Interdisciplinary Space Geodesy: Challenges in the New Millennium

Jean O Dickey
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109-8099, USA
jean.o.dickey@jpl.nasa.gov

Abstract: The sphere of influence of space geodesy is ever enlarging, with impressive achievements in the last few decades in many diverse areas (such as geodynamics, planetary and atmospheric sciences, oceanography, tectonics, and ice studies). Earth system studies have made major advances with the advent of accurate space geodetic techniques with high temporal resolution and the increasing availability of complementary geophysical data. Examples include positioning at the millimeter level, enabling determination of crustal deformation and strain with unprecedented accuracy at high time resolution; water vapor monitoring via GPS; and improved gravity modeling and orbit determination, permitting an unparalleled view of the 1997-1998 ENSO event. The new millennium holds even more promise, with many planned developments, such as GOCE, GRACE, and ICESAT missions, densification of GPS networks, and the development of new technologies. This paper will highlight recent geodetic advances and their interdisciplinary impact with a vision towards the future.

Keywords. Space Geodesy, Gravitational field, temporal variations of the potential, sea level and glaciology, ocean dynamics, ocean-bottom pressure, hydrology and water storage.

1 Introduction

According to Webster, geodesy is a branch of applied mathematics concerned with the determination of the size and shape of the Earth and the exact position of points on its surface and with a description of variations of its gravity field. Geodesy today is much more than this! In this paper, we highlight the transition from Classical Geodesy to the emerging Interdisciplinary Geodesy of today and feature a few of the recent remarkable geodetic advances (Section 2). We then examine expectations for the future for geodesy, featuring time-variable gravity as an emerging geophysical frontier (Section 3). Concluding remarks are presented in Section 4.

2 Recent Triumphs in Interdisciplinary Geodesy

In the past, the classical geodesist may have viewed the Earth with a more geometrical outlook, being concerned with the size and shape of the Earth and precise positioning on its surface, along with a description of its gravity. Today, we have enlarged our scope and are now examining the big picture; we are concerned with the various processes involved as well as the geophysical causes and implications. The role of the geodesist is no longer strictly defined with narrow boundary conditions; the sharp distinctions among classical disciplines have or are quickly fading. Clearly, geodesy is much more than applied mathematics and an observing system. For example, in the case of altimetry, a geodesist may indeed be both an oceanographer and geodesist; typically the doing of geodesy and oceanography concurrently actually results in maximizing the data return.

We also strive to understand the physics involved and endeavor to make the best use of the knowledge gained, teaming up with other communities. One application is the use of axial atmospheric angular momentum (AAM) results in Earth rotation determination and predictions. The atmosphere is the dominant Earth rotation excitation source on subseasonal to interannual time scales; as a consequence, the angular momentum of the Earth, length-of-day (LOD), is very highly correlated with the axial AAM. In addition to gaining a wealth of information on the solid Earth-atmosphere interactions from the joint study of axial AAM and LOD, geodesists have implemented the use of both AAM analysis and predictions to improve Earth rotation predictions needed for a broad range of applications, such as navigation.

Geodesists often look beyond the original objectives to ponder what more we can do and/or learn. A prime example of this is the immense variety of GPS applications; note that the original GPS system was geared to logistical positioning at the meter level. The growth and developments of space geodesy, in GPS in particular, have yielded routine positioning at the millimeter-level enabling the detection of crustal movement and strain with unprecedented accuracy and high time resolution. Local GPS arrays, such as the Japanese Network with over 1,000 receivers and the SCIGN (Southern California Integrated GPS Network) array with over 250 stations, provide a wealth of information about regional tectonics and a monitoring system for natural hazards. The development of precise GPS kinematic positioning techniques used in concert with other remote sensing methods, such as radar or laser methods, have given new opportunities to support environmental and mapping sciences. SAR (synthetic aperture radar) measurements over ice fields have opened a new chapter in glaciology. SAR images taken before and after earthquakes provide unique insights that complement GPS networks. Navigation has been revolutionized with GPS satellite orbit determination accurate at the few cm level, allowing TOPEX to provide a near real-time knowledge of the developing El Nino events. Work is underway in the use of GPS by the FFA (Federal Flight Administration, USA) in aircraft traffic control; other applications include (among others) farming with GPS, tracking shipments and even herds of elephants. I was told by one field worker in Greenland that he does not leave his tent without his GPS receiver. GPS receivers located on golf carts can even improve your golf game! These applications were enabled by geodesists, who were clever and resourceful enough to go beyond the initial goals of the GPS system.

An interesting phenomenon in geodesy is the transformation of stumbling blocks into stepping-stones. Uncertainties of water vapor in the atmosphere and its effect on signal propagation have long been recognized as a dominant error in VLBI, with similar effects in GPS and to a lesser extent in SLR. This problem has been turned into an opportunity with determination by GPS ground networks of total zenith delay, a new data type for the atmospheric community. In addition, GPS space occultation measurements permit the determination of water vapor at low altitudes as well as temperature at high altitudes, where the amount of water vapor is negligible. The GPS data type is all weather, unaffected by clouds, and brings robust coverage to the typically data sparse Southern Hemisphere and over the oceans; as a bonus, this system also provides new ways to map ionospheric irregularities. GPS meteorology is currently an intense area of activity bringing both geodesists and meteorologists together in a joint effort. Radio occultation experiments have been utilized many times to study planetary atmospheres; geodesists are now bringing this technique home to study the Earth's atmosphere.

3 Coming Attractions

The next millennium holds even more promise, with many planned developments, such as GOCE, GRACE, and ICESAT missions, densification of GPS networks, and the development of new technologies with advancements in many areas. Here we choose to focus on one topic, time-variable gravity, as an illustrative example of what the future may hold.

Traditionally, the gravity field has been treated as essentially steady state, or "static," over human lifetimes because over 99% of the departures of the field from a rotating fluid figure of the Earth's mass, mean radius, and moment-of-inertia are static in historic time. The static field is dominated by irregularities in the solid Earth caused by convective processes that deform the solid Earth on time scales of thousands to millions of years. Spaceborne gravity measurements have already led to dramatic advances in recent years in the understanding of the structure and dynamics of the core and mantle, the thermal and mechanical structure of the lithosphere, ocean circulation, and plate tectonics. For a review, the reader is referred to Nerem et al. (1995) and NRC (1997) and the references therein. The substantial improvements in the accuracy of static field measurements that would result from the upcoming satellite gravity missions would allow geophysically important smaller-scale features to be resolved and, by improving the geodetic reference frame, would greatly enhance other types of satellite measurements as well.

We envision that the most dramatic advances arising from the next generation of gravity satellites will be in the examination of the remaining less than 1% of the departure of the gravity field, which is caused by processes that vary on timescales ranging from hours to thousands of years. Temporal variations are caused by a variety of phenomena that redistribute mass, including tides raised by the Sun and Moon, and post-glacial rebound (i.e., creep in the mantle in response to the geologically recent removal of ice sheets). The hydrosphere—oceans, lakes, rivers, ground water—is the source of much of the irregular variations in the time-varying mass distribution from sub-daily (tides) to long-term (aquifer depletion). Variations of mass within the atmosphere are manifested as surface pressure changes and contribute significantly at seasonal and other time scales. The cryosphere—the part of the Earth's surface that is perennially frozen—also has seasonal and interannual variations, as well as a long-term secular effect. Particularly exciting is the potential to study sea level changes, post-glacial rebound, deep circulation of the oceans, and changes in soil moisture and ground and surface water in continental regions. Many of these have application to issues of importance to society such as global climate change and the availability of natural resources.

Many fields of study would be significantly advanced by improved knowledge of the Earth's time varying gravity field; a few highlighted here are sea-level rise and glaciology, ocean dynamics and continental water variation.

3.1 Sea-Level Rise and Glaciology

The sources of global sea-level rise (between 1.0 and 2.5 mm/yr over the last century) are uncertain; most, but not all, of the likely mechanisms involve the redistribution of mass from the continents to the ocean. Gravity measurements can help to discriminate between these sources through the continual monitoring of geoid changes, not only on global scales, but also on regional and basin scales. From a satellite-to-satellite tracking (SST) type mission (five-year mission assumed) similar to the GRACE scenario, an increasing mass of water in the ocean equivalent to 0.1 mm/yr of sea level rise can be measured (NRC 1997). Changes in the masses of the Antarctic and Greenland ice sheets are the major unknown contributions to non-steric sea-level rise. Gravity measurements over the ice sheets (particularly in combination with a laser-altimeter mission) would yield a much-improved determination of those contributions (see NRC 1997; Bentley and Wahr 1998; and Dickey et al. 1998).

Satellite gravity measurements are capable of yielding valuable information about the mass balance of individual drainage systems within the Antarctic ice sheet, as well as of the ice sheet as a whole. Glaciologists could use such information to test models of ice dynamics, which are essential to the prediction of future sea-level change. Satellite gravity could also be used to study secular, interannual, and seasonal changes in the mass of ice and snow in regions characterized by a large number of glaciers and ice caps. A prime example is the glacier system that runs from the Kenai Peninsula in southern Alaska down to the coastal ranges of the Yukon and British Columbia.

Accurate evaluation of post-glacial rebound models, together with improved ocean circulation models, should remove significant errors from old tide-gauge records, thus permitting improved estimates of sea level rise during the past century.

3.2 Ocean Dynamics

Surface currents can be estimated from the horizontal surface pressure gradient, which is proportional to the departure of the sea surface elevation from the marine geoid. The accuracy of ocean heights measured by satellite altimetry is presently approaching ~10 mm. Nevertheless, present geoid slope errors are much larger at resolutions shorter than about 3000 km, which prevents the accurate measurement of absolute surface pressure gradients at those scales (see Fig. 1). A satellite gravity measurement can eliminate the geoid uncertainty in horizontal pressure gradients at much shorter scales (to about 300 km—see NRC 1997 and Dickey et al. 1998). It would also allow recomputation of accurate altimetric orbits for past satellites, back to 1985, improving studies of long, global sea-level time series. Studies in ocean regions with a strong barotropic component will benefit from knowledge gained from the static geoid. These include the recirculation cells in the subtropical gyres of the western Atlantic, the Kuroshio Current, the Agulhas Current, and the Antarctic Circumpolar Current.

Most of what is known about the ocean occurs in the upper 500 meters. Studies suggest that uncertainties in the deep circulation and heat and mass transport will be reduced by a factor of two or more in oceanographic regions that are currently data sparse. Part of this reduction comes from an improvement in estimates of surface currents. For example, the geostrophic advective terms in the mixed-layer heat budget would be resolvable with an uncertainty of less than 10 W m-2 on length scales longer than 300 km.

The combination of altimetry and time-varying gravity will allow the separation of the steric and mass components of sea level rise variations, including secular change. This separation will substantially increase the usefulness of sea level measurements in testing ocean models and constraining ocean circulation.

Interesting and detectable signals that indicate changes in sea-floor pressure averaged over spatial scales of a few hundred kilometers and larger are expected. These will allow the detection of large-scale abyssal ocean current variations with seasonal to interannual time scales (see Fig. 2). Detection of these phenomena requires a multi-year mission lifetime and high accuracies at long wavelengths.

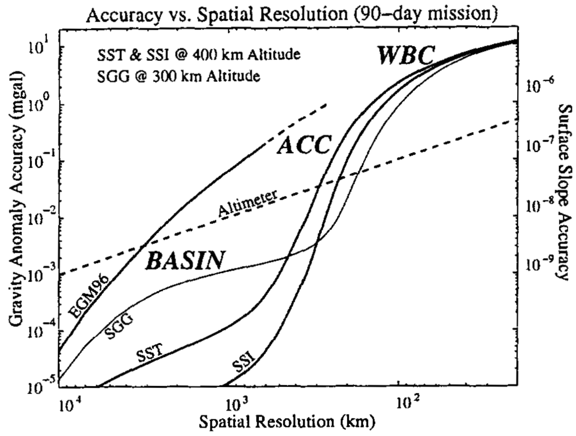

Figure 1. (from Dickey et al. 1998). Errors versus spatial resolution for the Spaceborne Gravity Gradiometry (SGG) 300-km mission, the Low-Low Satellite-to-Satellite Microwave Tracking (SST) and the Low-Low Satellite-to-Satellite Laser Interferometry (SSI) 400-km missions, and the EGM96 gravity model. The surface-slope scale is shown on the right-hand axis and the approximate slope magnitude and spatial scales of basin-wide currents (BASIN), the Antarctic Circumpolar Current (ACC) and Western Boundary Currents (WBC) are indicated. The dashed line indicates the slope error versus separation distance assuming a 10-mm uncertainty in altimeter height differences. The payoff for the static ocean problem appears to be in the range of about 300 to 3000 km where the gravity error is dominant without a gravity mission and becomes insignificant with a gravity mission.

3.3 Continental Water Variation

Gravity missions can provide estimates of changes in water storage over spatial scales of several hundred kilometers and larger that would be accurate to 10 mm or better (NRC 1997 and Wahr et al. 1998, see Fig. 3). These would benefit the Global Energy and Water Cycle Experiment (GEWEX) directly and would be useful to hydrologists for connecting hydrological processes at traditional length scales (tens of kilometers and less) to those at longer scales. Natural and human induced variations in soil moisture, groundwater level and snowpack can be expected to be detected. Improved knowledge of soil moisture would enhance estimates of agricultural productivity by helping to assess water available for irrigation. Water storage is important also to meteorologists because of the effect of soil moisture on evapotranspiration.

Both monitoring and prediction are technologically feasible and hold promise for the mitigation of natural hazards and ongoing evaluation of the state of one of the world's most important renewable resources, its fresh water. Measurements of gravity variations can

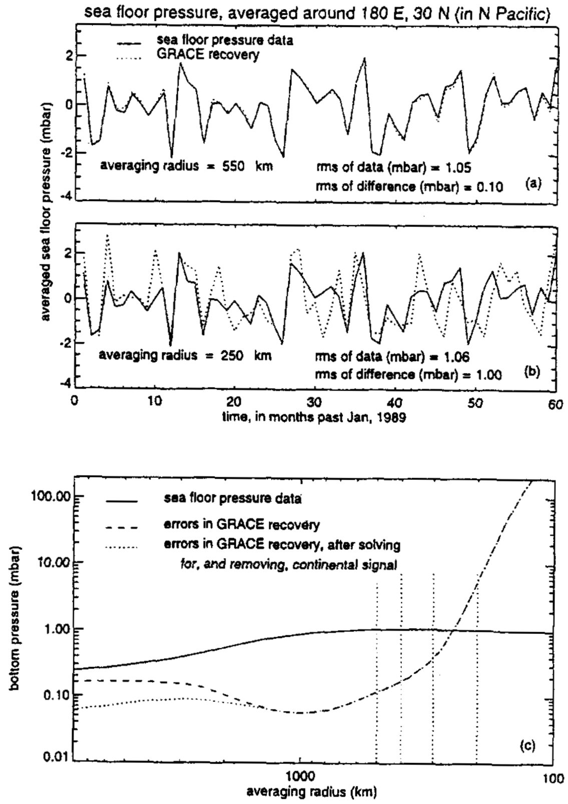

Figure 2 (from Wahr et al. 1998). The results of simulations in which synthetic GRACE data are used to recover the seafloor pressure at a location in the middle of the North Pacific Ocean (180^{0}E, 30^{0}N). Panels (a) and (b) show five years of monthly values for two averaging radii. The solid line is the signal that went into the simulation, and the dotted line is the signal inferred from the synthetic GRACE data. Panel (c) shows the rms of five years of monthly data as a function of averaging radius. The solid line is the estimate from the data. The dashed line represents the accuracy of the GRACE results, after solving for, and removing, the continental contributions.

help monitor aquifer depletion. Gravity results can aid in monitoring snow pack, predicting floods and the runoff available for irrigation, and assessing agricultural productivity on large scales.

4. Concluding Remarks

Geodesy is a science used in addressing a broad range of problems, and in the future many planned developments such as the GRACE, GOCE, ICESAT and CRYOSAT satellite missions, as well as new technological developments in positioning and gravity measurements will undoubtedly continue to broaden the influence of geodesy to a wide field of Earth, environmental and planetary sciences. The best is yet to come!

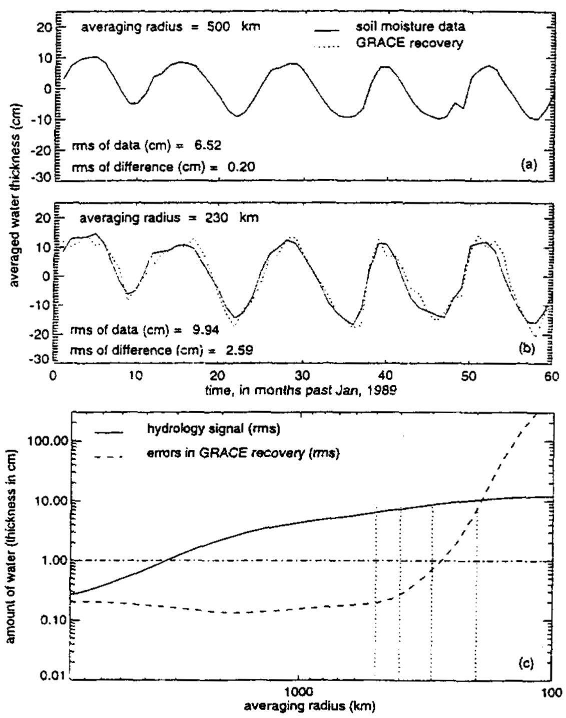

Figure 3 (from Wahr et al. 1998). The results of simulations in which synthetic GRACE data are used to recover the hydrological signal at Manaus, Brazil (in the Amazon River Basin). The simulated geoid data include the GRACE geoid errors, as well as contributions from hydrology and oceanography, and our estimated errors in the atmospheric pressure data. Panels (a) and (b) show five years of monthly values for two averaging radii. The solid line is the hydrology signal that went into the simulation, and the dotted line is the signal inferred from the synthetic GRACE data. Panel (c) shows the rms of five years of monthly data as a function of averaging radius. The solid line is the estimate from the hydrology data. The dashed line represents the accuracy of the GRACE results, estimated as the rms of the difference between the GRACE recovered values and the hydrology signal.

Acknowledgements. The author gratefully acknowledges the other members of the National Research Committee, Earth's Gravity from Space: Charles R. Bentley, Roger Bilham, James A. Carton, Richard J. Eanes, Thomas. A. Herring, William M. Kaula, Gary S.E. Lagerloef, Stuart Rojstaczer, Walter H.F. Smith, Hugo M. van den Dool, John M. Wahr, and Maria T. Zuber. The others members of the International Association of Geodesy Review Board (Gerhard. Beulter, Fritz Brunner, Martine Feissel, Rene Forsberg, Ivan I. Mueller, Reiner Rummel, Fernando Sanso, and Klaus-Peter Schwarz) are also acknowledged, with special thanks to Rene Forsborg for interesting e-mail exchanges. We also thank Steven L. Marcus for insightful comments on the manuscript. The work described in this paper was performed by the author at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

Bentley, C.R. and J.M. Wahr (1998) Satellite gravity and the mass balance of the Antarctic ice sheet, *Journal of Glaciology, 44*(147), 207-213.

Dickey, J.O., Time Variable Gravity: An Emerging Frontier in Interdisciplinary Geodesy, Gravity, Geoid and Geodynamics 2000, International Association of Geodesy Symposia, **123**, M. Sideris (ed.), Springer, New York, 1-5, 2001.

Dickey, J. O., C. R. Bentley, R. Bilham, J. A. Carton, R. J. Eanes, T. A. Herring, W. M. Kaula, G. S. E. Lagerloef, S. Rojstaczer, W. H. F. Smith, H. M. van den Dool, J. M. Wahr, M. T. Zuber (1998) Satellite Gravity and the Geosphere: Contributions to the Solid Earth and Its Fluid Envelope, *EOS, Trans. Amer. Geophys.Union, 79*, 20, 237-243.

Nerem, R. S., C. Jekeli, and W. M. Kaula (1995). Gravity field determination and characteristics: Retrospective and prospective, *J. Geophys. Res., 100*(B8), p. 15,053-15,074.

NRC (1997). Satellite Gravity and the Geosphere: Contributions to the Study of the Solid Earth and Its Fluid Earth, *Natl. Acad. Press*, Washington, D.C., 112 pp.

NASA (1987). Geophysical and Geodetic Requirements for Global Gravity Field Measurements, 1987-2000: Report of a Gravity Workshop, Colorado Springs, CO. NASA Geodynamics Branch, Division of Earth Science and Applications, Washington, D.C., 45 pp.

Wahr, J., M. Molenaar, M. and F. Bryan (1998) Time-Variability of the Earth's Gravity Field: Hydrological and Oceanic Effects and Their Possible Detection Using GRACE, *J. Geophys. Res., 103*,30205-30230.