Lecture Notes in Earth Sciences

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The Interdisciplinary Role of Space Geodesy

Springer-Verlag
1. INTRODUCTION

The structure of planet Earth and the dynamics of its constituent parts have received the intellectual attention of natural philosophers since ancient times. Only in the present century has the quantitative, physics-oriented approach led to a deeper and more profound understanding of the subject, and only in the past two decades has the role of satellite data become both well established and centrally important.

As we strive to learn more about geodesy from satellite data we are compelled to take into account that the data contain the effects of the atmosphere, noise and bias to the geodesist but signal to the meteorologist. Thus, it is not surprising that branches of geophysics other than geodesy are directly involved in the proper interpretation of satellite data. The relation between atmospheric angular momentum and the length of day, for example, compels geophysicists to understand the fluid dynamics of the earth's cores and atmosphere, and the coupling between them. Coupling occurs throughout the disciplines of geophysics, including geodesy, and is the theme of this chapter.

Beyond the Earth we realize that geophysical techniques, particularly those based on artificial satellites, allow us to study the other planets in the solar system.

In less than one year after the meeting in Erice that led to this report the planet Neptune will have been visited by a spacecraft. Interesting as such “flybys” may be, future studies of the other planets would benefit considerably from satellite data, one of the subjects treated in this chapter.

Careful design of interplanetary space probes can convert the solar system into a huge laboratory for experimental physics. Gravity is the subject of primary interest. The most enigmatic force in Nature, it is the focus of experiments on all scales, from antiproton experiments through geophysical investigations of the Newtonian constant to the large scale projects proposed and discussed in this chapter. The interaction between satellite geodesy and fundamental physics is intriguing and represents the breadth and depth of geophysics.
2. GEODYNAMICS

2.1 INTRODUCTION

Geophysical observations provide the principal source of information on the interior structure of the Earth. They include the travel times, amplitudes, and frequencies of seismic waves, the flux of heat through the surface, and magnetic field parameters. Geodetic observations of the external gravity field, of the shape of the planet and its time dependencies, and of the rotational motions, provide further constraints. Together with geological observations (including geochemistry and geochronology) these geophysical and geodetic observations provide the key to understanding the structure, dynamics, composition and evolution of the Earth's hydrosphere, crust, mantle, and core.

Central problems to which geodetic observations contribute are of two types. The first is where observations provide a measure of the response of the Earth to known forces (e.g., tidal deformation or post-glacial rebound). The second is where the observations are used to infer the forces themselves (e.g., the forces driving plate tectonics from surface strain observations). In neither case can the geodetic observations alone provide unique answers and the interpretation of these data requires complementary geophysical, meteorological, oceanographic and geological data. In particular, many geodetic signals pertaining to the solid Earth contain signals originating from the hydrosphere and atmosphere and these must be measured by independent techniques in order to understand the solid Earth signatures.

Plate tectonics has provided the major impetus to Earth Sciences in the past two decades and the kinematics of global plate motions are now fairly well understood. Major developments in the future will be directed towards understanding the dynamics of the mantle and the mantle-lithosphere interaction. Geodetic observations can provide important constraints on this problem by providing information on the planet's rheology through a wide range of measurements including the gravity field, planetary rotation, tides and crustal motion. One area of particular current interest is the dynamics of the lower mantle and nature of, and processes occurring at, the core-mantle boundary. A number of the geodetic observations complement the geophysical and geological evidence and arguments. Another important problem is the interactions at the solid Earth-hydrosphere boundary and here also the geodetic observations contribute through the study of tides and planetary rotation and through observations of mean sea level and sea level changes.

Most of the past progress in the Earth Sciences has come from the examination of long series of observations that were collected because of advances made in technology and engineering. Examples include the measurement of heat flow in the ocean crust, marine bathymetry and the use of satellites to measure the Earth's gravity field. It is important that observation programs of fundamental properties of the Earth be continued. In the geodetic context this includes satellite altimeter missions such as TOPEX and the high-spatial resolution Earth gravity field studies, missions to map the Earth's topography, and the magnetic field and its time dependence, and long-term observing programs of passive LAGEOS and STARLETTE type satellites using laser ranging. It includes long term VLBI observing programs for monitoring global motions and deformations of the planet and GPS- or GLRS-type missions for crustal deformation monitoring on regional and local scales. In parallel, observing programs in seismology and other geophysical (including oceanographic, glaciological
and meteorological) and geological quantities are essential, for without this the geodetic observations are only of limited value. Interactions between the geodetic and other Earth Science disciplines are essential in planning and executing the parallel programs of observation.

Some specific examples of the interactions between the geodetic observations and other Earth Science disciplines are given below (§2.3). The examples are not exclusive and many others, equally valid, can be found. Some specific requirements for ensuring that the geodetic data can now be collected by space techniques are compatible with the overall scientific goals of the study of the dynamic Earth are given in §2.2. These requirements also are more indicative than complete. The nature of science is such that major progress often occurs where it is least anticipated.

2.2 SUMMARY OF PRINCIPAL POINTS MADE BY SUB-PANEL

(1) Further LAGEOS and STARLETTE-type missions are required in different inclination orbits, to study, interalia, the time-dependent behavior of the Earth's gravity field. These time dependencies include the tidal deformations of the Earth and long-period and secular changes in the long wavelength components of the Earth's gravity field.

(2) Meteorological data must be collected to support the geodetic missions both for making appropriate corrections for the propagation characteristics of the satellite tracking data and for monitoring the mass movements of the hydrosphere and atmosphere.

(3) There is a need for continued improvements in ocean-tide and ocean-circulation models. It is particularly important to establish ocean-tide models free from geophysical inputs (assumed Earth responses to tidal forces and surface loading) in order to separate dissipation of tidal energy in the oceans from that in the solid Earth. The most appropriate way of achieving this is by using both tide gauge data, including deep ocean seafloor records, and satellite altimetry observations.

(4) There is an important need to upgrade the world network of sea-level monitoring stations to establish periodic and secular trends in sea level and to establish the global patterns of these changes. Such measurements should be made in conjunction with observations of changes in geocentric heights of the stations.

(5) Satellite altimeter missions are essential to achieve the above objectives. It will be important that successive missions permit long-term fluctuations in sea-surface topography to be monitored. All such satellite missions will need to be tracked with the highest possible accuracy. It is important that the orbital parameters of these missions are such as to give global ocean coverage.

(6) GPS-type missions for rapid and precise positioning (cm-level) are important for monitoring crustal motions and deformation in tectonically active regions. There is a need for relatively inexpensive equipment that can operate remotely in a wide range of environments. High accuracy, relative height measurements are particularly important. Such studies will contribute to understanding the deformations of the crust along plate margins as well as the study of the stress-strain cycles of large earthquakes.

(7) GLRS-type missions (geodynamics laser ranging system) with mm relative positioning precisions and of long operational lifetimes are strongly supported for future crustal deformation studies.
(8) High accuracy, sub-microgal, absolute and relative gravity meters need to be deployed at selected sites in support of vertical motion studies. Such monitoring should be conducted routinely at principal satellite stations and at VLBI sites.

(9) High spatial resolution gravity field studies are essential to support oceanographic altimeter missions. They also contribute significantly to studies of continental tectonics.

(10) There is an important need to measure the Earth’s topography with high resolution. This includes both continental and oceanic areas. Without such observations the full tectonic potential of the gravity missions cannot be achieved.

(11) Seismological studies of the radial and lateral variations in seismic velocities form a very important complement to the gravity, topography and magnetic observations, and the establishment of global digitally-recording, broadband seismic networks is strongly supported.

(12) There is a need to monitor the Earth’s magnetic field, both for separating the core and crustal components of the total field and for mapping the time dependent behavior of the field. It will be particularly important to be able to separate the time-dependent contributions from the internal and external sources. Such observations contribute to the understanding of the Earth’s dynamo, core motions, core-mantle coupling processes and lithospheric tectonics.

(13) There is a need to establish and maintain significant modeling programs for the routine interpretation of the data collected by these various programs. Innovative research based on these analyses as well as on the original data to complement these larger analysis programs should be encouraged.

2.3. EXAMPLES OF INTERDISCIPLINARY GEODETIC STUDIES

Temporal variations in Earth’s gravity field. High-accuracy laser tracking of the LAGEOS and STARLETTE satellites has revealed signatures in the orbits that have been interpreted in terms of temporal changes in the Earth’s gravity field. These include (i) periodic variations due to solid-Earth and ocean tides, (ii) seasonal variations associated with periodic redistribution of mass in the oceans and atmosphere, and (iii) quasi-secular changes driven by post-glacial rebound, and the present-day melting of mountain glaciers. A fourth possible change, not yet identified, are step-like changes in the Earth’s inertia tensor that are associated with major earthquakes.

Tidal variations provide a direct test of ocean models derived either from tide gauge data or from satellite altimetry. In particular, these tidal variations provide a direct measure of the dissipation of tidal energy in the Earth and, by combining these results with independent ocean model estimates of dissipation, they provide estimates of dissipation or Q within the solid Earth. If very accurate ocean tide models can be derived from satellite altimeter data, it may also become possible to detect lateral variations in the Earth’s response to the tidal force. Such observations contribute to understanding the structure and dynamics of the Earth. Accurate Earth-nutation data also places constraints on the solid Earth’s Q.

These objectives can only be achieved if ocean-tide models for the principal tidal frequencies can be established with accuracies of better than 5% for the long wavelengths in the ocean tide spectrum. The design of altimeter missions such as TOPEX, should be commensurate with this requirement. Complementary observations to these studies include surface tidal gravimetry observations and radial and horizontal station displacements of VLBI and
satellite laser ranging sites. From such observations it becomes possible to probe the lateral structure in the $S_2$ mode to complement seismic free oscillation studies.

Seasonal variations in the Earth's gravity field provide important global constraints on models of ocean and atmospheric circulation and on models of the Earth's water budget. When combined with accurate observations in the seasonal variations of the ocean height and air pressure such observations may help in determining the thermal contributions to the ocean height variations as distinct from contributions arising from water added into the ocean.

Secular variations in gravity measure the combined effect of the rebound of the Earth's crust to the removal of the Late Pleistocene ice sheets and any present day glacial melting. The actual rates of change will depend on the spatial and temporal distribution of these ice sheets and of the Earth's response to the change in surface loading. Any rate of change of tesseral coefficients or the geopotential will be primarily the result of northern hemispheric contributions whereas any change in the zonal coefficients, particularly in the odd harmonics, will be strongly influenced by any Antarctic contributions. Thus a combined data set of secular change in the potential coefficients should provide an important constraint on the poorly known Antarctic melting histories.

Discontinuous time-dependent changes in the gravity field have not yet been observed, mainly because there have been no major ($m \geq 8$) earthquakes since the launch of LAGEOS. Earthquakes such as the 1964 Alaska earthquake, have the potential of producing major changes in the low-degree gravity field coefficients the observation of which provides constraints on models of elastic seismic dislocation, pre- and post-seismic relaxation and of the Earth's fluid core spin-up time constant.

The harmonic spectrum of the time dependence of gravity parameters that can be derived from the LAGEOS and STARLETTE orbits is limited and satellites in different orbits are required. In designing these orbits, attention must be given to how such new satellites improve the accuracy of the time-variable gravity field. Near resonant orbits should also be considered as a means to probe the time dependence of the tesseral field. A realistic goal should be one that maps the slowly changing field to harmonic degree and order 3 and for zonal harmonics up to degree about 6 or 8 with an accuracy of a few parts in $10^{-11}$ yr$^{-1}$. Observation programs of satellite laser ranging should have a lifetime of the order of at least 2 decades to separate out long-period tidal oscillations from secular trends.

**The Earth's deep interior.** It is now widely recognized that significant dynamical processes may be occurring in all parts of the Earth, including the lower mantle and at the core-mantle interface. Geodetic observations make several contributions to the understanding of these processes. These include the Earth's gravity field and rotation.

Departures from axial symmetry in the thermal and mechanical boundary conditions, imposed on motions in the fluid core of the Earth by convection in the highly viscous lower mantle, may produce a number of observational consequences at the Earth's surface. For example, the density anomalies associated with deep mantle convection and a bumpy core-mantle interface would contribute to the long wavelength gravity field observed at the surface. Fluctuations in the fluid flow past the mantle produce torques at the core-mantle boundary which may result in variations in the length of day on the decade time scale and in polar motion. These torques are of two types: (1) tangential stresses produced by viscous forces in a thin boundary layer just below the interface, and the Lorentz forces associated with the electric currents in the lower mantle, and (2) normal stresses produced by dynamical pressure forces acting on the equatorial bulge and irregular topography of the core-mantle boundary.
By combining Earth rotation, geomagnetic, seismological and gravity data, it is possible to estimate the magnitude of this topographic coupling. These observations also contribute to models of the structure, dynamics and composition of the outer core and lower mantle, including the boundary layers on both sides of the interface.

To make use of the rotation data it is necessary to remove irregularities in rotation produced by meteorological and oceanographic variations in mass distribution for these make dominant contributions to the observed changes in length-of-day and polar motion. Daily components of all three components of the wind surface torques or of the atmospheric angular momentum are essential, including winds up to stratospheric heights. Information on seasonal variations in ocean circulation are desirable. Observations that part of the time-dependent part of the magnetic field that is of internal origin are also required.

Secular accelerations of the Earth and $C_{20}$. Astronomers have long been aware that the Earth's diurnal rotation has not been constant through time but that the rotational velocity has decreased slowly. Likewise, astronomers have long recognized that the Moon has been subjected to an acceleration in its orbit of about $-20$ arcsec/cy$^2$. These accelerations are small but if they have persisted throughout the history of the Earth-Moon system their consequences are dramatic for they imply that the Moon has been much closer to the Earth in the past than it is now. These accelerations are a consequence of the torque exerted by the Moon, and to a lesser degree by the Sun, on the tidally deformed and elastically imperfect Earth.

Evidence for the secular acceleration of the Earth can only be obtained from very long series of historical records of the motions of the Earth-Moon-Sun because of the existence of decade and century scale variations in rotations that are generally attributed to differential rotations of the core and mantle. New evidence for the lunar acceleration in its orbit comes from lunar laser ranging from relatively short records and significant improvements in accuracy can be expected. The tidal part of the secular acceleration of the Earth can therefore be computed with considerable accuracy and the difference between this estimate and the observed estimate constitutes the nontidal acceleration of the Earth. Estimates of this quantity have indicated a positive nontidal acceleration of the Earth but the amounts are generally unreliable. These accelerations have been attributed to several mechanisms, including a secular change in $G$, a consequence of ongoing isostatic adjustment of the crust and mantle to Late Pleistocene glacial unloading, to electromagnetic core-mantle coupling and to growth of the core. The nontidal acceleration would therefore provide a significant constraint on cosmological theories or on geophysical models, provided that one could establish that one or other mechanism was appropriate. As in many problems of the rotations of the Earth, a number of mechanisms are likely to operate together.

Some separation of these mechanisms is nevertheless possible. If glacial rebound is responsible for the acceleration then there should be a concomitant secular polar motion. All solutions of the equations of polar motion driven by realistic models of the deglaciation of the ice sheet predict a shift of the mean rotation pole that is remarkably close to the observed shift since about 1900. Electromagnetic torques could possess an equatorial component and hence contribute to the polar wander on this time scale but it would be fortuitous if this response aligned itself with that of glacial rebound. The agreement therefore suggests that the primary excitation of the secular polar wander is the Late Pleistocene deglaciation and it should be possible to predict the corresponding secular change in nontidal acceleration.
Another significant observation is the acceleration $\dot{\Omega}$ in the node of satellite orbits because glacial rebound will also contribute to this whereas electromagnetic torques do not. Because $\dot{\Omega}$ is proportional to $C_{20}$ it becomes possible to estimate the nontidal acceleration $\omega_{NT}$ and recent analyses suggest that the results are consistent.

<table>
<thead>
<tr>
<th>Author</th>
<th>$\Omega$ $10^{-23} s^{-2}$</th>
<th>$\dot{C}_{20}$ $10^{-19} s^{-1}$</th>
<th>$\omega_{NT}$ $(10^{-22} s^{-2})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yoder et al., 1983</td>
<td>-7.2 ± 0.6</td>
<td>11.1 ± 1.0</td>
<td>1.6 ± 0.4</td>
</tr>
<tr>
<td>Rubincam, 1984</td>
<td>-5.3 ± 1.2</td>
<td>9.2 ± 1.8</td>
<td>1.2 ± 0.26</td>
</tr>
<tr>
<td>Stephenson &amp; Morrison, 1984</td>
<td></td>
<td></td>
<td>1.7*</td>
</tr>
</tbody>
</table>


This also suggests that magnetic torques may not be important on this time scale. Any secular change in $G$ contributes to $\omega$ but not to the secular polar motion so that it also becomes possible to separate these two factors. While the observational precisions are still inadequate, observations of the secular changes in length-of-day, polar motion and the rate of precession of the node of satellite orbits have the important potential of being able to discriminate between quite different excitation mechanisms. Of importance is that the resulting mantle viscosity estimates complement the studies of glacially induced sea level change that are generally more sensitive to upper mantle than to lower mantle viscosity.

**Sea level change.** Analysis of long-term tide gauge records indicate that global sea level has been rising during the past century although estimates of the eustatic rate, taken here to mean the global average value, have differed significantly, ranging from 1 to 3 mm/year. There are several reasons for these different estimates. (1) Sea level changes, irrespective of their causes, are nonuniform over the Earth because the slowly changing sea surface remains an equipotential at all times. Hence, estimates of the secular rate vary with the region. (2) Sea level changes occur over a wide range of time scales and estimates of the secular trend are strongly dependent on how the other fluctuations have been eliminated and on the record length. (3) Vertical tectonics along many parts of the coastlines of the world are significant and this may contaminate the eustatic sea level rise estimates because the tide gauge observations only yield sea level positions relative to the Earth's crust. The result of an attempt at separating tectonic from eustatic contributions and at examining regional variations in the latter term, is illustrated in Fig. 1. The contribution (which also exhibits regional variation) from the melting of the present mountain glaciers as modeled by Meier (1984) has been removed. This contributes about 0.46 mm/year to the observed eustatic amount of 13 mm/year. Part of this regional variation illustrated in Fig. 1 can be attributed to the warming of the upper 100–200 m of the ocean surface then the required water warming is about 0.02–0.04°C/year, consistent with changes observed in, for example, Atlantic mean surface temperatures.

What results such as those in Fig. 1 indicate is that monitoring of secular change in sea-level cannot be accomplished successfully with a few tide gauges only. Nor can meaningful results be achieved from records as short as a decade or two. Whether these changes can be measured with satellite methods, by a combination of very high-accuracy laser ranging and satellite altimetry, is debatable and any monitoring program will be one of the most
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3. EARTH STRUCTURE

The first and basic step in the evolution of our knowledge of the dynamics inside the earth has to deal with a reliable determination of the structure. Only a detailed image allows us to infer the modes of the processes in act, in order to define them in a quantitative way. Many problems today remain open. In particular, the mechanisms of interacting (chemical, mechanical, magnetic) between different structural units are far from being fully understood. A detailed snapshot of the zones of transition between these units (mantle, outer core, inner core) represents a fundamental constraint for any dynamical theory. It is important, therefore, to recognize our need for improving the quality of the pictures.

In the last few years, renewed interest and new data yielded considerable progress in the study of lateral variations of the deep structure of the Earth. After decades of one-dimensional models, in which properties vary only with depth, geophysicists think now in terms of three-dimensional models. Seismology provides images of variations of elastic wave
speed in the mantle. These images derive from the analysis of observations spread over a very broad range of frequencies, including travel times, body waveforms, and normal modes of oscillation. Such velocity models can be translated into density models, and then used as an input datum in studies of mantle convection. Very encouraging results have been obtained which yield substantial agreement with surface plate motions and long-wavelength geoid anomalies. However, several elements are still missing, such as a detailed description of the effect of subducted slabs. The depth of penetration of slabs represent a fundamental piece of information for defining the convection style of the mantle. Slabs are currently imaged, on one side, by means of higher-resolution seismological techniques, and, on the other side, by means of jointly fitting geoid anomalies, plate velocity data and convection patterns.

As a consequence of the increased resolution achieve in the latest studies, laterally heterogeneous models of the mantle will presently show their importance in modeling the response of the earth to surface loading (post-glacial uplift, tides). The translation of seismic velocity into a viscosity model has to rely on assumptions about material properties of mantle constituents. This is related with the estimation of the mineral composition of the mantle, and therefore mineral physics is also involved.

The transition between mantle and core is perhaps the most critical region for our understanding of the dynamics active inside the earth. Core-mantle coupling (viscous, thermal, magnetic) has consequences on many different processes, like mantle convection, outer fluid motion—hence magnetic field generation—and earth rotation. The structure affects different observables. The inversion of seismic data yields models which do not satisfy the constraints which can be inferred by means of current theories and parameter estimates. Also, not all the different seismological observations properly fit into a unique picture. This means that our current view cannot be regarded as complete, and actions should be taken in order to develop a comprehensive picture.

In view of this, and considering unsatisfactory a situation in which every discipline has good models for its own data, but fails to explain the other observations, we believe that a recommendation for the immediate future of the research in earth structure can be formulated as follows:

All available pieces of information regarding the internal structure of the earth should be gathered and a concerted effort should be moved in an interdisciplinary way in order to derive a coherent picture. They include: gravity, magnetic, rotational, and seismic data. Theoretical interpretation of: (i) large-scale geoid anomalies and plate velocities, (ii) rotational data, and (iii) magnetic field observations in terms of: (i) mantle convection, (ii) core-mantle coupling, and (iii) core motions should be considered in an objective way, and uncertainties and assumptions be properly stated. Efforts toward models able to fit all available data—within their relative uncertainties—should be thrusted.

Higher detail will be possible in the future by virtue of improvements in instrumentation quality and deployment, as well as better computational techniques. In order for this higher detail to have real physical meaning, we need to find the coherent way to interpret observations. This necessarily passes through the cooperation among all of the disciplines involved.
4. OCEAN PHYSICS

4.1 INTRODUCTION

The ocean has traditionally been undersampled. Since the Williamstown report, however, major advances have occurred in the development and utilization of satellite-borne sensors, in situ instruments, and numerical models of the ocean circulation.

Table 1. Ocean-Related Satellite Missions

<table>
<thead>
<tr>
<th>Ocean Parameters</th>
<th>Mission</th>
<th>Launch</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>temperature</td>
<td>NOAA-n</td>
<td>continuing</td>
<td>operational</td>
</tr>
<tr>
<td>sea level, wave</td>
<td>GEOSAT</td>
<td>3/85</td>
<td>operational</td>
</tr>
<tr>
<td>temperature, color, sea ice</td>
<td>MOS-1,-1B</td>
<td>2/87,90</td>
<td>operational</td>
</tr>
<tr>
<td>wind, sea ice</td>
<td>DMSP-n</td>
<td>continuing</td>
<td>operational</td>
</tr>
<tr>
<td>sea level, temperature, wind vector, wave, sea ice</td>
<td>ERS-1,-2</td>
<td>9/90,93</td>
<td>app., prop.</td>
</tr>
<tr>
<td>sea level, wave</td>
<td>TOPEX/POSEIDON</td>
<td>12/91</td>
<td>approved</td>
</tr>
<tr>
<td>color</td>
<td>LANDSAT-6</td>
<td>91</td>
<td>approved</td>
</tr>
<tr>
<td>sea ice, wave</td>
<td>JERS-1</td>
<td>92</td>
<td>approved</td>
</tr>
<tr>
<td>color</td>
<td>SPOT-4</td>
<td>93</td>
<td>proposed</td>
</tr>
<tr>
<td>temperature, color, wind vector</td>
<td>ADEOS(w/NSCAT)</td>
<td>95</td>
<td>proposed</td>
</tr>
<tr>
<td>sea ice, wave</td>
<td>RADARSAT</td>
<td>94</td>
<td>proposed</td>
</tr>
</tbody>
</table>

SUPPORTING INFORMATION

<table>
<thead>
<tr>
<th>insitu data transmission and instrument positioning</th>
<th>NOAA-n/Argos</th>
<th>continuing</th>
<th>operational</th>
</tr>
</thead>
<tbody>
<tr>
<td>ship positioning</td>
<td>GPS</td>
<td>continuing</td>
<td>operational</td>
</tr>
<tr>
<td>high acc. satellite tracking</td>
<td>SPOT-2,-3</td>
<td>88,89</td>
<td>approved</td>
</tr>
<tr>
<td>high acc. satellite tracking</td>
<td>TOPEX/POSEIDON</td>
<td>6/92</td>
<td>approved</td>
</tr>
<tr>
<td>high acc. satellite tracking</td>
<td>ERS-1,-2</td>
<td>9/90,93</td>
<td>app., prop.</td>
</tr>
</tbody>
</table>

Advances in satellite altimetry, scatterometry, radiometry, and tracking have demonstrated that the sea surface slope, vector winds, color, temperature, wave height, and sea-ice cover can be sampled from orbiting satellites (see Table 1) with the accuracies, space-time resolution, and global coverage needed to solve a variety of open questions in Oceanography. Satellite sensors also track our ships, buoys, and drifters, and transmit the data from these and tide gauges to land stations in near-real time.

Advances in in-situ instrumentation (to measure temperature, salinity, pressure, velocity, and the concentration of tracers) have also occurred, and have shown the potential to greatly increase our knowledge of the ocean interior.
Advances in theoretical understanding and computer power have resulted in numerical models of the ocean circulation, driven by realistic winds, and including assimilation of satellite and in-situ data, that will lead to useful upper ocean predictions within the next decade.

Taken together, the observations from the above satellites and associated in-situ instruments represent a capability to address how the ocean is forced by the atmosphere, how it responds, how it advects heat and nutrients, how phytoplankton productivity responds, and how the sea ice changes.

Physical Oceanography is moving to establish new global programs to exploit these technological developments and to advance our understanding of both ocean dynamics and of how the global ocean interacts with the atmosphere and the rest of the Earth System. By contrast, all past oceanographic experiments were carried out in limited areas, because ships are about 1400 times slower in sampling the ocean than oceanographic satellites are, and because some ocean areas provide limited accessibility. These global experiments will also define the sensors and strategies needed to monitor the oceans both for operational utilization and for research leading to estimate the magnitude of climate changes. The World Ocean Circulation Experiment (WOCE) and the Tropical Ocean-Global Atmosphere experiment (TOGA) are key components of the World Climate Research Programme. For more information on these two efforts, the reader is referred to WOCE International Planning Office (1988), US WOCE Science Steering Committee (1988), and WMO/IOC Inter-Governmental TOGA Board (1988). A timely collection of papers outlining the present status of physical oceanography—including satellite techniques, in-situ techniques, and numerical modelling—can be found in Knox (1987) and the companion articles in that issue.

WOCE and TOGA have arisen from recognizing that the Earth climate system changes with time and that we do not have appropriate data to describe these variations and understand their physical mechanisms, and that in-situ technology has advanced to the point that basin-scale observation programs are feasible. WOCE is designed to provide the best possible global look at the ocean circulation to understand its present state. TOGA will observe and hopefully explain the interannual variations in the ocean and atmosphere that collectively are known as the El Nino-Southern Oscillation phenomenon, a shift in global weather and tropical ocean circulation patterns that affects many parts of the globe.

Among the space techniques useful in Physical Oceanography, satellite tracking, altimetry, and scatterometry are probably those closest to the interests of Geodesy. Satellite tracking and altimetry provide sea level and the gravity field, classical objects of geodetic study yielding the oceanographically important slope of sea surface relative to the geoid. Scatterometry provides winds which affect the Earth's rotation (another classical object of geodetic study) and are the driving force of ocean motions at most scales.

4.2 SEA LEVEL

From all the observables of use in Physical Oceanography, we now concentrate on the one more closely related to Geodesy—sea level. Our later recommendations are geared at extracting maximum oceanographic information from altimetry and tide gages, two techniques to measure sea level.

Studies of sea level time series reveal a variety of oceanic phenomena, including waves, tides, mesoscale eddies, the large scale circulation, the heating and cooling of the oceans, or
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the El Nino-Southern Oscillation (e.g., Wunsch, 1972; Wyrtki, 1984; 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 were briefly discussed in the Geodynamics section of this chapter.

Tide gages (e.g., Wyrtki et al., 1988) sample at a few locations over the Earth for long times with high resolution in time. Satellite altimeters (e.g., Fu et al., 1988; Douglas et al., 1987) provide unprecedented global coverage in a matter of days. Clearly, the two measurement systems are complementary.

Both techniques also benefit from geodetic advancements: positioning either the satellite or the tide gage is a geodetic concern; the gravity field estimate needed for both the satellite orbit computation and to estimate absolute surface currents (by the departure of sea level slope from the geoid) is a classic geodetic concern. Also, because both systems are complementary, it is important that they be positioned with comparable accuracies, in the same geodetic reference system, an issue discussed at length in the chapter on reference systems, and underlying current plans to deploy new sea level stations containing tide gages (Diamante et al., 1987).

4.3 ALTIMETRY

Using altimetry from Seasat (1978) and Geosat (1985), procedures were developed to estimate sea level variability, marine geoid, accurate orbits, and various altimeter corrections. We are confident that we understand the issues that need to be addressed to meet our future sea level data needs. This experience was already used in the design of TOPEX/POSEIDON (further discussed in the next paragraph). Seasat, in 90 days, provided global statistics on ocean mesoscale variability, detected strong currents and showed the potential to detect the longer wavelengths of the circulation. Geosat, in almost 2 years of oceanographic mission and still healthy, is supplying a blurred picture of the annual cycle and equatorial waves, somewhat tarnished by incomplete atmospheric corrections (due to the lack of a companion radiometer to measure atmospheric water vapor and a second radar frequency to measure ionospheric effects) and by a 3-m orbit error. Existing technology has produced data important for our discipline, and has shown us which improvements are needed to turn it into an operational tool to monitor the ocean.

The TOPEX/POSEIDON mission, to be launched in mid-1992, is expected to provide the most accurate sea level data yet obtained from space. It will use a dual frequency altimeter to correct for ionospheric path delays, a radiometer to correct for delays due to water vapor in the troposphere, relatively dense orbit tracking, a carefully chosen orbit to minimize tidal aliasing, and well understood algorithms. ERS-1 will include a single frequency altimeter, and a radiometer. The ERS-1 orbit will be chosen to satisfy the constraints of several instruments in addition to the altimeter, but it will reach a higher latitude than Topex/poseidon, providing complementary coverage. From these advances, we expect to resolve the time averaged circulation, interannual variability, and tidal variations out to the longest wavelengths and periods allowed by the mission duration and current technology. The satellite missions will profit from the in-situ oceanographic and meteorological observations of WOCE and TOGA, and will benefit them with their rapid global coverage. Satellite and
In-situ data will be combined in hydrodynamic models of the general ocean circulation and in models of specific processes, for example tides.

Inaccurate knowledge of the Earth's gravity field causes the two limiting errors in altimetry: orbit error and marine geoid error.

The 14-cm total accuracy (single pass) estimated for the Topex/Poseidon measurements of sea level are dominated by the orbit error, a consequence of both insufficient knowledge of the gravity field and the density of tracking stations. Interannual variability at intermediate and longer scales will most likely be seen with T/P as currently configured, assuming the total error in the surfaces built from the data can be brought down to a few cm by clever processing. The marine geoid model is presently known to 2 cm at basin scales (5000 km), and worse than 70 cm at wavelengths shorter than 1000 km. This restricts calculations of the time averaged circulation to the components at the longest length scales.

We recognize that it is a difficult technological feat to measure the gravity field so as to satisfy a "1 cm rss at n < 800" long-term goal stated in the recommendations below. The wide variety of time and space scales in the ocean, their nonlinear interactions, mass conservation, and complementary data allow us in principle to use accurate information in any wavenumber band to constrain the circulation at all wavelengths. As a guide to the accuracies required, at spherical harmonic degrees lower than 20 the variance in the mean circulation is about 30-50 times smaller than the variance in the gravity field. At shorter wavelengths a spherical harmonic representation is less useful due to regional variations, but the signals we try to recover cause slopes of 30 cm over 100 km.

With this background, we now proceed to a set of recommendations to maximize the return to physical oceanographic research of current and emerging geodetic advances.

4.4 RECOMMENDATIONS

Recommendation 1—Near Term. Utilize the approved future missions, ERS-1, Topex/Poseidon, and the proposed ADEOS/NSCAT, together with in-situ data and models, to estimate and model the 3-D large-scale seasonal and interannual variability of the oceans in the first period of WOCE (1990-95); to study its response to wind forcing; to estimate those wavelengths of the time-averaged circulation that orbit and marine geoid accuracies permit; to improve models of tides. Locate the satellite tracking stations (laser, DORIS, and GPS) and tide gauges with respect to a common Earth reference frame to a vertical accuracy approaching one cm.

Recommendation 2—Near Term. Immediately commence design and tradeoff studies to define the methods and space systems that will allow long-term monitoring of the oceans (WOCE second objective) with altimetry and scatterometry after 1995. This follow-on has to be defined within the next two years to ensure continuity, due to the long lead times required to put instruments in space. A continuing monitoring capability with uniform accuracy is essential to build the long, uninterrupted time series on which climate change predictions are based.

Recommendation 3—Medium Term. Measure the gravity field with the accuracy and resolution needed to:
(a) recompute the TOPEX/POSEIDON orbit a-posteriori leaving a radial orbit error whose gravity component is of the order of 1 cm (S. Klosko, 1988, pers. comm., stated a 1 cm gravity component of orbit error as an achievable goal).

(b) provide a marine geoid that is much closer to the goal of 25 km resolution, 1 cm uniform accuracy (rss over all degrees <800) than we have today.

(b') if (b) cannot be achieved, any improvements in the marine geoid at wavelengths larger than $2\pi \times 30$ km (the first baroclinic Rossby radius, which varies with latitude and stratification; see Gill, 1982), are useful to physical oceanographic research if the computation of the geoid model does not cause a correlation with oceanographic signals, and its error is below the oceanographic signals sought. Even regional geoid improvements are useful, but a global geoid improvement with uniform accuracy is most useful.

A dedicated satellite gravity mission is probably the best way to fulfill these goals, because of the need for uniform accuracy over the oceans and for the orbit calculation.

**Recommendation 4—Long Term.** We encourage technology developments that lead to the following long-term goals, while recognizing that advances that fail somewhat short of these goals may also be extremely useful:

(a) positions of tide gage and satellite tracking stations in the same reference system, with a vertical accuracy in the mm range. Local atmospheric and tectonic conditions at the stations must be monitored: atmospheric pressure, wind, etc, as well as long-term local gravity changes and vertical motions of the ground.

(b) orbits of altimetric satellites with no more than 1 cm rms error, single pass, without orbit discontinuities, relative to the reference frame mentioned in (4a). This differs from recommendation (3a) in that the total orbit error, not just its gravitational component, is decreased.

(c) altimetric measurements of sea level covering the ocean every 7 days at 25 km resolution to resolve energetic mesoscale features. This may achieved either by multiple simultaneous missions or by multibeam altimeters.

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5. ATMOSPHERE AND CLIMATE

5.1 INTRODUCTION

In November 1987 a workshop was held in Erice on "Interactions of the solid planet with the atmosphere and climate" dealing with most of the topics which overlap with this particular chapter of the Geodesy Workshop. In this section we shall refer mainly to the conclusions of that workshop dealing with the interactions of the present atmosphere and climate with the solid Earth and the oceans. There are several other topics discussed at the conference that will not be reported here, namely on the chemical evolution of planetary atmospheres and the role of planetary impacts. On the other hand, ocean circulation, which has been discussed during this Conference, has a well known influence on the regulation of the CO$_2$ level in the atmosphere, and, although barely touched at Erice last year, will be mentioned in what follows.
Interaction with Other Disciplines

Space Geodesy will soon reach such a high precision in the measurement of distance between two locations on Earth that the intervening atmospheric delays in travel time will become the main source of error, and, thus, will determine accuracy. On the other hand, space geodesy is needed for a multitude of environmental disciplines including atmospheric physics in two different ways. First, it helps in the location of any pixel of images from space missions through precise orbital elements from satellite tracking, and, second, it delivers distance measurements as a prerequisite for the understanding of many climate processes; sea level and inland ice cap height being two obvious examples for parameters to be measured.

If the atmosphere changes travel time, and, through dispersion, phases of electromagnetic waves with different wavelengths, there should exist, in principle, a possibility to derive from space geodetic data such atmospheric (and surface) parameters as temperature, pressure and humidity.

The following subsections outline the basic features for atmospheric correction, space geodesy’s value for the other disciplines, and the combination of space geodesy instruments for geodetic atmospheric and surface parameters from which the recommendations in the final section are derived.

5.2 CORRECTION OF THE ATMOSPHERE

The refractive index $n$ of air as a measure of refraction and the deviation of the propagation velocity of an electromagnetic wave from that in vacuum is for all wavelengths a function of the total number of air molecules; thus temperature $T$ and pressure $p$ and especially for radio waves, also a function of the number of polar molecules thus depending on absolute humidity. If $n = 1.000282$ for $p = 1013$ hPa, $T = 288.15$ K and 60% relative humidity at 0.69 µm wavelength is needed to an accuracy of $10^{-6}$ tolerable pressure $p$, temperature $T$ and water vapor pressure $e$ errors are $\Delta p = \pm 3.6$ hPa, $\Delta T = \pm 1.0$ K, $\Delta e = \pm 25.6$ hPa within the optical domain. Within the microwave range we find $\Delta p = \pm 3.7$ hPa, $\Delta T = \pm 0.8$ K and $\Delta e = \pm 0.23$ hPa. Humidity, therefore, is the most critical parameter in the microwave space geodesy. Past and current instruments measuring water vapor include the Scanning Multichannel Microwave Radiometer (Seasat) and the Special Sensor Microwave Imager (DMSP8).

The wave traveling time increase translates into a large distance, reaching more than two meters ($\sim 2.30$ m) for the dry air contribution and fluctuating (only for microwaves) between a few centimeters and half a meter for the “wet” contribution, if both ranges are given for zenith observations. Present simple models of refractivity, $N = (n-1) \cdot 10^9$, versus height compared to meteorological soundings leave, at given surface observations of pressure, temperature and humidity, a root-mean-square error of a few centimeters (at least 2 cm) due to water vapor fluctuations but also to errors in temperature profiles for the dry air contribution. The bias for the humidity contribution is strong for the tropical areas and may reach 4 cm at 5.5 cm rms error certainly also partly due to radiosonde errors.

A presently possible strong improvement would be the use of models accepting global meteorological analyses on main pressure surfaces available from meteorological forecasting centers. However, if accuracies below the cm level are needed a direct measurement of temperature and humidity, best in the form of profiles, along the line of sight of a geodetic instrument would be the optimum choice.
5.3 GEODETIC INSTRUMENTS FOR ATMOSPHERIC PARAMETERS

The masking of all raw data by the effects of the atmosphere either through refraction, absorption, or scattering is not only a reason for correction and the cause of growing relative contributions to errors (see §5.2) but should also be exploited for the derivation of atmospheric parameters.

Refraction effects of systems like GPS and GLOM MASS equipped with sensors like PRARE/DORIS could be used to derive stratospheric temperature profiles with sufficiently dense horizontal resolution in the height interval between tropopause and 35 km using all satellite occultations. Present sounding systems onboard operational meteorological satellites show rms errors above 2 K for the stratosphere; thus the GPS/PRARE/DORIS has to show its superiority.

All laser tracking stations could record the backscattering from aerosol layers in order to establish an aerosol backscattering climatology not available at present.

The parameters most urgently needed in meteorology and climatology, especially over oceans, are precipitation amount and rate. Scanning multi-frequency altimeters are candidates for this purpose, since their signals are attenuated frequency dependent by rain drops of different size and their footprint is small enough to resolve convective precipitation.

5.4 ANGULAR MOMENTUM BUDGET OF THE EARTH- ATMOSPHERE

The measurements of the length of day and the position of the rotation pole of the Earth have revealed that part of the short term changes in the frequency range of 0.01 cycles per day to 1 cycle per day are due to changes in angular momentum of the atmosphere (Hide, 1984). Thus geodetic data together with global meteorological wind data open the possibility of separating the core-mantle boundary dynamics contribution from the atmospheric one. Length of day time series in turn would allow a hindcasting of atmospheric circulation anomalies like El Niño.

A comparison has been made by Rosen (1989) between the estimate for the total angular momentum of the atmosphere obtained with the European Center for Medium Range Weather Forecast (ECMWF) and with the National Meteorological Center (NMC) models. He found that the NMC gives a higher estimate with a rms difference of $5.68 \times 10^{24}$ Kgm$^2$s$^{-1}$ which would translate in l.o.d. of about 0.095 ms. The difference between the atmospheric and geodetic series is 0.13 ms and the mean uncertainty in l.o.d. is 0.045 ms so that the error in the atmospheric analysis of $M$ is comparable to the one obtained from independent estimates. Subsequent analysis of the two data sets indicates that most of the overestimate in the NMC may be due to the absence in that model of the stratospheric levels. This example, however, is useful to clarify that most of the comparison between geodetic and atmospheric data is through the calculation of the atmospheric momentum with winds data on a grid with a resolution of about 300 km which is large enough to neglect the smaller scales. Tibaldi (1989) showed that such scales are of primary importance to explain the recent progress in weather forecasting. In the near future it is expected that satellite wind measurement could improve the accuracy from the present one of 5 m/s to about 2 m/s. This would probably affect the torque evaluation.
Interaction with Other Disciplines

Rosen has also shown a loose correlation between the averaged standard deviation in the filtered l.o.d. and the global temperature regime (Salstein and Rosen, 1986). The same authors have shown that ENSO signature is clearly recognizable in the l.o.d. data set.

Madden (1989) has also shown a loose correlation between the averaged standard deviation in the filtered l.o.d. and the global temperature regime (Salstein and Rosen, 1986). The same authors have shown that ENSO signature is clearly recognizable in the l.o.d. data set.

Madden (1989) has studied the effect of 40-50 days tropical oscillation on the l.o.d. record and shown that this could be an important mechanism for the exchange of momentum between the Earth and the atmosphere. The geodetic data should also be studied as an independent validation for theories on atmospheric blocking.

5.5 ATMOSPHERIC LOADING

Atmospheric disturbances cause displacement of the solid Earth. In some instances these could be used to learn more about earth/atmosphere coupling processes. Wahr (1989) has shown that meteorological disturbances could cause displacements in surface of the oceans up to 1 cm. This result could be of some importance especially in the interpretation of gravity observations and gauge measurements of the ocean level. Dickman (1989) has shown the importance of considering the ocean response to atmospheric pressure and wind stress in evaluating the exchange of angular momentum between the atmosphere and the ocean.

5.6 LONG RANGE CLIMATIC AND ATMOSPHERIC EVOLUTION

Berner et al. (1983) have proposed an explanation for the warmer cretaceous based on a larger content of atmospheric carbon dioxide possibly due to a faster rate of seafloor creation with respect to the present epoch. Gaffin (1989) has developed a simple model which relates eustatic sea level changes in the last $10^7$-$10^8$ years to seafloor creation rate changes and also found an anticorrelation with the rate of geomagnetic reversal. These studies are relevant for a precise estimation of seafloor spreading and plate motions and a possible reconstruction of the same data in the past.

5.7 OCEAN CIRCULATION AND ATMOSPHERIC CARBON DIOXIDE

The ocean is the main buffer for CO$_2$ in the atmosphere with surface water removing the gas and maintaining an equal pressure between the ocean and the atmosphere. The characteristic time of this circulation is only 10–20 years so that when water with a specific content of CO$_2$ goes back to the surface it will dissolve more gas that has increased in the meanwhile due to the burning of fossil fuel and deforestation. The organic compounds formed at the surface will settle to the bottom of the ocean where, in presence of oxygen, it will liberate nutrients (phosphates and nitrates) and again carbon (Broecker and Peng, 1982). The deep circulation of the ocean will then transfer carbon from the surface to the bottom together with
oxygen. Sources of this deep water are also sources of carbon dioxide and changes in the ocean deep circulation would influence the climate both through the carbon dioxide content and the latent heat release.

5.8 CONCLUSION AND RECOMMENDATIONS

The problem of atmospheric masking, the value of geodetic data for other disciplines and the desirable combination of sensors for geodetic and atmospheric parameters have led to the following recommendation divided into four parts. Although part 1 is no real space geodesy problem, it is nevertheless kept, since most imaging missions would be of strongly increased value if geodetic information is improved. The other parts are a straight consequence of the foregoing discussion.

Recognizing (1) the need for more precise geodetic data for all imaging missions in meteorology and climatology, (2) the growing importance of the correction of atmospheric effects on space-borne geodetic measurements, (3) the strong links between motions of the Earth's pole and angular momentum of the atmosphere, and (4) the relation between paleoclimatic ice volume and glacial rebound of the entire Earth's crust, it is recommended that

1. Adequate geodetic information should be added to operational and preoperational satellite data from meteorology, ocean and climate missions (this information should include time, orbital elements and satellite attitude allowing the location of any pixel from the imaging radiometer with the highest spatial resolution to a small fraction of a pixel).

2. Planned geodetic space missions should be exploited for atmospheric and surface parameters, examples being (i) land surface roughness (emphasis on vegetated surfaces) laser altimeters), (ii) precipitation rate from scanning multi-frequency, radar altimeters, (iii) stratospheric temperature profiles from GPS/PRARE/DORIS satellites and ground stations, and (iv) aerosol particle backscattering from (multi-wavelength) satellite laser tracking.

3. Information on atmospheric temperature profiles and water vapor content should be combined with geodetic raw data in order to reach the 1 mm accuracy goal for any distance between stations on Earth.

4. Meteorological and climatological data should be provided for angular momentum patterns of the atmosphere in order to separate the core-mantle dynamics contribution to polar motions and crustal dynamics from the atmospheric one, both for short-term weather fluctuations and (paleo-)climatic states or time series. However, improvements of the initialization data of general atmospheric circulation models (which presently provide the angular momentum data) are required. Global coverage of wind vectors could be provided by satellite scatterometers for surface winds and a laser atmospheric wind satellite for profiles. A direct involvement of the World Meteorological Organization (WMO) would be helpful also considering the feedback Earth rotation data might have in explaining meteorological or climatological phenomena.

5. A more realistic data base is needed to compare the geodetic data on angular momentum with those evaluated with meteorological data. A promising approach is provided by the next generation of satellite that will measure winds from space on a global basis with better spatial resolution and precision.
6. EXTENSION TO THE PLANETS

6.1 INTRODUCTION

During the last two decades many important advances in our knowledge and understanding of the Earth have been made through the application of space geodetic and geophysical methods. These advances include the measurement of present-day tectonic plate kinematics, the measurement and interpretation of variations in the Earth’s gravity field and tides, the measurement of the topography of the world’s oceans and our understanding of its circulation, and the construction of models of the Earth’s core and crustal magnetic fields.

In addition, major new technologies have been developed that have made the scientific advances possible, including the introduction of centimeter level tracking systems for spacecraft and very long baseline interferometry of extra-galactic radio sources, centimeter level laser and microwave altimeters, gravity gradiometers, and sophisticated software systems for determining orbits, processing data, and extracting the geodetic and geophysical results.

In order to further develop our understanding of the basic mechanisms and processes involved it is necessary (and technically feasible) to address the corresponding geophysical and geodetic problems as they occur on other planetary bodies in our solar system. These geophysical processes require that certain (space) geodetic measurements be made over appropriate time scales and with certain accuracies. These measurements include, but are not limited to: the gravity field of the planet and its variation with time due to external and internal forces, the rotation of the planet on its axis and the existence of any variations with time, the topography of the planet on the scale commensurate with the resolution of the gravity field and/or our knowledge of the geological processes, and the relative motions of blocks or segments of the planets crust arising from tectonic forces or realignments of material in the planets interior. In addition, direct geophysical measurements of magnetism, heat flow and seismology are needed. With these geodetic and geophysical data sets inferences can be made about several fundamental planetary processes and parameters, including, the elastic thickness of the lithosphere, the planet’s mass, the state of isostasy, the nature of the planets rotation and possible connection with its atmosphere, the existence of present-day tectonic processes, and the possible existence of a fluid core, etc, etc. These processes may then be compared with those occurring on the Earth.
Table 2. Geodetic and Geophysical Experiments on Future Planetary Missions

<table>
<thead>
<tr>
<th>Year of Launch</th>
<th>Mission</th>
<th>Destination</th>
<th>Geodesy/Geophysical Investigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>Phobos 1&amp;2</td>
<td>Phobos</td>
<td>Size, shape, gravity of Phobos. Transponder left on Phobos for orbit determination</td>
</tr>
<tr>
<td>1989</td>
<td>Magellan</td>
<td>Venus</td>
<td>Imaging radar, altimeter (30m, 20-30 km spot), Gravity experiment, limited to low and medium latitudes, eccentric orbit (250 km–??)</td>
</tr>
<tr>
<td>1992</td>
<td>Mars Observer</td>
<td>Mars</td>
<td>Altimeter (~ 1 m, 100 m spot) Gravity (~ 50 by 50) orbit, polar, 360 km–410 km Magentics</td>
</tr>
<tr>
<td>1994</td>
<td>Mars 94</td>
<td>Mars</td>
<td>Radar (sounder) Magentics Gravity (?)</td>
</tr>
<tr>
<td>1998(?)</td>
<td>Lunar Observer</td>
<td>Moon</td>
<td>Gravity(?) Altimetry (?) 100 km polar orbit</td>
</tr>
<tr>
<td>2000(?)</td>
<td>Sample Return Mission (US &amp; USSR)</td>
<td>Mars</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

6.2 PLANETARY MISSIONS AND PRESENT KNOWLEDGE

Several planetary missions are planned for the next several years; Table 2 summarizes these missions and briefly describes their geodetic experiments. None of these missions has geodesy or geophysics as their primary objective but some are undertaking gravity and topography measurements, albeit in a nonoptimal mode; some missions will also make magnetic field measurements. In order to improve our understanding of the processes already mentioned it will be necessary to move toward a full global scale program of observations and measurements on at least one planetary body, and preferably more, where the conditions appear to differ from those on Earth.
Table 3. Present Geodetic Knowledge of the Moon and Terrestrial Planets

<table>
<thead>
<tr>
<th>Planet</th>
<th>Quantity</th>
<th>Knowledge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>Rotation variation</td>
<td>unknown</td>
</tr>
<tr>
<td></td>
<td>$\sigma(GM)$</td>
<td>1 part in $10^4$</td>
</tr>
<tr>
<td></td>
<td>$\sigma(J_2)$</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td>Mean radius</td>
<td>+/- 1 km</td>
</tr>
<tr>
<td></td>
<td>Topography</td>
<td>unknown</td>
</tr>
<tr>
<td></td>
<td>Flattening</td>
<td>unknown</td>
</tr>
<tr>
<td>Venus</td>
<td>Rotation variation</td>
<td>unknown</td>
</tr>
<tr>
<td></td>
<td>Rotation period</td>
<td>234 days +/- 0.1 days</td>
</tr>
<tr>
<td></td>
<td>&quot;Chandler&quot; wobble:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>amplitude</td>
<td>200 km (?)</td>
</tr>
<tr>
<td></td>
<td>period</td>
<td>$10^5$ years (?)</td>
</tr>
<tr>
<td></td>
<td>$\sigma(GM)$</td>
<td>1 part in $10^6$</td>
</tr>
<tr>
<td></td>
<td>Gravity field</td>
<td>7x7, limited coverage</td>
</tr>
<tr>
<td></td>
<td>Mean radius</td>
<td>+/- 0.1 km</td>
</tr>
<tr>
<td></td>
<td>$\sigma$ (Topography)</td>
<td>$\pm 100$ m, 50 km block range $\leq 1$ km</td>
</tr>
<tr>
<td></td>
<td>Flattening</td>
<td>very small</td>
</tr>
<tr>
<td></td>
<td>Atmospheric angular momentum</td>
<td>$10^{-3}$ of solid body</td>
</tr>
<tr>
<td>Mars</td>
<td>Rotation variations</td>
<td>l.o.d. ~ 1 msec, nothing since Viking</td>
</tr>
<tr>
<td></td>
<td>$\sigma(GM)$</td>
<td>1 part $10^5$</td>
</tr>
<tr>
<td></td>
<td>Gravity</td>
<td>18x18, patchy, not near poles</td>
</tr>
<tr>
<td></td>
<td>Mean radius</td>
<td>+/- 0.1 km</td>
</tr>
<tr>
<td></td>
<td>Topography</td>
<td>+/- 1 km, near equator</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+/- 2 km, poles</td>
</tr>
<tr>
<td></td>
<td>Atmospheric motions</td>
<td>25% of atmosphere moves from</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pole to equator annually, change in gravity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$J_2$ observable</td>
</tr>
<tr>
<td></td>
<td>Magnetic field (core)</td>
<td>undetected</td>
</tr>
<tr>
<td>Moon</td>
<td>Rotation variations</td>
<td>nothing observed</td>
</tr>
<tr>
<td></td>
<td>$\sigma(GM)$</td>
<td>1 part $10^6$</td>
</tr>
<tr>
<td></td>
<td>Gravity</td>
<td>16x16 near side poor, far side</td>
</tr>
<tr>
<td></td>
<td>Radius</td>
<td>0.03 km</td>
</tr>
<tr>
<td></td>
<td>Topography</td>
<td>100 m near side—not near poles</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Earth-based radar) poor, far side</td>
</tr>
</tbody>
</table>

Table 3 summarizes our present geodetic knowledge of the moon and terrestrial planets and indicates the considerable variation in our depth of knowledge of these bodies.

It is apparent that any attempt at understanding these kinds of measurements in a systematic way will involve a long term program and the basis of any program of geodetic and geophysical exploration of the terrestrial planets should begin with a primary description of the fundamental parameters that describe the body. These should include, but not necessarily be limited to:
• mass
• gravity field
• topography
• core magnetic field
• crustal magnetic field
• rotation rate and any variations
• polar motion
• geodetic control (a few features established in a center of mass reference frame)

and if obtained globally on a uniform basis would enable some assessment of many of the processes described earlier. Further, the geodetic and geophysical requirements must in many cases be combined with more common planetology investigations, such as imagery and spectroscopic analyses.

Table 3 shows that our present knowledge of Mercury is very limited and that none of the parameters listed above are available for Mercury, and that only after Magellan will we have a preliminary model of the static gravity field and topography for Venus, and only after Mars Observer will the gravity field, topography, and magnetics be adequate for initial studies of Mars. For the Moon, nearly all our present knowledge is limited to the near side.

For none of the terrestrial planets do we have significant information about its rotation and no information about any time dependent changes in the gravity field arising from tidal distortions of the planet or mass redistributions due to atmospheric motions, as is believed to take place on Mars. The former is important as it can be used to provide information about tidal Love Numbers and the latter is important as it can be used to provide estimates for viscosity of the planet’s interior. These methods have been successfully used for Earth by analysis of the observations of Lageos and other spacecraft over many years. Thus a spacecraft in orbit about a planet can, over a long period, provide important information about the planets interior as well as its gravity field.

6.3 A PROGRAM CONCEPT

The first step in such a program could therefore be the establishment of a geodetic spacecraft in orbit about the planet. In its simplest form this spacecraft would be in a close geodetic type orbit and carry only a radio beacon for very precise tracking. This system could provide the low degree and order gravity field, the planet’s mass, and any time variation in the gravity, including tides and J2 dot. Inclusion of a magnetometer could be the next level of complication, followed by an altimeter. Other possible instrumentation includes a gravity gradiometer, and deployment of sub-satellites that permit closer approach to the surface. Whether several instruments could be combined on one spacecraft would depend on other factors and specific objectives. To obtain details of the planet’s rotation will require visiting the surface of the planet and amounts to step two in any program because of its obvious increase in difficulty. With one or two beacons placed appropriately, estimates of rotation rate would be derivable and with three or more the complete rotation of the planet, including any polar motion, should be observable. At the same time the detection of tectonic motions through the change in relative positions of the beacons becomes possible. However, having reached the surface of the planet there are many other important geophysical measurements that should be made, including, seismology, heat flow etc. Knowledge of the positions of
Interaction with Other Disciplines

these "beacons" would be a requirement at probably the decimeter level or better, requiring some special space geodetic method, such as a GPS type measurement, or VLBI, to be applied or established on and around the planet. These locations could then become the components of a control net for the planet in a center of mass coordinate system.

6.4 RECOMMENDATION

The next long-range plan for geodynamics should include a planetary component and that we should:

1. initiate a program of geodetic and geophysical exploration of the moon and terrestrial planets (in cooperation with existing programs in planetology);
2. determine the following parameters for each planetary body: mass, gravity (dynamic and static), topography, magnetism, rotation rate and variations, polar motion, and establish a geodetic control grid on the surface.

The first step in the program could be the placing of a geodetic spacecraft into a stable orbit around one of the planets. A suitable choice would be the moon or Mars. The precise tracking of such a mission alone could provide detailed gravity information, including time variations, the planets mass and possibly details about the atmosphere. The mission could logically be extended to conduct topographic and/or magnetic field measurements.

The second step in the program could be the establishment of one to three instrumented sites on the surface that would enable the measurement of polar motion, planetary rotation, tectonic motions, and the measurement of heat flow, seismology, etc.

7. FUNDAMENTAL PHYSICS

7.1 INTRODUCTION

An important interdisciplinary field for Space Geodesy is the tie between areas of Astrophysics and Geophysics. In this century theoretical physics has created concepts which have provided us with dramatic changes in our perception of reality. Experiments in Space Geodesy have provided important confirmation of many of these theoretical physical concepts. There are a number of new and important continuing experiments in this field which need to be carried out in the coming decades. Currently there are three main areas of experimental physics in which the techniques of Space Geodesy can make significant contributions to fundamental physics. These are in the areas of (1) the search for gravitational waves, (2) the measurement of first- and second-order post Newtonian effects (PPN parameters in modern theories of gravitation), and (3) the measurement of feeble short-range forces associated with various higher-order theories in physics.
Chapter 4

7.2 GRAVITATIONAL WAVES

Interplanetary spacecraft tracking is now used routinely to search for very low frequency gravitational waves. Interplanetary plasma, ionosphere and troposphere effects are currently limiting the detection capability of these experiments.

Improvement in correcting for or eliminating these effects must be pursued. This means the utilization of higher microwave frequencies for interplanetary spacecraft communication links, with the possibility of using laser carrier frequencies in the future. Development of these technologies should be pursued.

Alternative methods of detecting gravitational waves in space should be investigated. This includes the tracking of interplanetary spacecraft from space based observatories, the operation of tracking observatories on the moon, and in particular the building of dedicated multiarm interferometers for detection of gravitational waves. These interferometers should have the potential to measure spatial strain to 1 part in $10^{18}$ or greater.

7.3 FIRST- AND SECOND-ORDER POST-NEWTONIAN EFFECTS

The relativity gyroscope experiment GPB is now in an advanced stage of development. The predicted effect of the gravitomagnetic effect for this experiment is about 42 marcs per year and the accuracy to which it is to be measured is about 0.5 marcs. Geodesists should take account of all requirement and possible auxiliary data collection necessary to guarantee a successful outcome to this experiment. In particular this experiment represents an example of interdisciplinary cooperation which should be followed more often in future experiments.

In the field of the theory of gravitation it is possible to parameterize effects which are predicted by post-Newtonian theories of gravitation, such as those in General Relativity. These are called post-Newtonian (PPN) parameters as they can be made to show a deviation from a Newtonian reference frame.

Several of these parameters have been determined through spacecraft tracking experiments and currently set some of the best limits to these parameters. The gamma or time delay parameter and beta or perihelion shift parameter are currently known to a few parts in $10^6$. It is feasible to measure these parameters to a few parts in $10^5$ by requiring more precise tracking of spacecraft, including drag free design and the technology to carry very precise frequency standards that operate in space for long durations. A number of solar system missions including Solar Probe, Icarus lander and Mercury orbiter are representative for these studies.

The most stringent limits to a possible change in the gravitational constant $G$ have been set by precise ranging to Mars using the Viking planetary lander. These measurements are being extended in a cooperative experiment between the US and USSR using the recently launched Phobos spacecraft. Similar experiments should be encouraged in the future to allow even more precise limits to possible changes in this fundamental unit of gravitation to be determined.
7.4 FEEBLE SHORT RANGE FORCES

The inverse square law of gravity has most recently come under intense theoretical and experimental scrutiny. In some modern theories of physics the existence of particles of small but nonzero mass (axions in QCD, dilations in superstrong theory, hyperphotons, gravitons, etc.) can lead to Yukawa type contributions to the potential between bodies.

Fig. 2. The figure shows the current limits (solid lines) and projected limits (dashed lines) that can be placed on the anomalous potential, where

$$\phi = -\frac{GM}{r} (1 + \alpha e^{-r}).$$

For ranges in excess of about 300 km the strength of such forces are constrained by planetary and satellite orbit observations. In the range 1 meter to 300 km the constraints are weaker. Space experiments designed to measure these potentials, such as precise gravity gradiometry, should be considered and may play an important role to discriminate between various fundamental theories of physics. Fig. 2 indicates the current limitations that can be set to these anomalous potential interactions. Where appropriate future space geodetic experiments should include planning for possible measurement of feeble short-range forces.
7.5. SUMMARY

A natural role for space geodesy exists in the bridging of experimental gaps between the fields of Astrophysics and Geophysics. Fundamental physical effects can be successfully measured and theoretical model parameters can be studied using techniques developed for space geodetic experiments. There is an opportunity for Space Geodesy to make important fundamental contributions to physics and this should be exploited in the planning of future missions.

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