy estimates in section 4.2, will decrease for wider valleys and less rugged topography.

5. Discussion and conclusions

SRTM2gravity is the first successful attempt to transform global 3″ elevation data to implied gravity effects at ~28 billion computation points covering all of Earth's land areas within −60° to 85° geographic latitude and to release the grids into the public domain for free use. SRTM2gravity is based on an efficient computational methodology (section 3) that was applied in a globally consistent manner on a supercomputing facility.

The main product is a 3″ global grid of gravimetric terrain corrections that is immediately applicable to reduce the topographic signal in detailed gravimetric surveys. It contains the gravity effect of the Bouguer shell and that of the terrain irregularities around the globe in a single product. As such, complete Bouguer gravity anomalies as a modern kind of Bouguer gravity are obtained (e.g., Kuhn et al., 2009). Different to classical planar approaches that often use ~167-km integration zones (e.g., Fowler, 2005; Leaman, 1998; Nowell, 1999; Pasteka et al., 2017; Torge & Müller, 2012), our new gravimetric terrain corrections take into account the gravitational attraction of the topographic masses around the globe in spherical approximation. As a result, the topography-implied gravity effect is modeled much more completely and realistically.

The SRTM2gravity project can be thought of a logical continuation of the Kuhn et al. (2009) study that presented gravimetric terrain corrections over Australia at ~270-m resolution based on global numerical integration. Different to Kuhn et al. (2009), our model covers all land areas (apart from Antarctica), while now achieving ~90-m point density, being a standard resolution for contemporary global DEM data sets. Compared to Balmino et al. (2012) who have globally modeled gravimetric terrain corrections with spectral techniques at ~2-km resolution, our new 90-m SRTM2gravity grids provide a more than 20-fold improvement in detail resolution, allowing to capture gravity signals induced by local topography too. Given the sensitivity of gravity measurements for near topographic masses, the 90-m SRTM2gravity resolution may be crucial to improve the spectral consistency with measured ground gravity. On the other hand, in favor of Balmino et al. (2012) is that their maps are not restricted solely to land areas and a single constant mass density, as done in this study, but take into account also density contrasts associated with bathymetry, lakes, and ice caps.

SRTM2gravity is related to the GGMplus gravity maps (Hirt et al., 2013). Similarly to GGMplus, short-scale gravity signals have been modeled at scales less than ~10 km using DEM data and numerical integration techniques. SRTM2gravity, however, offers higher detail resolution (3″ instead of 7.2″ as in case of GGMplus) and uses improved data and modeling methods. Data improvements include (a) reduced radar errors and removal of canopy signals in the DEM (Yamazaki et al., 2017), (b) artifact screening and removal (Hirt, 2018), and (c) coverage of high northern latitudes (Yamazaki et al., 2017), while methodological improvements concern a more rigorous short-scale forward modeling (Hirt et al., 2019) and improved spectral consistency (Rexer et al., 2018). GGMplus primarily contained measured gravity data (via EGM08, GOCE, and GRACE) at scales larger than 10 km, whereas the SRTM2gravity model depends on topographic data at all spatial scales. As such, GGMplus was never a model of (complete) gravimetric terrain corrections, as it is now the case with SRTM2gravity.

SRTM2gravity represents a new milestone for ultrahigh resolution global gravity modeling combining global scope with local detail. In the context of the new 30-m NASA-DEM, an increase in spatial resolution to the 1″ level for future gravity products is foreseeable. This will further reduce very short-scale signal omission errors in future terrain correction products. On the other hand, modeling of gravity signals associated with ice and water masses at highest possible resolution is considered important future work; issues such as outliers and inconsistencies between land topography and ocean bathymetry in coastal zones (Hirt et al., 2014) will need to be carefully addressed in such future endeavors.

Data Statement

The SRTM2gravity products are freely available via ddfe.curtin.edu.au/models/SRTM2gravity2018, and further information are found at the project website (http://www.bgu.tum.de/en/iapg/forschung/schwerefeld/S2g/).

Acknowledgments
This project received support by the German National Research Foundation (DFG) via Grant Hi1760/01. The authors gratefully acknowledge computing time on the SuperMUC supercomputing facility by the Leibniz Supercomputing Centre (www.lrz.de) for the production of the SRTM2gravity model and the Pawsey Supercomputing Centre (www.pawsey.org.au) for the model validation. M. K. acknowledges Curtin University for the opportunity to contribute to this project as part of an academic study program. Providers of ground-truth data (Bayerisches Landesamt für Digitalisierung, Breitband und Vermessung, Swisstopo, Geoscience Australia) are kindly acknowledged.

References

Balmino, G., Vales, N., Bonvalot, S., & Briais, A. (2012). Spherical harmonic modelling to ultra-high degree of Bouguer and isostatic anomalies. *Journal of Geodesy*, *86*(7), 499–520. https://doi.org/10.1007/s00190-011-0533-4

Blakeley, R. J. (1996). *Potential Theory in Gravity and Magnetic Applications*. Cambridge: Cambridge University Press.

Bonvalot, S., Balmino, G., Briais, A., Kuhn, M., Peyrefitte, A., Vales, N., et al. (2012). World Gravity Map, 1:50000000 map, Eds. : BGI-CGMW-CNES-IRD, Paris.

Bucha, B., & Janák, J. (2014). A MATLAB-based graphical user interface program for computing functionals of the geopotential up to ultra-high degrees and orders: Efficient computation at irregular surfaces. *Computers and Geosciences*, *66*, 219–227. https://doi.org/10.1016/j.cageo.2014.02.005

Cella, F. (2015). GTeC — A versatile MATLAB® tool for a detailed computation of the terrain correction and Bouguer gravity anomalies. *Computers and Geosciences*, *84*, 72–85. https://doi.org/10.1016/j.cageo.2015.07.015

Chao, B. F., & Rubincam, D. P. (1989). The gravitational field of Phobos. *Geophysical Research Letters*, *16*(8), 859–862. https://doi.org/10.1029/GL016i008p00859

Featherstone, W. E., & Kirby, J. F. (2002). New high-resolution grid of gravimetric terrain corrections over Australia. *Australian Journal of Earth Sciences*, *49*(5), 733–734.

Forsberg, R. (1984). *A study of terrain reductions, density anomalies and geophysical inversion methods in gravity field modelling. Report 355*. Columbus: Department of Geodetic Science and Surveying, Ohio State University.

Forsberg, R., & Tscherning, C. C. (1981). The use of height data in gravity field approximation by collocation. *Journal of Geophysical Research*, *86*(B9), 7843–7854. https://doi.org/10.1029/JB086iB09p07843

Förste, C., Bruinsma, S. L., Abrikosov, O., Flechtner, F., Marty, J. C., Lemoine, J. M., et al. (2015). EIGEN-6C4 The latest combined global gravity field model including GOCE data up to degree and order 2190 of GFZ Potsdam and GRGS Toulouse. https://doi.org/10.5880/icgem.2015.1

Fowler, C. R. M. (2005). *The Solid Earth—An introduction to global geophysics* (2nd ed.). Cambridge: Cambridge University Press.

Hammer, S. (1939). Terrain corrections for gravimeter stations. *Geophysics*, *4*(3), 184–194. https://doi.org/10.1190/1.1440495

Heck, B., & Seitz, K. (2007). A comparison of the tesseroid, prism and point-mass approaches for mass reductions in gravity field modelling. *Journal of Geodesy*, *81*(2), 121–136. https://doi.org/10.1007/s00190-006-0094-0

Hirt, C. (2012). Efficient and accurate high-degree spherical harmonic synthesis of gravity field functionals at the Earth's surface using the gradient approach. *Journal of Geodesy*, *86*(9), 729–744. https://doi.org/10.1007/s00190-012-0550-y

Hirt, C. (2018). Artefact detection in global digital elevation models (DEMs): The Maximum Slope Approach and its application for complete screening of the SRTM v4.1 and MERIT DEMs. *Remote Sensing of Environment*, *207*, 27–41. https://doi.org/10.1016/j.rse.2017.12.037

Hirt, C., Bucha, B., Yang, M., & Kuhn, M. (2019). A numerical study of residual terrain modelling (RTM) techniques and the harmonic correction using ultra-high degree spectral gravity modelling. *Journal of Geodesy*. accepted for publication

Hirt, C., Claessens, S. J., Fecher, T., Kuhn, M., Pail, R., & Rexer, M. (2013). New ultra-high resolution picture of Earth's gravity field. *Geophysical Research Letters*, *40*, 4279–4283. https://doi.org/10.1002/grl.50838

Hirt, C., & Kuhn, M. (2014). Band-limited topographic mass distribution generates full-spectrum gravity field: Gravity forward modeling in the spectral and spatial domains revisited. *Journal of Geophysical Research: Solid Earth*, *119*, 3646–3661. https://doi.org/10.1002/2013JB010900

Hirt, C., Kuhn, M., Claessens, S. J., Pail, R., Seitz, K., & Gruber, T. (2014). Study of the Earth's short-scale gravity field using the ERTM2160 gravity model. *Computers & Geosciences*, *73*, 71–80. https://doi.org/10.1016/j.cageo.2014.09.00

Hirt, C., Reußner, E., Rexer, M., & Kuhn, M. (2016). Topographic gravity modelling for global Bouguer maps to degree 2,160: Validation of spectral and spatial domain forward modelling techniques at the 10 microgal level. *Journal of Geophysical Research: Solid Earth*, *121*, 6846–6862. https://doi.org/10.1002/2016JB013249

Jacoby, W., & Smilde, P. L. (2009). *Gravity interpretation: Fundamentals and application of gravity inversion and geological interpretation*. Berlin, Heidelberg: Springer.

Kuhn, M., Featherstone, W. E., & Kirby, J. F. (2009). Complete spherical Bouguer gravity anomalies over Australia. *Australian Journal of Earth Sciences*, *56*(2), 213–223. https://doi.org/10.1080/08120090802547041

Kuhn, M., & Hirt, C. (2016). Topographic gravitational potential up to second-order derivatives: An examination of approximation errors caused by rock-equivalent topography (RET). *Journal of Geodesy*, *90*(9), 883–902. https://doi.org/10.1007/s00190-016-0917-6

Leaman, D. E. (1998). The gravity terrain correction—Practical considerations. *Exploration Geophysics*, *29*, 476–471.

Li, Y. C., & Sideris, M. G. (1994). Improved gravimetric terrain corrections. *Geophysical Journal International*, *119*(3), 740–752. https://doi.org/10.1111/j.1365-246X.1994.tb04013.x

Nowell, D. A. G. (1999). Gravity terrain corrections—An overview. *Journal of Applied Geophysics*, *42*(2), 117–134. https://doi.org/10.1016/S0926-9851(99)00028-2

Pasteka, R., Mikuska, J., & Meurers, B. (2017). *Understanding the Bouguer anomaly—A gravimetry puzzle* (1st ed.). New York: Elsevier.

Pavlis, N. K., Holmes, S. A., Kenyon, S. C., & Factor, J. K. (2012). The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). *Journal of Geophysical Research*, *117*, B04406. https://doi.org/10.1029/2011JB008916

Rexer, M., Hirt, C., Bucha, B., & Holmes, S. (2018). Solution to the spectral filter problem of residual terrain modelling (RTM). *Journal of Geodesy*, *92*(6), 675–690. https://doi.org/10.1007/s00190-017-1086-y

Rexer, M., Hirt, C., Claessens, S. J., & Tenzer, R. (2016). Layer-based modelling of the Earth's gravitational potential up to 10km-scale in spherical harmonics in spherical and ellipsoidal approximation. *Surveys in Geophysics*, *37*(6), 1035–1074. https://doi.org/10.1007/s10712-016-9382-2

Rodriguez, E., Morris, C. S., & Belz, J. E. (2006). A global assessment of the SRTM performance. *Photogrammetric Engineering & Remote Sensing*, *72*(3), 249–260. https://doi.org/10.14358/PERS.72.3.249

Tenzer, R., Abdalla, A., & Vajda, P. (2010). The spherical harmonic representation of the gravitational field quantities generated by the ice density contrast. *Contributions to Geophysics and Geodesy*, *40*(3), 207–223. https://doi.org/10.2478/v10126-010-0009-1

Torge, W., & Müller, J. (2012). *Geodesy* (4th ed.). Berlin, New York: W. de Gruyter.

Tsoulis, D. (2001). Terrain correction computations for a densely sampled DTM in the Bavarian Alps. *Journal of Geodesy*, *75*(5–6), 291–307. https://doi.org/10.1007/s001900100176

Tsoulis, D. (2012). Analytical computation of the full gravity tensor of a homogeneous arbitrarily shaped polyhedral source using line integrals. *Geophysics*, *77*(2), F1–F11. https://doi.org/10.1190/geo2010-0334.1

Yamazaki, D., Ikeshima, D., Tawatari, R., Yamaguchi, T., O'Loughlin, F., Neal, J. C., et al. (2017). A high accuracy map of global terrain elevations. *Geophysical Research Letters*, *44*, 5844–5853. https://doi.org/10.1002/2017GL072874