Rupert Deese

Harvey Mudd College

Erik R. Ivins

Climate, Oceans and Solid Earth (3242)

Jet Propulsion Laboratory, California Institute of Technology

Eric J. Fielding

Climate, Oceans and Solid Earth (3242)

Jet Propulsion Laboratory, California Institute of Technology

Software Analysis of New Space Gravity Data for Geophysics and Climate Research

Both the Gravity Recovery and Climate Experiment (GRACE) and Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellites are returning rich data for the study of the solid earth, the oceans, and the climate. Current software analysis tools do not provide researchers with the ease and flexibility required to make full use of this data. We evaluate the capabilities and shortcomings of existing software tools including Mathematica, the GOCE User Toolbox, the ICGEM's (International Center for Global Earth Models) web server, and Tesseroids. Using existing tools as necessary, we design and implement software with the capability to produce gridded data and publication-quality renderings from raw gravity data. The straightforward software interface marks an improvement over previously existing tools and makes new space gravity data more useful to researchers. Using the software we calculate Bouguer anomalies of the gravity tensor's vertical component in the Gulf of Mexico, Antarctica, and the 2010 Maule earthquake region. These maps identify promising areas of future research.

I. Background

The science of gravimetry uses gravity data to discern the composition and structure of the earth, as well as how the earth changes over time [1][2]. The field of satellite gravity geodesy, revolutionized in 2000 with the launch of the CHAllenging Minisatellite Payload (CHAMP), is now producing unprecedented amounts of data for gravimetric study. Gravity data returned by three satellites (CHAMP, GRACE, and GOCE) has been used to produce satellite-only global gravity models of unprecedented resolution, exceeding 100 km. The correction and integration of data from local gravity surveys increases this resolution to nearly 10 km in some models [3][4]. In addition, new space gravity data is updated on a monthly basis, allowing for the study of very recent changes.

Researchers can use gravity data when it is represented in a meaningful form; several conventional forms exist. Calculation of the geoid, an equipotential gravitational surface coinciding with mean sea level, is useful for engineers and oceanographers. From the geoid, both free-air and Bouguer gravity anomalies can be calculated. A gravity anomaly is "the difference between a measured [gravity] value and a predicted value for the same point derived from some theoretical reference model" [5]. While a free-air gravity anomaly uses a uniform ellipsoidal reference model, a Bouguer anomaly improves upon this by taking into account topography and bathymetry [6]. The gravitational attraction of features above the sphere's surface is directly subtracted from the basic anomaly. For features below the surface of the sphere, the effect of excess density assumed by the basic anomaly is calculated and removed.

Gravity anomalies are most commonly calculated for G_z, the vertical (local spherical normal) component of the gravity vector. G_z is measured in Galileos and mGal:

$$1\mathbf{Gal} = 1.0 * 10^{-2}\frac{\mathrm{m}}{\mathrm{s}^2} \tag{1}$$

Anomalies of components of the gravity tensor, which is the gradient of the gravity vector, can also be calculated [7]. The gravity gradient and its components are measured in Eötvös:

$$1\mathbf{E\ddot{o}tv\ddot{o}s} = 0.1\frac{\mathbf{mGal}}{\mathbf{km}} = .1\frac{\mathbf{nGal}}{\mathbf{m}} \tag{2}$$

The gravity tensor, specifically G_{zz}, the vertical gravity gradient, has a better theoretical resolution than the gravity vector for some geophysical features [8]. The vertical gravity gradient is 3100 E at the earth's surface. For scientific analysis, the geoid and gravity anomalies are graphically rendered on maps.

Computers can be used to automate the non-trivial calculations required to produce gravity anomaly maps. Software has been designed to carry out each of the required calculations for the basic anomalies explained above, but no existing program can completely compute and render a variety of maps, while giving the user control over key steps of the process. In the absence of such a program, scientists spend significant amounts of time learning to use a variety of programs, in order to produce a finished product from gravity data. Knowledge of this gap in the existing software motivated a project to improve the software capability for handling gravity data. Specifically, these improvements would increase ease-of-use and efficiency, rather than refine theoretical aspects of the calculations.

II. Objectives

The goal of the project was: firstly, to use a combination of existing programs to create publication quality maps of both free-air and Bouguer anomalies; second, to create a powerful, efficient, and easy-to-use program automating the creation of anomaly maps; third, to demonstrate the usefulness of this program by exercising it on several areas of geophysical interest.

III. Approach

All research was conduced on a late-2011 MacBook Pro with an 8-core Intel processor. A diverse group of programs were thoroughly tested to determine their capabilities, strengths, and weaknesses. These included Mathematica, the GOCE User Toolbox (GUT), the International Center for Global Earth Models (ICGEM) Web Server, Tesseroids, and the Generic Mapping Tools (GMT) [9][10][5][11][12]. Across programs with a variety of intended functions and levels of sophistication, no rigorous standard of testing was applied--the goal of testing being to assess the suitability of each piece of software for use in the combined program. The calculation speed, range of functionality, and flexibility of input and output data of each program were assessed as best as possible.

After the completion of testing, free-air and Bouguer anomalies were created using a combination of the best tested programs. Free-air gravity anomalies were calculated using the ICGEM online service, and rendered into finished maps using GMT.

Bouguer anomalies were produced in a multi-step process, shown in Figures 1-3 for the Gulf of Mexico. First, a free-air anomaly using a spherical approximation was calculated using the ICGEM online service (Figure 1). Second, the GTOPO30 dataset was processed in GMT to create a coordinate grid of topographical heights [13]. A Python program was used to assign a density to each height: 2.670 g/cm^3 for features above sea level and -1.644 g/cm^3 for features below sea level. In Antarctica, large areas are below sea level but not below liquid water; for these, a density of -2.670 g/cm^3 was used. The BEDMAP dataset was used for Antarctic topography, and projected using GDAL [14][15]. The resultant coordinate grid of heights and densities was input into Tesseroids, which produced a coordinate grid estimating the gravitational attraction of the topography at each point (Figure 2). Finally, GMT was used to difference the free-air anomaly and topography correction, creating a Bouguer anomaly (Figure 3).

After these plots were produced, a program was written in the Unix Bourne shell to automate the process of calculation and rendering. The program consisted of one executable shell script with several callable methods, allowing for the calculation of either free-air or Bouguer anomalies, by the procedures described above.

Finally, comprehensive data sets for several regions were produced using the new program. The areas considered were the Gulf of Mexico, Antarctica, and the region surrounding the 2010 Maule earthquake [16]. For the topographical, free-air anomaly, and Bouguer anomaly maps were produced, and analyzed to gauge their potential usefulness in further geophysics research.

IV. Results

Mathematica contains several built in functions for the evaluation of spherical harmonics. These functions used different normalization factors than those required to process gravity data; for the purposes of the present project, correctly normalized functions were implemented from the ground up. These functions were used to process gravity data successfully. Figure 4 shows a plot of a simple spherical harmonic function plotted at low degree and order, the grid values for which were calculated using Mathematica. Processing time for a spherical harmonic function at degree and order 20 was 184 seconds.

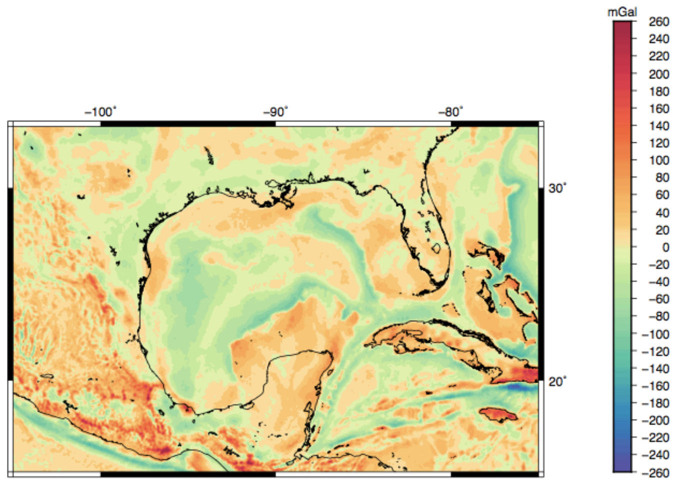


Figure 1. (Deese, 2012) Free-air anomaly of the Gulf of Mexico, calculated by ICGEM. This map, an end product in and of itself, is used to calculate the Bouguer anomaly.

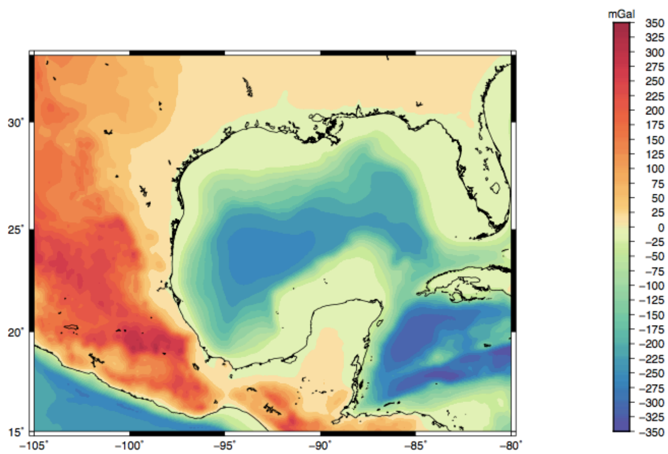


Figure 2. (Deese, 2012) Topographical gravity correction, calculated using Tesseroids. The gravitational correction is calculated using the difference in densities predicted by the topographical and ellipsoidal models. Thus the correction for the oceans is

(1.026 - 2.670) = 1.644 g/cm^3.

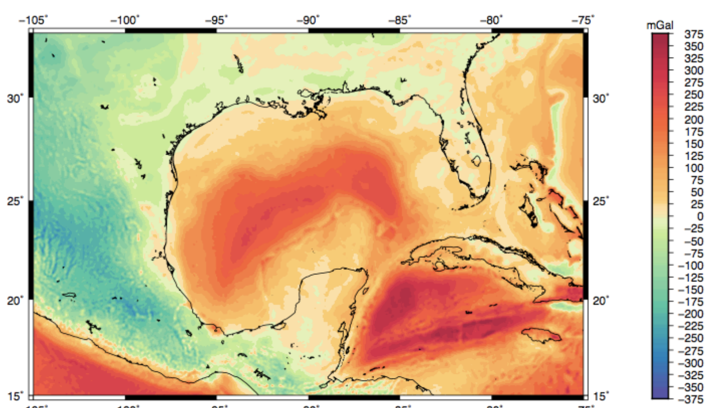


Figure 3. (Deese, 2012) Bouguer anomaly of the Gulf of Mexico, calculated by subtracting the topographical correction from the free air anomaly. The Bouguer anomaly reveals variation in crustal structure, thickness and density.

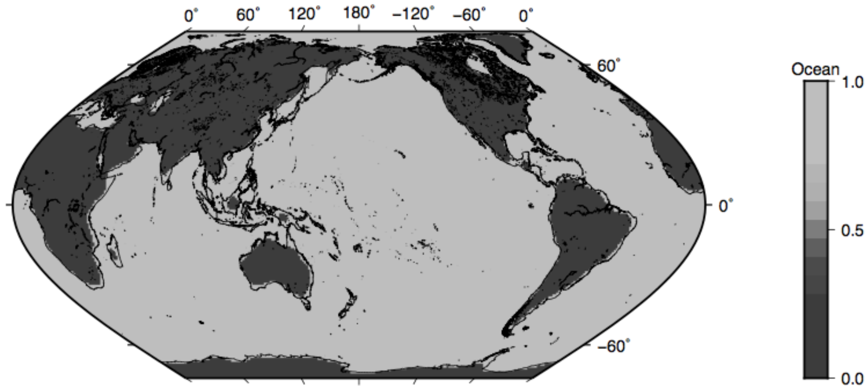


Figure 4. (Deese, 2012) A plot of spherical harmonic coefficients defining the 'ocean function' to degree and order 40, processed using Matlab and rendered with GMT. Note that the truncation level is such that the continents are rendered, but smaller features such as Madagascar and the Yucatan Peninsula are not resolved.

The GOCE User Toolbox (GUT) was used to process spherical harmonics relatively efficiently, and allowed for the manipulation of processed data in many ways. While GUT has a user interface for manipulating graphical products, we found that a command-line interface must be used to generate these graphs. Furthermore, exported graphs, like the one in Figure 5, allowed few options for improving clarity and aesthetics.

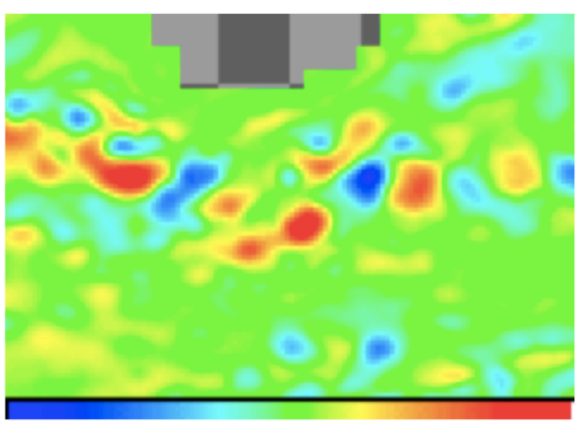


Figure 5. (above; GUT, 2012) Example of default graphical output from the GOCE User Toolbox. Note the absence of overlaid geography, or scale information.

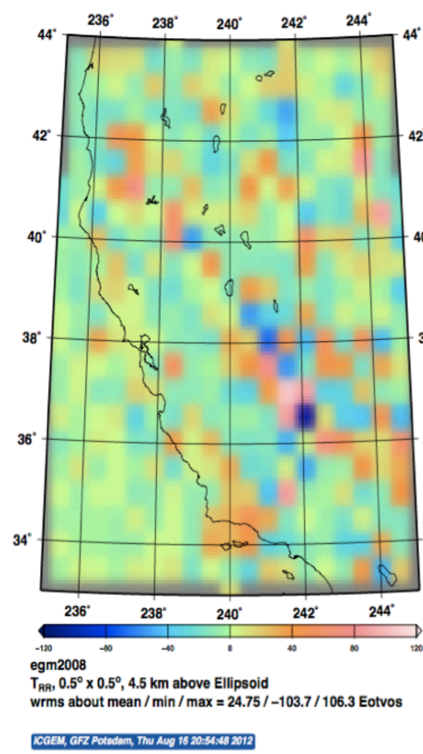


Figure 6. (right; GFZ Potsdam, 2012) Example of default graphical output from the ICGEM web server. Note the lack of smoothing.

The ICGEM web server represented the final option for the processing of spherical harmonics. Calculation times were found to be far shorter than when using GUT, because the web server performed all calculations remotely, presumably running better optimized and parallel subroutines on more powerful computers than those available to us for use with GUT. The web server provided access to a wide range of models and calculable functions, such as geoid height and gravity anomaly. Like GUT, we found that the web server afforded limited control over visual output. Figure 6 shows graphical output from ICGEM.

Tesseroids, a gravity modeling tool, was used to create topographical corrections. We found it to compute these corrections quickly, making good use of parallel processing over multiple cores. Tesseroids processes gridded digital elevation model data, and produces gridded data as output. It is operated from the command line.

GMT is a standard set of tools for the manipulation and rendering of gridded data. We found it to have an impressively wide range of functionality. It allowed for the summation and differencing of two datasets, as well as the filtering, smoothing, and interpolation of data, with good speed considering the size of the datasets. We found that it gave the user great control over rendering data using both gradients and contours, along with a suite of functions for overlaying geographical or other supplementary information.

Evaluation of newly implemented program

The program we implemented functioned as intended. It read text input from the user in response to text-based prompts. The program calculated and rendered gravity anomalies using the process described in III, and illustrated in Figure 1. The program was able to replicate these maps exactly. The quality of the maps produced sheds light on the efficacy and usefulness of the program.

The Bouguer anomaly of the vertical gravity gradient in the 2010 Maule earthquake region, as calculated by the program, agrees closely with previous calculations. Figure 7, a Bouguer anomaly of the region produced by the creator of the Tesseroids software, [11] agrees closely with Figure 8, the map created using the program. This indicates that the new program operates as intended to produce accurate data.

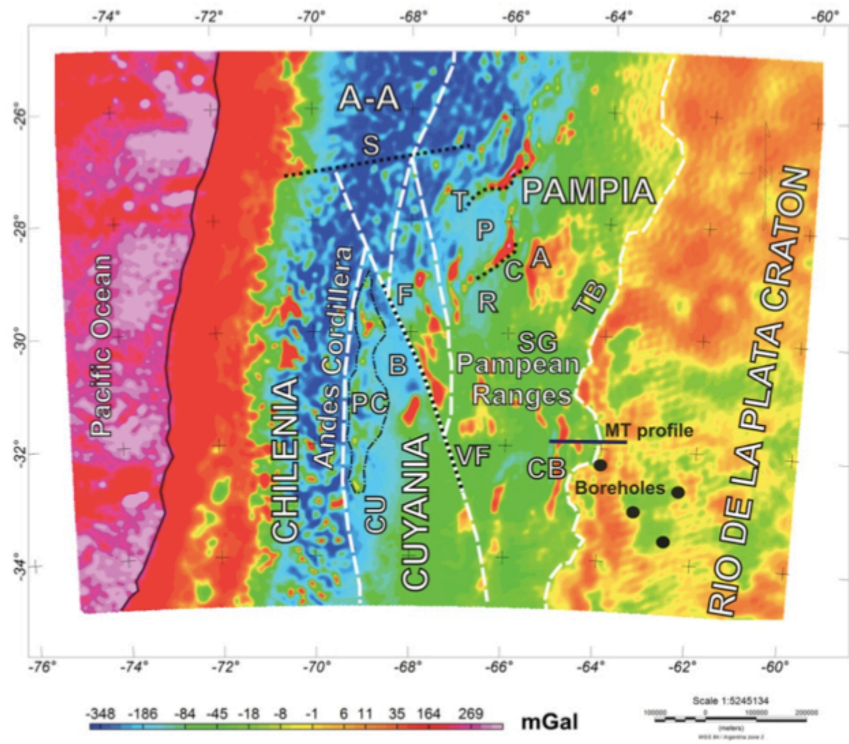


Figure 7. (Alvarez, 2012) Bouguer anomaly map of the 2010 Maule earthquake region, on a logarithmic scale. Annotations label geophysical features made visible by this analysis.

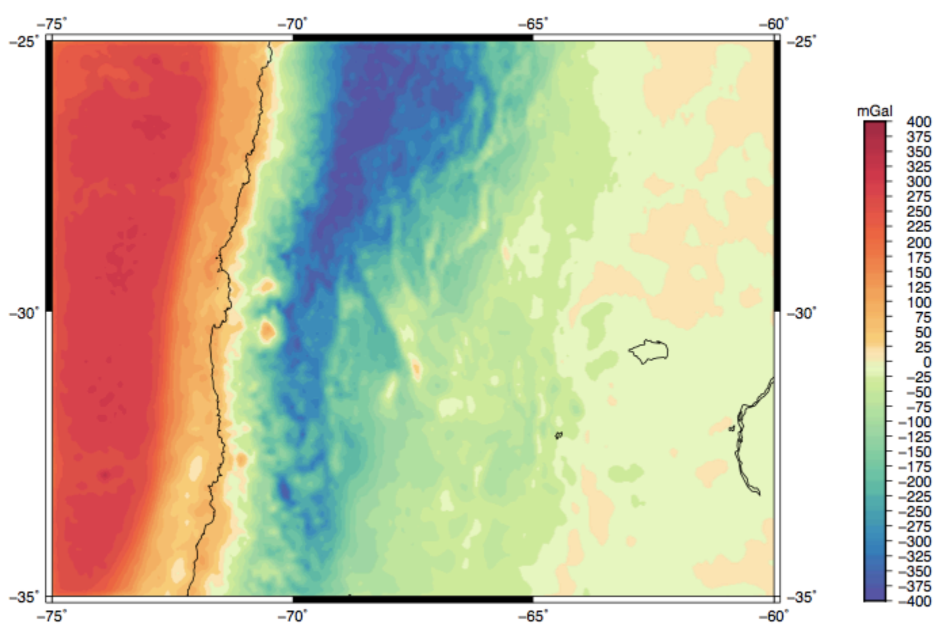


Figure 8. (Deese, 2012) Bouguer anomaly map of the 2010 Maule earthquake region produced using the newly developed software. The features annotated in Figure 7 are clearly visible, and the resolution of the two maps is comparable.

The free-air and Bouguer anomaly maps of the vertical gravity gradient show clear signatures of processes such as volcanism, isostatic compensation, and flexure. Figure 9 shows 2009 data suggesting the presence of an enormous impact crater in the Wilkes Land, along with free-air and Bouguer anomalies of the vertical gravity gradient taken from EIGEN-6C data [17]. The ring feature is also visible in the free-air vertical gradient, shown in Figure 10, but disappears after a topographical correction is made (Figure 11). New satellite data and analysis neither support nor rule out the existence of an impact crater in the Wilkes Land.

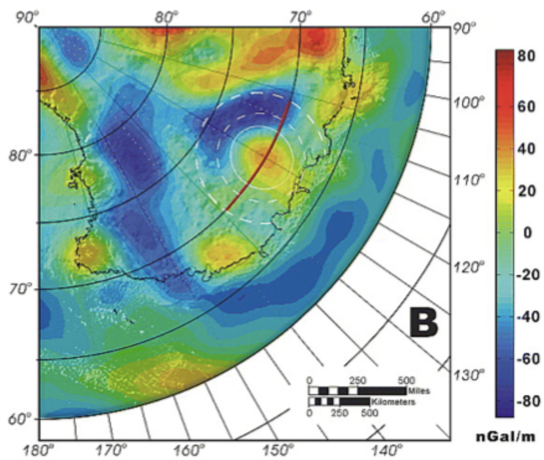
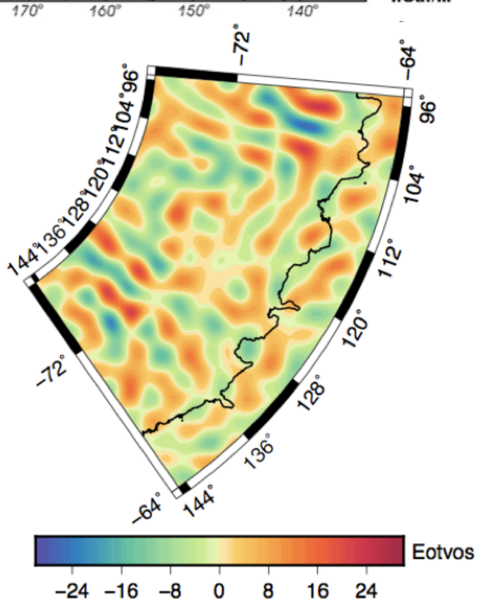


Figure 9. (von Frese et al., 2009) Gravity anomaly data suggests the presence of an enormous impact crater in the Wilkes Land. White dashed lines indicate the center and various radii of the putative crater.



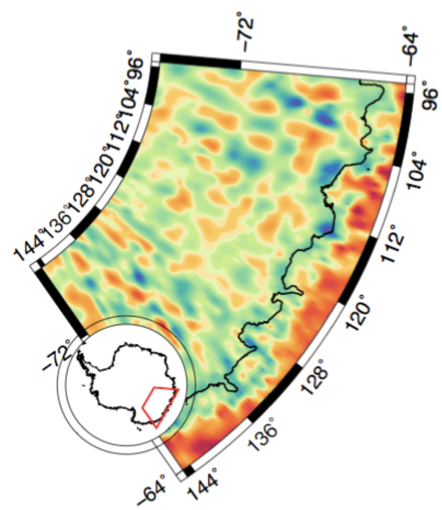


Figure 10. (Deese, 2012) A ring feature is also visible in the free air anomaly of the vertical gravity gradient.

Figure 11. (Deese, 2012) The Bouguer anomaly of the vertical gradient shows only high degree and order noise, and no clear ring feature.

In sum, maps of the three regions are detailed, accurate, and provide new data for geophysical research. Evaluating the program by the quality of the maps produced, and the ease with which they were created, the program worked as planned.

V. Discussion

The project met expectations in all respects. Not only were free air and Bouguer anomalies produced, but the process of their production was streamlined into a single new program. This program vastly simplifies the calculation of a wide range of gravity anomalies, using the vertical gravity gradient as well as gravity vector magnitude. The program also provides much control over the rendering of maps.

The maps produced by the program are detailed, and, as confirmed by comparison with published maps, accurate. The maps of the Wilkes Land indicate that, where recent data provides higher resolution, the new program can facilitate new research in fields reliant on gravity data, such as geophysics. To a degree not anticipated at the start of the project, existing data has not been available to researchers simply because the labor necessary in creating anomaly maps is too time-consuming. Speaking with various geophysics researchers at JPL, it became apparent that maps produced by the program using data several years old were highly desirable for use in current research. Although this need was foreseen at the outset, real instances of demand for the new program provided validation of its theoretical usefulness. Gravity data need not be the focus of research; gravity maps can provide excellent background for many kinds of geophysical research. A map of the Gulf of Mexico made using the program was deemed suitable for a recently submitted AGU abstract [18].

VI. Conclusions

The research conducted showed that existing gravity mapping software is computationally powerful, but flawed in accessibility, completeness, and design. However, the power of existing software was harnessed, creating a program unique in its scope and convenience. The new program we created makes the entire process of working with gravity data, from spherical harmonics to plotting datasets, efficient and accessible to those unfamiliar with the multiplicity of programs that it requires. The program represents a further step towards a software infrastructure that makes viewing and manipulating gravity data as easy as panning around in Google Earth. A more immediate consequence of the program is that it can capitalize on new data of diverse types and sources, making new research possible. Brief inquiries into the Gulf of Mexico, the Maule earthquake region, and the Wilkes Land show this conclusively. Newer and more accurate space gravity data, paired with more capable and more accessible programs, will continue to advance gravimetric study of the earth, and aid geophysical and climate research. Nor is gravity-based science limited to terrestrial applications: gravity mapping of the moon, Mars, and other bodies in the solar system has and will continue to make invaluable contributions to the field of planetary science.

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