SECTION VIII.

REPORT OF THE PANEL ON GEOPOTENTIAL FIELDS: GRAVITY FIELD

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1.0 SUMMARY

1.1 Introduction

For nearly three decades models of the Earth's gravity field based on satellite tracking data have been under continual development. These models, of ever increasing size and accuracy, have been used to help understand the structure of the solid Earth and the shape of the ocean surface.

Several geodetic spacecraft have been launched during the last two decades during which most of the progress has been accomplished. The GEOS-1, -2, & -3 spacecraft of the mid-sixties to mid-seventies introduced flashing lights and altimetry, and brought laser ranging methods to the forefront. The Transit series of spacecraft exploited Doppler tracking and the Lageos spacecraft brought definitive recovery to the low degree and order field, including the first measurements of both the secular change and the seasonal variations in the Earth's flattening term, J_2. Secular variations of J_2 and J_3 have been observed using Starlette.

On global scales, present satellite models have accuracies of order +/-7 mGal at their highest resolution of 400 km. Over ocean areas, where altimeter data are available, our knowledge at 100 km is about +/-4 mGal, along-track accuracies can be much better. The fundamental limitation is track spacing. Over the continents surface gravity data are available in a number of areas, particularly North America, Europe and Australia. However, there are many continental areas for which there is very limited good quality data. It is estimated that only 20% of the continental areas are known to +/-5 mGal at a horizontal resolution of 100 km (Mueller and Zerbini, 1989).

1.2 Science Requirements

The requirements for gravity modeling have been described in the reports of several recent workshops. For the purposes of preparing a program plan, we assume that the overall requirements for gravity, taking into account the technology that can be expected to be available during the next decade, stipulate an accuracy of 1 mGal at 100 km resolution on a global scale and 2 mGal at 10 km resolution in local regions.

Specific gravity field requirements for oceanography, the continental lithosphere, the ocean lithosphere, mantle convection, and temporal variations in gravity are discussed in this report.

1.3 Data Acquisition

The only method available for improving the long wavelength gravity field to date has been through the tracking of spacecraft from stations on the Earth's surface and by the tracking of one spacecraft by another. Ground-based tracking of the next decade will include laser ranging, and several microwave techniques, including GPS, the French DORIS system, and the German PRARE. At the present time, these methods represent the most precise techniques for ground-based spacecraft positioning.

For the determination of the short wavelength terms in the gravity field the satellite-to-satellite tracking technique appears to have the potential of providing 100 km scale information. To obtain shorter wavelengths a low altitude spacecraft is necessary but the limited visibility from ground stations fails to produce adequate data to properly resolve the large number of high frequency terms. Two basic methods for satellite-to-satellite tracking exist; the high-low method and the low-low method. The high-low tracking of a satellite with present-day GPS could yield the gravity field down to wavelengths of 250 to 500 km with high precision. Candidates for this type of approach are TOPEX/Poseidon, Gravity Probe-B, and ARISTOTELES.

An important method for obtaining the global short wavelength gravity field is with an orbiting gravity gradiometer. Currently two approaches are being developed: one in Europe and the other at the University of Maryland. The former is aiming at a precision of 10^{-2} EU and is the prime instrument on ARISTOTELES. The latter, a superconducting gravity gradiometer, is the instrument that is planned to be flown on the SGGM which would have a precision of 10^{-4} EU as it's goal.

An even greater resolution of the gravity field by space methods (1 mGal at 10 km) can be obtained indirectly by satellite altimetry with very close cross track spacing. In addition, airborne gravity or gradiometry combined with GPS tracking can be applied to specific areas of interest.

Absolute gravity measurements are important for determining time varying components of the Earth's gravity field. These measurements are of particular interest at VLBI, SLR and GPS and tide guage sites for relating gravity changes to crustal motion. Surface gravimeter measurements can be acquired in small regions of specific interest to support these efforts.

Higher resolution recovery of periodic and secular changes could be obtained by one of the following concepts: a) a series of separate missions that can solve for the long wavelength field with high precision such as with GP-B and SGGM; b) tracking of geodetic satellites with different inclinations such as Lageos and Etalon; c) using a constellation of low cost satellites with laser, microwave, or GPS tracking by selecting appropriate altitude, eccentricity and inclination; and d) by extending the lifetime of the drag-free GP-B equipped with GPS significantly beyond the nominal lifetime.

1.4 Recommended Program

The program in priority order recommended by the Panel on the Earth's Gravity Field is as follows:

1. *Fundamental, and of high priority, is the funding for the analysis of the proposed missions, of existing data, and the data to be acquired from the missions.*

2. *ARISTOTELES augmented with a GPS receiver (1997).*

3. *Advanced Gravity Field Mission with the technology to be defined (1999).*

4. *GPS guided airborne gravity (or gradiometry) acquisition in selected land areas (1993).*

5. *GP-B with GPS (1996).*

6. *Gravity Field Time Variation Missions (1998).*

7. *Ocean altimeter with a 10 km resolution (1997).*

2.0 INTRODUCTION

For nearly three decades, models of the Earth's gravity field based on satellite tracking data have been under continual development. These models, of ever increasing size and accuracy, have been used to help understand the structure of the solid Earth and the shape of the ocean surface. In the United States, these techniques have been developed at the Smithsonian Astrophysical Observatory, the Goddard Space Flight Center, the Ohio State University, at the University of Texas at Austin, and at the Air Force Geophysics Laboratory. In Europe, where similar research was underway the main centers of activity were at Groupe de Recherche de Geodesie Spatiale (GRGS) in France and Deutsches Geodatisches Forschungsinstitut (DGFI) in Germany.

The method from which the gravity field is derived from spacecraft tracking data is by the standard process of inversion to estimate the mathematical parameters used in describing the gravity field. The tracking data provides information about the motion of a satellite. The deviations of the motion predicted by a prescribed theory using numerical values for the model parameters are used to determine the additional forces, including corrections to the gravity model parameters, that need to be applied to explain the spacecraft motion. The advantage of the space data is that a global representation of the Earth's gravity field can be obtained in this manner. Solutions for the Earth's gravity field derived from a global network of satellite tracking stations provide an almost homogeneous representation of the field that is capable of representing nearly all the longer wavelength features and providing the framework for higher resolution modeling. The addition of surface gravity data and altimeter data into these "satellite solutions" to form "combination solutions" has permitted the resolution to be improved over both continental and oceanic areas.

Several geodetic spacecraft have been launched during the last two decades during which most of the progress has been accomplished. The GEOS-1, -2, & -3 spacecraft of the mid-sixties to mid-seventies introduced flashing lights and altimetry, and brought laser ranging methods to the forefront. The Transit series of spacecraft exploited Doppler tracking and the Lageos spacecraft brought definitive recovery to the low degree and order field, including the first measurements of both the secular change and the seasonal variations in the Earth's flattening term, J_2. Together these spacecraft, and many others of "opportunity", have been used to develop the present models of the Earth's gravity field and components of the ocean tides.

Temporal variations of the gravity field include contributions from the solid Earth and ocean tides caused by the gravitational attraction of the sun and the moon; from tides due to meteorological effects such as atmosphere, ground water and snow; from changes in the Earth's structure due to earthquakes and volcano eruptions; and the post-glacial rebound caused by the Pleistocene deglaciation which began about 18,000 years ago. The state-of-the-art solid Earth Tide model is developed by Wahr [1981]. Ocean tide solution developed using hydrographic techniques include Schwiderski and Parke solutions, etc. A partial list of recent satellite derived tide solutions include the GEM-T1 tide solutions and the TEG-1 tide solutions. Secular variations of J_2 have been observed using Lageos, and secular variations of J_2 and J_3 have been observed using Starlette.

With the availability of new *in-situ* and satellite data and the computational resources to assimilate the observations into numerical models, all fields of oceanography are moving to establish global observing programs. Such measurements will greatly constrain estimates of oceanic transport of heat, salt and other tracers, as well as the exchanges between the oceans and atmosphere. Studies of sea level time series have revealed a variety of oceanic phenomena, including waves, tides, mesoscale eddies, the large scale circulation, the heating and cooling of the oceans, and the El Nino-Southern Oscillation (e.g., Wunsch, 1972; Wyrtki, 1981; Cheney, et al., 1983). Secular trends in sea level (e.g., Barnett, 1983) and some tidal effects can reflect either oceanographic or geophysical phenomena and distinguishing their effects is essential for understanding long term ocean processes.

The objective of the Geopotential Panel is to:

> *Develop a program of data acquisition and model development for the Earth's gravity and magnetic fields that meet the basic science requirements of the solid-Earth and ocean sciences.*

In the following sections, the requirements for gravity information and models through the end of the century is briefly reviewed, the present status of our knowledge and data acquisition techniques is described, and an outline of a program to meet the requirements is presented.

3.0 SCIENCE REQUIREMENTS

The requirements for gravity modeling have been described in the reports of several recent workshops, including the Interdisciplinary Nature of Space Geodesy held in Erice, Sicily, Italy, (Mueller and Zerbini, 1989) and the Gravity Field Workshop held in Colorado Springs, Co, (NASA, 1987). Much of the following summary has been excerpted from the Erice Report. These reports and the more detailed requirements described in the other sections of this document state the scientific problems that can be addressed with better gravity information and it is evident from these reports that the better the data the greater range of scientific problems that can be studied. For the purposes of preparing a program plan, we assume that the requirements for gravity, taking into account the technology that can be expected to be available during the next decade, can be described by the spectrum shown in Figure 1. This states that the smallest resolution required globally is 100 km with local regions represented at scales of 2-20

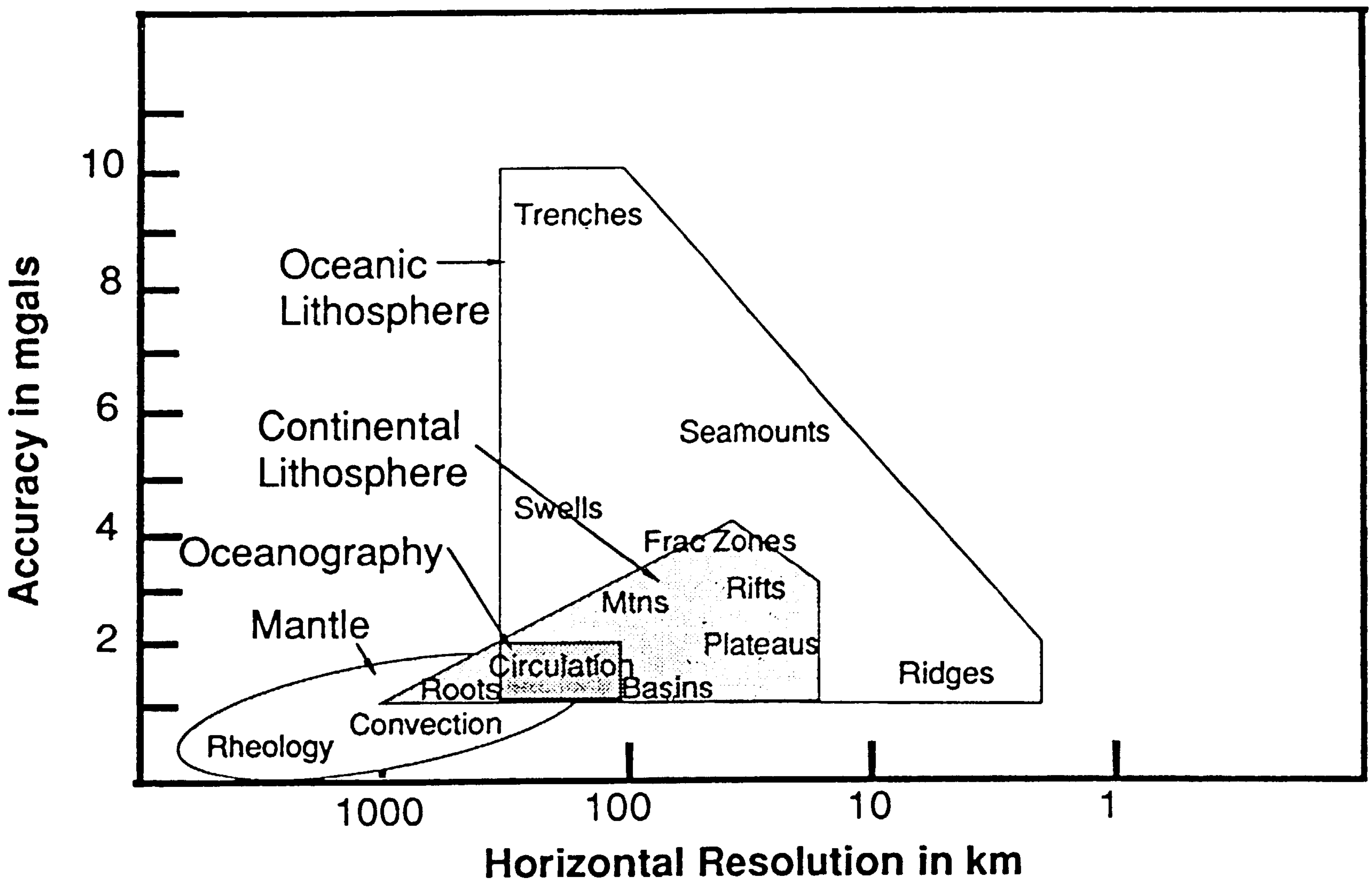

Figure 1 Summary of requirements for gravity measurement accuracy as a function of spatial resolution for the problems discussed in this report.

km. An accuracy of 1 mGal at 100 km resolution is required on a global scale and 2 mGal at 10 km resolution in local regions.

The importance of gravity information to the understanding of processes that affect the Earth on a timescale of decades is predominantly through the oceans and their interaction with the atmosphere. The undisturbed mean ocean surface conforms to the ocean geoid and departures of sea level from this surface imply circulation and the transport of heat and nutrients. Knowledge of the geoid is essential for understanding the input of the circulation to the atmosphere and changes in these quantities have major implications for Earth's climate.

The locations at which gravity is desirable varies appreciably not only with their intrinsic nature, between regions of intense volcanism and tectonism, such as ocean ridges or underthrust belts, but also with the other data available. Since gravitational attraction is indeterminant as to source depth, it must be constrained. The interpretation of gravity also is generally dependent on some model of activity in the region interpreted, such as the direction of motion and thickness of lithosphere involved in an underthrusting. The existence of correlative data and models varies appreciably from place to place. Obviously, those where they already exist, without adequate gravimetry, should have priority. But also it can be said that gravimetry itself will stimulate ideas and generate campaigns to collect the complementary data (e.g., the seamounts turned up by satellite altimetry). Hence the primary guide, if uniform coverage on a continental scale is not affordable, should be the existence of intense activity, as indicated by the topography. Among the land areas not yet surveyed, most obvious are large segments of the Andean and Alpine orogenic belts.

3.1 Oceans

Knowledge of the gravity field is useful in three ways for ocean studies: a) to compute the mean ocean currents (proportional to the gradient of the difference between mean sea level and the geoid) and constrain transports of heat, tracers and nutrients; b) to distinguish time changes in sea level caused by time changes in the geoid from those associated with ice melting or ocean heating; and c) to compute precise orbits for altimetric satellites, which requires an extremely precise estimate of the gravity field at $l,m < 40$.

For oceanographic purposes the accuracy of the geoid in ocean areas is required to be less than 5 cm for half wavelengths greater than 500 km. To achieve their maximum utility, altimetric satellites need to be tracked with the greatest possible accuracy: presently laser ranging and GPS. Geodetic reference systems consistent across satellites and tide gauges need models of the gravity field that both introduce minimum error in the orbit computation for altimetric satellites and that can be subtracted from altimetric sea level to yield the time-averaged dynamic topography of the oceans. Finally, to properly interpret observations of slow apparent changes in sea level tied to "global change", whether observed by satellites or tide gauges, the reference systems must be consistent over time scales where plate motion and crustal deformation affect the positions of satellite tracking and tide gauge sites, and the time changes in the gravity field with equivalent geoid changes must be distinguishable from oceanographic trends in sea level. For the geoid, such changes need to be known to a centimeter over a decade.

Specific gravity field requirements for oceanography are: a) a field of sufficient accuracy and resolution for the *a-posteriori* computation of the TOPEX/Poseidon orbit to 1 cm radially (gravity field error); b) a marine geoid of 25 km resolution and 1 cm accuracy (rss); c) the time history of satellite tracking station positions in a common reference system; and d) changes in the low degree and order gravity field for understanding the changes in mean sea level (geoid accuracy) of 1 cm/decade.

3.2 Continental Lithosphere

Although tremendous advances have been made in understanding the oceanic lithosphere from satellite-derived data, understanding the continental lithosphere has progressed much less. Global geoid models derived from perturbations in satellite orbits (to degree and order 50), and surface measurements have contributed some to our understanding of the continents. Currently, gravity data with a resolution of 4 mGals at 100 km is only available for 22% of the Earth's continental areas. But these areas are more heterogeneous and variable than the oceanic areas.

Continental rifting and extension is directly related to the process of mountain building and earthquake generation, as well as mineral and petroleum distribution. A few rifting areas continue into opening new oceanic areas, most fail. Mapping of continental extensions, both vertically and horizontally, is far from complete, but addressable with gravity data. Gravity is available in detail for North America and study thereof shows large scale structure in North America, with some offsets from the topography, indicating buried loads. Thermal structure of these areas can be addressed with gravity data with a resolution of 1-2 mGals over 100 km. But tectonic structure requires going down to 10 km.

Sedimentary basins and passive continental margins have been a prime focus of exploration geophysics for some time due to the deposits of petroleum reserves. The cause and changes in subsidence rates reflect in the mechanical behavior of the continental lithosphere. Gravity data of 1-2 mGal over 20 km would provide new and invaluable information in this area.

Models of compensation of mountain belts have been completely turned around with proper gravity maps. These belts are not simply isostatically compensated, but are partially supported by lithospheric flexure and entail significant subsurface loads. Continental areas, world-wide, are in a wide variety of relative ages; gravity data of 2-5 mGals over 50-100 km over all continental areas would better quantify the lithospheric structure. The deep structure of the continental lithosphere is often tied to the chemical or thermal boundary of the base of the lithosphere. Mapping this base requires 1-5 mGal data with 100-400 km wavelengths.

3.3 Oceanic Lithosphere

Altimeter data from GEOS, Seasat and Geosat have led to a significant increase in our understanding of the thermal and mechanical structure, and evolution of oceanic lithosphere, an advance not shared by the understanding of the continental lithosphere. Although the sub-satellite tracks have inter-track gaps of up to 150 km, along-track data provides information of mass distribution within about 10 km of the track. Decreasing inter-track spacing to 10 km will lead to resolution of most of the gravity signatures of the detailed volcanic and tectonic processes generating the lithospheric structure, whose scale is comparable to the thickness of the oceanic crust, 6 km.

Gravity signatures indicate that mid-ocean ridges are largely compensated at shallow depths: i.e. the ups and downs of topography are matched by internal variations of opposite sign. At wavelengths >400 km, the topography seems supported by thermal isostasy and/or dynamic mechanisms in the mantle. However, at shorter wavelengths, other processes (thermal, mechanical, chemical and hydrothermal) are important, and are not well understood. Data relevant to these processes have been measured by spatially limited ship tracks, which have poorer resolution than the satellite-derived oceanic geoid. The morphology of the oceanic lithosphere is strongly dependent on the spreading rate, which in turn affects the levels of isostasy, which in turn affects the gravity signal and topography. Understanding lithospheric structure leads directly to understanding the geophysical processes in spreading zones. Gravity data, especially on a world-wide scale, is very important in these studies.

Fracture zones are not as well understood as are spreading zones. There are significant variations in the correlation of geoid height indicative of differing generation at oceanic rises and differing post-rise volcanic history. Supporting datasets must have a 1 mGal resolution at 50 km wavelength.

Oceanic plateaus extend over 30% of the oceans, lack focused seismicity, and have complex magnetic patterns. Seismic data are ambiguous as to whether these areas are continental or oceanic in character. Gravimetry will help infer the processes and histories of these plateaus.

Mapping the seafloor has been remarkably advanced by satellite-derived geoids. Not only large-scale features, such as subduction zones, are clearly evident, but even small, previously uncharted seamounts are evident. With the oceanic lithosphere covering the majority of the Earth's surface, solid statistical analysis can be had in comparing the geoid and bathymetry. The transfer function relating the two breaks down at wavelengths <200 km, largely due to the inadequacy of the track spacing in existing altimetry data. Seafloor topography, in regions lacking adequate bathymetry, could be determined from a geoid with 20 km resolution of 20 km and 0.3 mm sea-surface height.

Subduction zones have the largest anomalies in the oceanic portion of the Earth. Gravity data for these areas are required at 5-10 mGal at 20 km wavelengths. Much progress has been made in understanding these areas, but dissipating processes, effective rheology, and eventual deposition of oceanic slabs are still poorly known. The key in these studies is a consistent dataset transitioning from the ocean, over the subduction zones and continental margins, well into the continental lithosphere. These data cannot be obtained from satellite altimetry, and hence aircraft must be used.

3.4 Mantle Convection

Mantle convection processes are fundamental to the evolution of the entire Earth. The existence of oceans, atmosphere, volcanism and plate tectonics (hence the existence of life itself) is intricately linked with mantle convection. Continental crust has lifetimes approaching the lifetime of the Earth, while oceanic crust is frequently, on a geologic scale, recycled. Gravity measurements provide some of the few available direct views of mantle processes, and are particularly sensitive to density irregularities that generate flow.

Seismic tomography has had an outstanding history over the past decade, but cannot unambiguously define the geochemistry of the mantle. However, maps of seismic velocity provide a severe constraint on rock density, which in turn constrains gravity models. This is an important constraint on the degree to which mantle flow is compartmented, both laterally and vertically. The depth of oceanic slab penetration beyond the subduction zones, small-scale convection directly beneath the lithosphere, and even the number of vertical convection cells are not yet known. Proper mapping of the mantle obviously required global datasets. Gravity information with an accuracy from 0.1 mGal at 500 km wavelength is desirable to address these problems.

The age of the lithosphere can often be measured by the age of rocks as the lithosphere passes over hot spots. Hot spots are long-lived thermal anomalies, thought to be tied to the core-mantle boundary, or the boundary between the upper and lower mantle. Thermal expansion over hot spots, thinning of the lithosphere and the structure of plume-lithosphere interaction can be addressed with gravity data of a few mGals over 30-50 km. Identification of plume signatures could lead to the discovery of new or forming hot spots (most obviously as seamounts in areas of poor bathymetry).

3.5 Temporal Variations in Gravity

Temporal changes in gravity that may be measurable arise from post-glacial rebound, ocean and solid Earth tides, large earthquakes, seasonal variations in groundwater and melting of icecaps. Many details are not known and timescales can range from minutes to hundreds of years.

Post-glacial rebound is a current vigorous subject of research, because it is the principal measure of mantle viscosity important to convection. Vertical rebound rates are as high as 1 cm/yr, changing local gravity by 0.001 mGal/yr. Gravity data to this accuracy over 3000 km wavelengths are required. Current glacial melting will raise sea level by 0.05 cm/yr, changing gravity by only 0.00002 mGal.

The driving mechanism for the Chandler Wobble is most likely seasonal weather variations, but seasonal variations of ground water may have some effect. Gravity variations associated with this mass transfer will be about 0.004 mGal/yr.

Volumetric changes due to magma flow in volcanic areas or due to thrust faults result in 0.2-1.0 mGal/m vertical movement, measurable by nearby surface gravimeters, but have too short wavelengths to measure from space. The 1964 Alaskan earthquake should have had a change of 0.1 to 1.0 mGal. Consistent and long-term monitoring of global gravity might lead to remote gravity observations of volcanic and earthquake activity.

4.0 CURRENT STATUS

Since 1985, there has been an intensive effort to re-analyze the existing satellite tracking and altimeter data and to include improved surface gravity data in the gravity model effort. The investigations have been stimulated by requirements for improved gravity models to support the objectives of altimeter satellite missions such as TOPEX and ERS-1 and the positioning and baseline measurement requirements of the Crustal Dynamics Project.

The largest global satellite gravity models are currently of degree and order 50 and have been derived from tracking data on as many as 30 different spacecraft. These models incorporate a variety of data types, some including altimetry. There is a critical need for a gravity mapping mission to extend the results of this current effort. Table 1 lists potential new spacecraft missions that can be expected to contribute to our knowledge of the gravity field during the next decade. All the missions listed in Table I will contribute to improve the gravity field but only the last three missions are dedicated to studying the static, short-wavelength component of the Earth's gravity field. None of these three missions is currently approved. The others all contribute to the low degree and order (only) or through altimetry to the oceanic geoid but none will be able to significantly improve upon our knowledge at the 100 km resolution.

On global scales, present satellite models have accuracies of order +/-7 mGal at their highest resolution of 400 km. Over ocean areas, where altimeter data are available, our knowledge at 100 km is about +/-4 mGal, along-track accuracies can be much better. The fundamental limitation is track spacing. Over the continents surface gravity data are available in a number of areas, particularly North America, Europe and Australia. However, there are many continental areas for which there is very limited good quality data. It is estimated that only 20% of the continental areas are known to +/-5 mGal at a horizontal resolution of 100 km (Mueller and Zerbini, 1989).

Large global gravity models that incorporate virtually all available data, including tracking, altimetry, and surface gravity data, have been developed over a number of years. These models, complete to degree and order 180, and 360, use the satellite models as the basis for the low degree field and subsequently add on the altimetry and surface gravity to provide the higher resolution over the oceans and the continents. These models thus try to retain the long wavelength information best derived from the satellite tracking data while introducing additional data that extends the model into the short wavelength regime.

5.0 MEASUREMENT TECHNIQUES

The only method available for improving the long wavelength gravity field to date has been through the "classical" method of tracking spacecraft from stations on the Earth's surface and by the tracking of one spacecraft by another. Ground-based tracking of the next decade will include laser ranging, and several microwave techniques, including the GPS, the French DORIS system and the German PRARE. At the present time, these methods represent the most precise techniques for ground-based spacecraft positioning.

TABLE 1: POTENTIAL NEW SATELLITE MISSIONS USEFUL FOR GRAVITY MODELING

LAUNCH	MISSION	TRACKING SYSTEM	APPROVED
1989	Etalon-2	laser	yes*
1989	SPOT-2	DORIS	yes*
1992	ERS-1	laser, altimetry, PRARE	yes
1992	Lageos-II	laser	yes
1992	TOPEX	laser, altimetry, DORIS, GPS	yes
1993?	Stella	laser	no
1994 ?	Lageos-III	laser	no
1996 ?	GP-B	laser, GPS	no
1997 ?	ARISTOTELES	gradiometry, GPS	no
1999?	SGGM	superconducting gravity gradiometer	no

* in orbit

So far there has been only a minimal amount of the satellite-to-satellite tracking data type suitable for gravity modeling but its potential through the application of GPS probably makes it the most important method for the next decade. Indeed, continuous tracking of a spacecraft has already been found from the experiments conducted between the ATS spacecraft and GEOS-3, for example, as a powerful data source for gravity modeling.

For the determination of the short wavelength terms in the gravity field the satellite-to-satellite tracking technique appears to be a tracking method that has the potential of providing 100 km scale information. To obtain the shorter wavelengths a low altitude spacecraft is necessary. However, the limited visibility of such a spacecraft from a reasonable number of fixed ground stations fails to produce adequate data to properly resolve the large number of high frequency terms. Two basic methods for satellite-to-satellite tracking exist; the high-low method, such as GPS tracking a lower altitude spacecraft, and the low-low method that was proposed for the Geopotential Research Mission (GRM) in which two spacecrafts in almost identical orbits track each other at a separation of about 100 km. For GRM the tracking was microwave Doppler with a planned capability of around 1 micrometer/second. Recently, a new low-low satellite-to-satellite concept involving laser Doppler has been proposed as an alternative to microwave with the claim that considerable greater accuracy (two orders of magnitude) may be obtainable. However, the high-low tracking of a satellite with present day GPS could yield the gravity field down to wavelengths of 250 to 500 km with high precision. Candidates for this type of approach are TOPEX/Poseidon, Gravity Probe-B, and ARISTOTELES.

An important method for obtaining the global short wavelength gravity field is with an orbiting gravity gradiometer. Several instrumental techniques have been proposed over the last two decades and currently two approaches are being developed, one in Europe and the other at the University of Maryland. The former is aiming at a precision of 10^{-2} EU and is the prime instrument on ARISTOTELES. The latter, a superconducting gravity gradiometer, is the instrument that is planned to be flown on the SGGM which would have a precision of 10^{-4} EU as it's goal.

An even greater resolution of the gravity field by space methods (1 mGal at 10 km) can be obtained indirectly by satellite altimetry with very close cross track spacing. However, this method is limited to ocean areas and contamination due to ocean circulation is unavoidable, reduced only by averaging over repeating ground tracks. In addition, airborne gravity or gradiometry combined with GPS tracking can be applied to specific areas of interest. This method is not yet fully operational, but field tests so far look promising.

Absolute gravity measurements are important for determining time varying components of the Earth's gravity field. These measurements are of particular interest at VLBI, SLR and GPS and tide guage sites for relating gravity changes to crustal motion. Surface gravimeter measurements are the standard "classical" measurement of gravity and can be acquired in small regions of specific interest to support these efforts.

Time variations of the long-wavelength components of the gravity field can be divided into periodic variations, such as tides, and secular variations, such as due to post-glacial rebound. Earth and ocean tides can be recovered by classical satellite tracking methods but with limited resolution. The low degree and order tide solution can be determined using tracking data collected from geodetic satellites such as Lageos and Starlette. There are good indications that higher degree and order tide solutions can be recovered using ocean altimeter data.

Secular variations of gravity have been recovered in J_2 and J_3. Higher resolution recovery of periodic and secular changes could be obtained by one of the following concepts: a) a series of separate missions that can solve for the long wavelength field with high precision such as with GP-B and SGGM; b) tracking of geodetic satellites with different inclinations such as Lageos and Etalon; c) using a constellation of low cost satellites with laser, microwave, or GPS tracking by selecting appropriate altitude, eccentricity and inclination; and d) by extending the lifetime of GP-B equipped with GPS significantly beyond the nominal lifetime.

6.0 PROGRAM ELEMENTS

In order to define the elements of the gravity program we considered the requirements to be divided into four classes:

o *Gravity Data Analysis*

An on-going gravity data analysis and technique development program, which will improve the gravity field using data from historical and approved missions. This program will be critical in maintaining the program resource base to support future gravity missions.

o *High Resolution Gravity Field*

This requirement is for the determination of the gravity field to a resolution of 50 km with an accuracy of 1 mGal and a 2 cm ocean geoid. A complementary need is the determination of the global geoid through degree 40 (450 km resolution) with an accuracy of 5 cm. A determination of the gravity field with a 10 km resolution, 2 mGal accuracy in the oceans, and selected land areas is an additional requirement.

o *Long Wavelength/Moderate Resolution Gravity Field and Ocean Geoid*

The longer wavelength parts of the Earth's gravitational field are considered here to include gravity models up to degree 50. This is a substantial change from the usual definition which has been up to degree 10. However, we use this distinction to make a substantial contrast with new requirements and possibilities.

o *Time Variations*

The time variations to be considered are periodic (tidal) and secular in nature. The ocean tide variations are to be determined for a satellite at 1000 km altitude, to degree 15, 60 constituents, to 0.01 cm. At the ocean surface the expansion should be complete to degree 60, 60 tidal constituents, to 1 cm. The secular variations of the geopotential should be determined to degree and order 8 with a geoid change accuracy of 1 cm/decade.

To meet the above requirements we consider the techniques needed in several categories.

6.1 High Resolution Gravity Field Information

The high resolution gravity field is considered (very loosely) to be defined by spherical harmonic expansion greater than degree 100. Several types of missions are feasible and should be supported.

A mission that will satisfy some of the high resolution requirements is the ARISTOTELES mission and the recovered anomaly field will be a significant improvement over existing information. In order to obtain useable long wavelength information a GPS tracker should be added through a NASA/ESA cooperative effort. It is expected that 100 km resolution to an accuracy of 4 mGals, with a substantial improvement in long wavelength information will be obtained. This mission is planned for 1997.

In order to obtain an improved resolution and accuracy it is necessary to have an advanced technology gravity field mission. This advanced mission would achieve a resolution of 50 km with an accuracy of 2 mGal. This mission would be launched by the end of the decade. The prime candidate for this mission is the SGGM. Other alternatives, such as the laser Doppler system, should be studied.

High resolution information in the ocean areas could be derived from a satellite altimeter mission. This mission should have a repeat cycle of 180 days to achieve a 10 km resolution. The length of the mission should be at least two years so that noise-like effects can be averaged out. The ESA ERS-1 mission could come close to meeting these requirements.

The acquisition of gravity data over land, at a resolution of several km is essentially impossible with a space mission. To acquire such data a ground-based mission is required. This is best done by airborne gradiometer with GPS navigation. Such technology now exists and is being developed by the U.S. Navy and the U.S. Air Force (through the Defense Mapping Agency). Interagency agreements could be pursued to obtain this data in areas of high geophysical interest.

6.2 Long Wavelength/Moderate Resolution Gravity Field Determination

The determination of the very long wavelengths can be improved through the analysis of data to be obtained from satellites recently placed in orbit, or being proposed for launch in the near future.

Significant information to degree 50 can be obtained with satellites having a precise GPS tracking instrument. A prime candidate for such a mission is GP-B which is planned for an altitude of 650 km. Error analysis indicates that such a mission could define the potential field to degree 40 (450 km) with an implied cumulative geoid accuracy of 5 cm. This high accuracy geoid determination will be of specific value in ocean circulation studies.

It should also be noted that the ARISTOTELES with GPS mission has the potential for significant gravity field improvement at the longer wave length. Advantages over GP-B would be lower (200 km) altitude. A disadvantage would be the effect of drag at the lower altitude.

6.3 Determination of the Time Variations of the Geopotential and Tidal Phenomena

As noted earlier, the time variations of interest, which may be related to global climate change lie in two areas: periodic (tidal) and secular changes in the geopotential caused by mass displacements in the Earth. The secular changes are related to rheological changes in the Earth's mass distribution associated with post-glacial rebound of continental land mass and with possible melting of polar ice caps. The seasonal changes, which are stochastic in nature, are related to the mass exchange by the solid Earth and atmosphere with weather and/or climatic phenomena.

Tidal phenomena give critical information related to the structure of the Earth as well as providing information needed in orbit determination. There are a number of scenarios to meet the requirements outlined in Section 6.0. These include:

A. Utilize data from three missions separated in time by several (3-5) years. Candidate missions could be TOPEX/Poseidon (1992), GP-B (1996) and the Advanced Gravity Field Mission (1999). Each of these missions would be equipped with a GPS tracker.

B. An alternate technique is to launch a specific satellite whose orbit would be optimized to determine time variations.

C. Another alternative would be to launch several inexpensive satellites to be placed in orbits of different inclinations and eccentricities. Analysis of long time variations from such satellites as Lageos-I, Lageos-II, Ajisai, Etalon, Starlette, Stella, etc., provide estimates of changes in the low-degree and order terms.

6.4 Computational Techniques

The standard approach to the solution of the gravity field is the use of the least squares inversion method. The general solution for a high resolution gravity field involves a comprehensive geophysical inverse problem which places unique requirements on both advanced numerical algorithms, efficient data processing techniques and on improvement in supercomputer technology. Significant efforts will be required for the development of a vectorized, efficient, out-of-memory, numerical algorithm to perform the solution of a linear system on the order of 140,000 parameters, which is beyond the memory capability of current supercomputers. Other computational techniques associated with the numerical property of geopotential field solution include the use of the orthogonal properties of the geopotential and the use of stable algorithms for the evaluation of a large series. These methods place special requirements on the measurement sampling rate and the orbit properties, but, if these requirements are satisfied, they can lead to a substantial reduction in the computational requirements.

7.0 PROGRAM PRIORITIES

The various missions and activities discussed in this report have been examined in terms of the scientific requirements for gravity field data and the availability of funding. In Table 2 these missions and activities are prioritized assuming no increase in funding (0% growth rate), a 10% growth rate, and a 20% growth rate.

The Panel's recommended program assumes a 10% growth rate, and is described below in priority order:

1. *Fundamental, and of high priority, is the funding for the analysis of the proposed missions, of existing data, and the data to be acquired from the missions.*

2. *ARISTOTELES augmented with a GPS receiver (1997).*

   A low cost mission augmenting the ESA mission

3. *Advanced Gravity Field Mission with the technology to be defined (1999).*

   A major mission with much background work completed.

4. *GPS guided airborne gravity (or gradiometry) acquisition in selected land areas (1993).*

   A low cost mission to be based on existing technology.

5. *GP-B with GPS (1996).*

   A low cost augmentation of a planned mission. This priority may be higher depending on aspects of the ARISTOTELES mission. Ideally, both ARISTOTELES and GP-B, both of which are low cost missions to the SES program, should be flown.

6. *Gravity Field Time Variation Missions (1998).*

7. *Ocean altimeter with a 10 km resolution (1997).*

   This mission may be satisfied in a number of ways including new satellite launches, utilization of data from missions at various times, or the extension of the length of one (e.g., GP-B) or more missions.

TABLE 2: PROGRAM PRIORITIES AT DIFFERENT FUNDING GROWTH LEVELS

	Growth Rate		
Priority	**0%**	**10%**	**20%**
1	Data Analysis	Data Analysis	Data Analysis
2	ARISTOTELES	ARISTOTELES	Adv. Gravity Mission
3	GP-B	Adv. Gravity Mission	ARISTOTELES
4	Adv. Gravity	Airborne GPS Mission	Airborne GPS
5	Airborne GPS	GP-B	GP-B
6	(High-res. altimeter)	Time Variations	Time Variations
7		(High-res. altimeter)	High-res. altimeter

Note: Projects in ( ) cannot be accomplished at this growth rate

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