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THE TERRESTRIAL ENVIRONMENT: SOLID-EARTH AND OCEAN PHYSICS

Prepared by
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge, Mass.
for Electronics Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1970

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THE TERRESTRIAL ENVIRONMENT:

SOLID-EARTH AND OCEAN PHYSICS

1. Geophysics
2. Oceanography

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FOREWORD

This report is the result of a study supported by the National Aeronautics and Space Administration to explore the possible contributions of accurate position, velocity, and acceleration measurements to the solution of problems in solid-earth and ocean physics and to make program recommendations.

Solution of these problems would greatly facilitate improved understanding of the ocean circulation and of the crust and mantle tectonics. This understanding will be important to maintaining the quality of man's environment (including earthquake and tsunami prediction), the management of the oceans as a food source, and the continued exploitation of the crust as a materials source.

The seminar was conducted at Williams College, Williamstown, Massachusetts, August 11-21, 1969. Over 65 scientists, including 15 NASA officials, participated. Most of the work was accomplished in four panels, chaired by George C. Weiffenbach (instrumentation); William S. von Arx (ocean physics); Charles A. Lundquist (short-term dynamics of the solid earth); and Lynn R. Sykes (long-term dynamics of the solid earth).

Cochairmen of the seminar were Gerald L. Pucillo, NASA Electronics Research Center, and Stephen Madden, MIT Measurement Systems Laboratory. Arthur LaPointe, MIT Measurement Systems Laboratory, and his staff helped greatly by handling the administrative arrangments for the seminar. This report was prepared by the Publications staff of the Smithsonian Institution Astrophysical Observatory.

William M. Kaula

WILLIAM M. KAULA
Chairman, Central Review Committee

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PRINCIPAL RECOMMENDATIONS

This study identified several ways in which space and astronomic techniques could contribute in solid-earth and ocean physics. We therefore recommend that NASA undertake an integrated program, including both short-term components attainable by existing technology and longer term components requiring appreciable development. The major components of this program are herewith set forth in approximate order of importance.

1. Start development of minimum altitude satellites (less than 250-km altitude) with ±10-cm accuracy altimeters, drag-free for at least 2 years, tracked by ±0.05-mm/sec accuracy range-rate from distant satellites (more than 6000-km altitude): to measure the geopotential and mean sea level accurately enough to define the baroclinic and barotropic pressure fields and thus to determine the general circulation of the oceans; to resolve the spatial variations of the gravity field to 100-km half-wavelength.

2. Meanwhile, implement as soon as practicable close satellites (about 350-km altitude) with ±1-m accuracy altimeters, tracked by ±1-mm/sec accuracy range-rate from distant satellites(s) (at more than 6000-km altitude — possibly geosynchronous): to resolve the variations of the gravity field to 250-km half-wavelength, greatly enhancing oceanographic and geotectonic analyses, in particular setting firm bounds on the long-term mechanics of the earth's interior, as well as making tests toward system 1 above.

3. Start development of ranging and very long-baseline radio interferometry (VLBI) systems to obtain relative positions with ±2-cm accuracy to define directions with respect to the inertial reference with ±0".001 accuracy: to monitor relative rates of motion of different parts of the earth's crust well enough to infer irregularities in plate tectonic motions, and to monitor the wobbles and rotational variations to infer their excitations and dampings, as well as to determine accurately the orbit of the above-described distant satellites.

4. Emplace as soon as practicable laser ranging and VLBI systems of ±15-cm accuracy to define directions with respect to the inertial reference with ±0".005 accuracy: to measure tectonic changes as secular motions of rigid plates, and to improve resolution of the wobble and rotation spectra, as well as to make tests toward system 3 above.

5. Develop navigation systems capable of economically determining ship velocities to ±5 cm/sec over several-minute time averages and ship positions to ±100 m at the same time, plus free instrument float locations with ±2-km accuracy at intervals of about 5 days: to obtain better knowledge of current patterns and diffusion rates.

6. Supplement the long-range measuring systems with accurate surface geodetic surveys: to determine the patterns of deformation along fault zones and to use more effectively conventional geodetic controls, both terrestrial and satellite.

7. Increase the use of geostationary satellites to transmit seismic and ocean data from remote surface instruments for tsunami warnings, ocean current studies, and other geophysical purposes, with an override capability for the occasional rapid transmission of a limited quantity of data for warnings.

8. Support observing programs with a commensurate level of fundamental research (in some cases entailing large-scale computer use) within NASA as well as at universities.

We further recommend that NASA establish a mechanism, such as an Earth Missions Board, for continued participation by scientists in planning of NASA programs in solid-earth and ocean physics, meteorology, and earth-resources survey.

CHAPTER 1
INTRODUCTION

1.1 PURPOSE

Scientists and NASA management personnel recognize that space and astronomic techniques utilizing gravitational and geometric methods offer new opportunities in solid-earth and ocean physics. In order to discuss and develop these ideas, a conference was held in August 1969 to exchange knowledge and to make program recommendations. The resulting document seeks to describe the present state of knowledge in these fields, to identify the important problems, to examine how space and astronomic techniques may contribute to their solution, to recommend the best ways to attack the problems, and to assign priorities so as to facilitate rational decision making.

1.2 SCOPE

This report covers essentially those aspects of geophysics that can be aided by precise measurements of position, velocity, or acceleration with the use of objects outside the earth. The fields involved are mainly solid-earth physics and those parts of oceanography concerned with water motion and the related shape of the sea surface. The instrument that links solid-earth and ocean physics most closely is the satellite-borne altimeter.

A program in solid-earth and ocean physics is logically one of three parts of the NASA effort in earth observations. The other parts are the meteorology program (essentially wide-angle frequent coverage by optical and infrared sensors) and the earth-resources survey program (essentially narrow-angle infrequent coverage over as wide a spectrum as possible).

1.3 HISTORY

This 1969 study arises from the NASA efforts in satellite geodesy, initiated in 1962, that resulted in the National Geodetic Satellite Program (NGSP) in 1964. The goals of the NGSP, a joint endeavor of the Department of Defense (Army, Navy, Air Force), the Department of Commerce (ESSA-Coast and Geodetic Survey), and NASA, are to develop a unified world datum accurate to ±10 m and to refine the description of the earth's gravity field. Analytical and technological developments were supported to achieve these goals. One of the developments of most significance to earth and ocean physics was the laser tracking system, whose ±1-m capability was an order of magnitude better than previously available.

On this basis, an ad hoc Scientific Advisory Group was formed in 1966 to advise the NASA Geodetic Satellite Office of the potential application to the geosciences of the ability to measure to ±1 m and ±10 cm. The group's report[1] established the significance of these applications and led to a limited funding support for further investigation of relevant tracking systems as well as the applications themselves.

Problems in oceanography and geodesy-cartography were also studied, and recommendations were formulated in the National Academy of Sciences Space Applications Seminar Study at Woods Hole in 1967.

In 1968, it became apparent that the requisite measurement accuracy from space could be achieved. It was therefore necessary to expand these applications and evaluate them before initiating programs to establish these accuracies. One of the ways to do so was to invite a multidiscipline group in solid-earth and ocean physics to study the applications. NASA Electronics Research Center presented a proposal for such a study to the NASA Geodesy and Cartography Subcommittee of the Space Science and Applications Steering Committee, who approved the idea and made further recommendations concerning the organization of topics to be studied and the scientists to be invited to participate. During this same period, NASA's planning activities resulted in the publication (April 1969) of the Earth Surveys Planning Report (Blue Book), which provided considerable impetus to this group study. The NASA Electronics Research Center sponsored the study in cooperation with the MIT Measurement Systems Laboratory, whose administrative support made possible this conference at Williams College, Williamstown, Massachusetts, August 11-21, 1969.

1.4 PLAN OF THE REPORT

Any recommendations regarding scientific research must be based on some balance between feasibility and importance. Feasibility in turn depends mainly on instrumental capability. Chapter 2 discusses instrumentation: the accuracies, resolutions, lifetimes, averaging times, and power and weight requirements that appear attainable within the next 5 or 10 years to measure directions, ranges, range-rates, altitudes, accelerations, etc. Chapters 3 through 5 discuss various problem areas of geophysics: physical oceanography, the short-term dynamics of the solid earth, and the long-term dynamics of the solid earth. In each of these areas, the present status is described, the outstanding problems are defined, the prospects for improvement are examined, and recommendations are formulated. Chapters 2 through 5 correspond to the four panels formed for

[1]NASA SP-158: Potential Applications of Satellite Geodetic Techniques to Geosciences, 1968.

this group study and in which most of the work was done. Essentially, each chapter can be considered as the separate deliberations and recommendations of a panel, although, of course, there was appreciable consultation back and forth between panels.

Chapter 6 discusses a variety of related considerations: other earth-oriented programs with which there might be some interaction; practical applications of the programs recommended by the panels; and technologies, programs, or agencies that might help to realize the recommendations. Chapter 7 is the conclusion of the report. It discusses the social benefits of the recommended programs, formulates scientific goals based on the several criteria of importance, and places the recommendations in two priority-ordered lists of decision elements (the minimal blocks of research, development, and fabrication that should be undertaken to realize a particular measurement capability). These two lists correspond to two levels of feasibility: "immediate," for which fabrication of the necessary instrumentation could be undertaken at once, and "eventual," in which the items appear technically feasible, but which require appreciable development to attain the desired accuracies, resolutions, and lifetimes.

1.5 DISCUSSION OF RECOMMENDATIONS

Of the principal recommendations heading this report, the first seven are essentially groupings of the decision elements appearing in the final chapter. It is evident that further combination and specification (e.g., range as well as range-rate tracking) would be necessary to define complete systems. However, it is felt that there are too many questions to be settled by further analysis (e.g., whether use of geosynchronous satellites would alias terms in the wobble and rotation spectra) to make complete system specification feasible in this study.

The principal recommendations do not depend on the manned-space-flight capability. However, advantage could be taken of the manned systems, for such projects as the launching of subsatellites or the visual evaluation of surface conditions in radar altimeter testing. There are one or two aspects of the recommended systems in which the use of a manned spacecraft would considerably increase engineering difficulties: in particular, the drag-free instrumentation.

Detailed breakdowns of the principal recommendations, as well as several additional recommendations, are given in Chapter 7.

To carry out the recommendations of this report in a time scale commensurate with a reasonable rate of increase in our understanding of the geophysical phenomena described in Chapters 3-5 would require completion of all the systems described in the principal recommendations, except the first and the third, by 1975. Such an effort would require an annual budget on the order of $10 million. To maintain this reasonable rate of increase in understanding will require the deployment of the very accurate and elaborate systems described in recommendations 1 and 3 by 1980. The proper utilization of the systems requires several distant satellites in optimized orbits and many sites for the accurate ranging and VLBI, thus increasing the costs by a factor of three or more to around $50 million annually in the late 1970s.

The above program is not technologically limited. A considerably greater level of support could be utilized. Furthermore, the increase in public concern about the quality of the environment may dictate a much greater expansion of activity in solid-earth and ocean physics as well as other earth-oriented space programs. Such a maximal effort could well use over $100 million per year. This question of program level is further discussed in the final chapter.

CHAPTER 2

INSTRUMENTATION

2.1 INTRODUCTION

Since the advent of the first artificial satellites, geodetic measurements have improved by some two orders of magnitude. This improvement in measuring accuracy, coupled with the development of new techniques, notably laser ranging, very long-baseline interferometry (VLBI), satellite radar altimetry, and the direct mapping of a gravity field through range-rate measurements, suggests that we take a new look at the measurement of the earth from space. It appears that accuracies of at least 0.05 mm/sec in satellite-to-satellite range-rate, 5 cm in laser ranging, and 0.″001 in VLBI measurements will be available within a decade.

An examination of the totality of observations in the earth sciences that would be of interest in the light of these capabilities strongly suggests that we should try to see if a unified system can be devised to obtain these observations concurrently on a global basis (this would be of considerable importance in many geophysical investigations).

In this chapter we postulate such a unified system. This system will not necessarily represent the optimum configuration, but it does demonstrate that the geophysical objectives described in the sections on oceanography and solid-earth physics can be attained. No technological breakthroughs are needed. All the accuracy requirements can be met with identifiable improvements in current techniques.

The general configuration of this system will be described following a brief resumé of the geophysical requirements that comprise the system objectives. The technology needed to support this system will then be examined in some detail in terms of the specific functions that must be performed by each of the major system elements. We will then identify specific areas where additional research and development are needed and complete this chapter with an estimated schedule for implementing the system, including those steps along the way where intermediate capabilities will be available.

2.2 SUMMARY OF OBJECTIVES

Since the scientific objectives are discussed at length in the subsequent chapters on oceanography and solid-earth physics, we will confine ourselves here to listing the separate needs of the various disciplines in a form suitable for defining system objectives.

1. Measurement of spatial variations of the geoid to ±10 cm.

2. Measurement of mean sea level on a global basis to ±10 cm. A wide range of frequencies must be determined, essentially a continuous spectrum from periods of 10 sec to many years.

3. Measurements of time variations in the geoid to ±5 cm. These variations include a well-defined set of tidal frequencies plus random, seasonal, and secular variations.

4. Variations in rate of rotation of the earth, and wandering of the pole to accuracies of ±0.''005 for averaging times of 1 day.

5. Relative movement of sections of the earth's surface to an accuracy of ±10 cm or better. These are secular motions at rates of 2 to 10 cm/yr, preferably measured relative to an inertial reference system.

6. Relative motions of earth's surface across faults. These motions are similar to 5) but may not be steady and need not be related to an inertial reference.

7. Ship's velocity to an accuracy of 5 cm/sec and position to accuracy of 10 to 100 m at least once every 15 min.

8. Buoy positions to 2 km once per week.

9. Transmission of geophysical data from remote sensors, such as on buoys, or from remote observing stations.

2.3 AN OCEANOGRAPHIC AND SOLID-EARTH PHYSICS MEASUREMENT SYSTEM

An appropriate system might be comprised of the following:

1. A satellite in a minimum-altitude, circular polar orbit for mapping the gravity field directly through doppler measurements, and possibly for altimetry.

2. Satellites in moderately low-altitude (~700 km) circular polar orbits for satellite altimetry.

3. A constellation of three geostationary satellites spaced equidistant in longitude (120° apart) for tracking 1) and 2) and for data relay from 2) and from surface sensors.

4. A primary ground tracking and data-acquisition network to track 3) with laser and VLBI observations, to track the low-altitude satellites in 1) and 2), and to observe variations in earth's rotation rate and polar motion via VLBI.

5. A surface network of geophysical positioning stations to monitor continental drift, etc. through laser and/or VLBI observations of 3).

Separate spacecraft are suggested for 1) and 2) because of conflicting requirements. For 1), it is of paramount importance that we reach the lowest possible altitude to get maximum sensitivity to detailed structure of the gravity field. Operating life of the spacecraft need be designed only to provide adequate geographic sampling of the field (including whatever redundancy is deemed necessary). (For example, adequate coverage of 1° squares might be accomplished in 60 days of operation.) This spacecraft will undoubtedly take the form of a rather sizable thrustor (>500 lb including fuel and power) for drag compensation, to which will be appended a small electronics package and laser reflector for (ground-based) tracking plus a transponder for the satellite-to-satellite range-rate measurements. It should be noted, however, that if a thrustor (such as the ion engine now being developed) is available that can maintain a drag-free condition at low altitude for a year or more, it may be possible to combine missions 1) and 2) in a single satellite. This possibility should be examined further.

For the most accurate satellite altimetry, the orbital altitude should be higher to attenuate short-period gravity perturbations, and the operating life should be as long as possible, but in any event greater than 1 yr, to allow observation of seasonal and other long-term variations in sea level. On the other hand, the altitude should be low enough to permit the altimeter to operate at reasonable power levels and to provide adequate payload weights with a given launch vehicle. An altitude of 700 km would be reasonable.

The satellites in 3) are actually orbiting tracking stations (like the SCOTT* system described by J. W. Siry[1]). In this context, geostationary satellites have two very important charcteristics: first, they are continuously available, and second, it is a simple matter to point directional antennas at them. The constellation of three such satellites affords coverage over almost all the earth, which together with the continuous availability of each satellite provides an ideal means for simultaneous observation of positions on a global basis, as well as convenient access to ground sensors and low-altitude satellites for data collection and transfer to a central ground terminal.

The basic function of the triad of geostationary satellites is to serve as a "working" coordinate frame for the other system elements. To this end it will be necessary to determine:

1. the geometry of the triangle defined by the three spacecraft;
2. the orientation of the triangle in inertial space;
3. the relationships of the triangle with respect to the earth.

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*Synchronous Continuous Orbital Three-dimensional Tracking.

[1]Siry, J. W., "Earth Physics and Geodesy Programs," Memo to NASA HQ (Enclosure to letter to J. E. Naugle, 27 August 1969).

The first item can be accomplished by the direct measurement of satellite-to-satellite separation by either laser or radio ranging. Tropospheric and ionospheric effects are insignificant, so that the only error sources of concern are those associated with the instrumentation per se. It is not unreasonable to expect two-way ranging to an accuracy of 1.5 cm (0.1 nsec), resulting in a measurement of the satellite-to-satellite range of 7.3×10^9 cm to 2 parts in 10^{10}.

It may be useful to digress in order to consider two points of controversy that are raised from time to time. The first concerns the "incompatibility" of measuring range to 2×10^{-10} when the vacuum velocity of light, c, is "known" to only 3×10^{-7}. This is not a problem in our system. The accuracy of 3×10^{-7} is of concern only to how well we can relate c to a laboratory standard of length (and time). There is no point in our system where we must establish such a relation, with the possible exception of such cases as the measurement of motion at a fault line – even there only the changes in distance need to be so related, and then only to very modest accuracies. In general, we need only assume that c is constant and use it consistently throughout as a scale factor. In other words, we adopt the light-second as our basic unit of length. The only other requirement is that measurements of the time of flight of laser pulses, frequency, wavelength, etc. should be consistently referred to a sufficiently accurate primary standard such as A1.

The other point of controversy concerns the fact that "geostationary" satellites are not in fact stationary but are perturbed by the sun, the moon, longitude-dependence of the earth's gravity field, solar radiation pressure, etc. Although this raises several engineering problems, such as the need for station keeping, it need not interfere with our concept of a "stationary" satellite. It is only necessary that our system be designed to provide adequate data rates to ensure that we always know the constellation geometry to sufficient accuracy. Since the motions are either slow secular or have periods of several hours or more, this is not an onerous requirement. The main problem is whether small errors of 10-cm magnitude would alias terms in the earth's wobble and rotation.

A careful and detailed study will be necessary to find the best way to meet requirements 2) and 3). In principle, the orientation of the geostationary constellation could be measured to impressive accuracy relative to the celestial sphere by use of the three satellites as an orbiting VLBI system. A ground-based interferometer with a baseline of 10^8 wavelengths has produced a resolution of 0."0006 (in observing astronomical radio sources). At a wavelength of 18 cm (1600-MHz hydroxyl lines) the synchronous satellites would provide baselines of 4×10^8 wavelengths, or at $\lambda = 3$ cm, baselines of more than 20×10^8 wavelengths, from which one might expect angular resolutions of 0."00015 to 0."00003. In the absence of atmospheric refraction, these might conceivably result in accuracies of better than 0".0001 in observations of celestial radio sources. However, the engineering problems involved in the implementation of orbiting VLBIs are formidable. To start with, it is not obvious how one might solve the basic mechanical problem of orbiting a precisely shaped 20-m diameter parabola and then maintaining its mechanical properties while it is aimed from one radio star to another, in view of the complex thermal effects resulting from changing solar aspect, etc.

Another possibility is to make optical angle measurements from each satellite. (It is very tempting to find some means of making these measurements from a satellite where the awkward problems caused by the atmosphere are completely eliminated.) However, the straightforward use of the classical technique of photographing the stars does not seem attractive, since it is not obvious that it will be feasible to orbit a camera that is competitive in accuracy with a VLBI. Van de Kamp[2] describes the Sproul refractor as one of the better astrometric instruments and cites an accuracy of 0".04 for this 61-cm aperture, 1093-cm focal length telescope. Although a significant portion of this 0".04 error must be attributed to atmospheric effects that would be eliminated in orbit, the major contributions arise from instrumentation and reading errors, so that it is clearly not a trivial matter to design an instrument for 0".001 accuracy (expected of ground-based VLBIs) that can be launched on a satellite. Nonetheless, this possibility should not be discarded until VLBI accuracies have been established experimentally and an adequate catalog of celestial radio sources has been assembled.

It would appear at this time that the best approach will be to establish a connection to an inertial frame by means of VLBIs on the earth's surface. Within a decade it should be possible to attain ±0".001 accuracies, which are more than adequate for all our objectives. It will then be possible to measure the orientation of a network of radio receivers on the earth's surface relative to celestial radio sources to ±0".001 with averaging times of substantially less than 1 day. And, by use of collocated lasers to tie together the primary system of ground stations and the three synchronous satellites, the geometry of the entire system can be determined to better than 10 cm.

If each of the geostationary spacecraft is equipped with a VLBI beacon of adequate power, in addition to laser retroreflectors, it will be possible to make VLBI observations from the earth's surface without the need for a major antenna installation. As an example, a duty cycle of six 10-min operating periods each day may be adequate for observing body tides, motions across fault lines, and continental drift. Such a duty cycle would allow quite high levels of radiated power and correspondingly modest antenna arrays on the ground. Furthermore, because the satellites are stationary, the

[2] Van de Kamp, P., Astrometry with long-focus telescopes. In "Astronomical Techniques," ed. W. A. Hiltner, The University of Chicago Press, pp. 487-536, 1962.

antennas can be fixed. In fact, it will also be possible to use fixed mounts for laser observations if we station-keep (the synchronous satellites) to 1 km, which is a quite modest requirement.

The system as described above does not satisfy objectives 7) and 8) in Section 2.2 relating to the positioning of oceanographic ships. To provide this capability, we must either add more satellites to the system or add an angle-measuring function to each of the geostationary spacecraft. From the standpoint of technology, the latter course is the more difficult one. It is highly improbable, for example, that a satellite-borne interferometer with the desired accuracy of $0''.1$ will be available within a decade. On the other hand, a range-only system for 10-m positioning is well within the present state of the art. However, a range-only satellite system, which would provide both latitude and longitude in all areas of interest, would entail the addition of six or more satellites in nonstationary (inclined and eccentric) synchronous orbits. The TRANSIT system would satisfy this requirement if the number of satellites were increased to provide more frequent fixes.

This problem of ship navigation will be discussed in great detail elsewhere and requires no comment here except to state that almost all the satellite navigation system proposals now extant are designed to provide a maximum accuracy of 0.1 nm or 200 m. It should be emphasized that this limitation is not the result of technological restrictions. For example, the most probable choice of carrier frequency for a civil navigation system is 1600 MHz. This choice is based on compelling practical considerations but is not compatible with a positioning accuracy of 10 to 100 m. Under moderately severe ionospheric conditions, the range error introduced by the ionosphere can exceed 30 m at this frequency. Because of geometric factors, the position error will exceed 100 m under these conditions. From a strictly technical point of view, there is an obvious means for reducing this error — raise the operating frequency. For our application, 5 GHz would be a satisfactory choice.

It will be important to have some means of obtaining accurate and frequent ship's positions because of their impact on the accuracy of surface gravimetry. It is questionable whether it will be possible to determine fully the geoid to an accuracy of ±10 cm by use of satellite measurements alone, because of the computational difficulty of the downward continuation of detailed short-wavelength geoid features from orbital altitudes to the sea surface. It appears necessary to fill in local gravity anomalies by surface gravimetry, and this can be done to sufficient accuracy only if ship's velocity is known to within ±5 cm/sec (0.1 knot).

2.4 TECHNOLOGY

2.4.1 Camera Tracking

Camera tracking has provided the largest existing body of precise data for satellite triangulation and gravimetry. By photographing a satellite against the star background, cameras can at present provide directions in an inertial coordinate system to an accuracy of $\pm 0''.5$ to $1''.0$. This accuracy is roughly two orders of magnitude short of our requirements.

To improve this accuracy it will be necessary:

1. to improve the cameras. Present technology can provide precision instruments capable of an accuracy of $\pm 0''.05$; somewhat longer focal lengths (2000 mm) than are used in existing cameras would be required. It is difficult to predict what further improvement might be attained in the next decade.

2. to improve our knowledge of atmospheric refraction. Refraction (and its variation with time, the "seeing") is a serious limitation to the accuracy of camera tracking.

3. to improve the star catalogs. Present catalogs used for camera tracking are accurate to $0''.3$ to $0''.5$. Special catalogs with accuracies of $0''.01$ are available but do not contain enough stars. For tracking we need at least one star per square degree. Programs are now in progress to produce a large star catalog (over 200, 000 stars) with an accuracy of $0''.15$. This catalog should be available by 1975. An even better solution would be the preparation of a star catalog from observations made with an astrographic camera located outside the atmosphere on a satellite. Accuracies of better than $0''.01$ could be achieved.

2.4.2 Laser Ranging

There is no doubt that laser ranging will be a basic technique in any future system that requires maximum accuracy. Present laser transmitters have the capability of generating extremely short (5 nsec), high-power (1 GW) pulses at optical frequencies that can be concentrated into beamwidths as narrow as a few seconds of arc. With quartz cube-corner retroreflective arrays of modest size, two-way ranging has been accomplished at lunar distance. These arrays are extremely long-lived in orbit and introduce no unknown or variable time delays in a range measurement. Thus, both existing transmitters and the satellite "transponders" have the ability right now of providing 0.1-nsec ranging.

Receivers, however, are currently able to yield an accuracy of only about 1 nsec. To attain an instrumental resolution of 0.2 nsec (corresponding to a two-way range accuracy of 3 cm), it will be necessary to improve the photodetectors. If it is necessary to use two-frequency laser measurements for the purpose of obtaining a tropospheric correction, a resolution of 0.02 nsec will be required, necessitating improvements in both transmitters and receivers.

Tropospheric propagation errors will, in fact, be a basic limitation in laser ranging from the earth's surface. It should be noted, however, that these errors are less serious at optical than at radio frequencies.

Present US satellites equipped with reflector arrays for laser tracking are BE-B, BE-C, GEOS-1, and GEOS-2. Two French satellites D1-C and D1-D are similarly equipped. The reflectors are cube-corners, made of radiation-resistant fuzed silica, with silvered or aluminized reflecting surfaces.

Optical properties of the reflectors should be matched to the expected "velocity aberration" for the particular satellite orbit. Typical arrays at present consist of reflectors with apertures about 2.5 cm in diameter, but not "diffraction limited;" i.e., imperfections in material and geometry cause a divergence of the reflected rays greater than would be expected from a perfect reflector. The reflected rays from GEOS have a divergence cone of about 15" full angular width at half maximum intensity, or about twice theoretical, but well matched to the orbit. The reflector arrays weigh about 10 lb.

Although cube-corner retroreflectors are effective over a wide range of incidence angles, the reflector arrays must be located on a downward facing surface of the satellite: there must be at least rough attitude stabilization such as magnetic or gravity gradient, or, if spin-stabilized, they must be on a de-spun portion, or, if not stabilized, they must be distributed on all surfaces. For 10-cm precision, the effect of a distribution of ranges to reflectors not on a plane normal to the line of sight must be considered.

Measurements can be made at a rate of one per second. This could be increased to two or three per second if found really desirable. With reasonably accurate range and angle predictions, and automatic pointing and range gating, measurements can be made both day and night above an elevation of 30°. A transportable and programable laser tracking station consists of two or three vans, requires an operating crew of four or five people, and probably costs a total of about $300,000. Primary output is accurate range vs. accurate time, although with some effort, angle data could be produced with an accuracy of 5" to 10".

Present systems use ruby lasers, which transmit single pulses having an energy of about 1 joule, pulse duration of about 15 to 20 nsec, and transmitted divergence of about 1". Reflected signals received by the photomultiplier detector are strong enough to permit use of threshold detection circuits to activate the time interval counters.

Internal consistency or precision of present systems can be estimated by fitting observations during a satellite pass (typically 400 to 500 range measurements) to a least-variance best-fit satellite orbit. The residuals show a rms scatter of about 1 m, typically. The distribution is very close to gaussian, and statistical tests show no correlation between residuals. Scatter is not affected by operation during day or night.

Calibration is performed by ranging to a distant (5 km) ground target that has been carefully surveyed. Uncertainty introduced by calibration procedures will have to be very carefully studied when approaching 10-cm precision, but seems to be no limit at that level.

Intercomparisons of laser satellite-tracking performance with various radio tracking systems were performed in a number of collocation tests. Range discrepancies at satellite distances were typically within 4 m.

Laser range measurements to GEOS-1 from a single station were compared with orbits fitted to several days of data from the SAO Baker-Nunn network and were also compared with orbits fitted to several days of data from the TRANET doppler network. The orbit bias was about 6 m. These comparisons also showed apparent epoch timing errors of several milliseconds between the laser system and each of the other networks.

A high-altitude earth satellite, suitably equipped with optimal corner reflectors, can provide precise measurements of the distances between earth stations for geodetic and geophysical applications. By use of the techniques developed in the lunar ranging experiment, the available precision is better than 50 cm.[3]

For a weight-limited payload, the maximum signal return from a corner array is determined by the relation between the velocity aberration due to the relative motion of station and satellite and the diffraction spreading of the return laser beam. As a concrete example, a synchronous satellite with a station latitude of 30° is considered in Figure 2-1. Thus, for a nonrotating satellite we may have an array of 1-cm corners

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[3]Bender, P. L., C. O. Alley, D. G. Currie, and J. E. Faller, Satellite geodesy using laser range measurements only, J. Geophys. Res., 73, pp. 5353-5358, 1968.

with a total array weight of 1 lb and an area 45 cm × 45 cm. With a 30-in. telescope, this will give a return signal about two orders of magnitude larger than that of the lunar experiment. The detailed calculation results in approximately a 7/2 power dependence of return signal on orbit radius, when the optimum size of diffraction-limited corner reflector is chosen for each radius.

The advantages of a synchronous satellite in conjunction with simultaneous ranging or accurate short-arc interpolation, with respect to a lunar retroreflector array, are 1) somewhat more accurate interstation distance and 2) significantly simpler and less expensive ground stations. The telescope does not need to track since the required pointing to the synchronous satellite can be obtained by a beam-guiding device near the focus of the telescope. The disadvantages are the requirements of a well-determined orbit for the satellite or simultaneous observations by four stations. The simultaneous observations will be made difficult by weather problems.

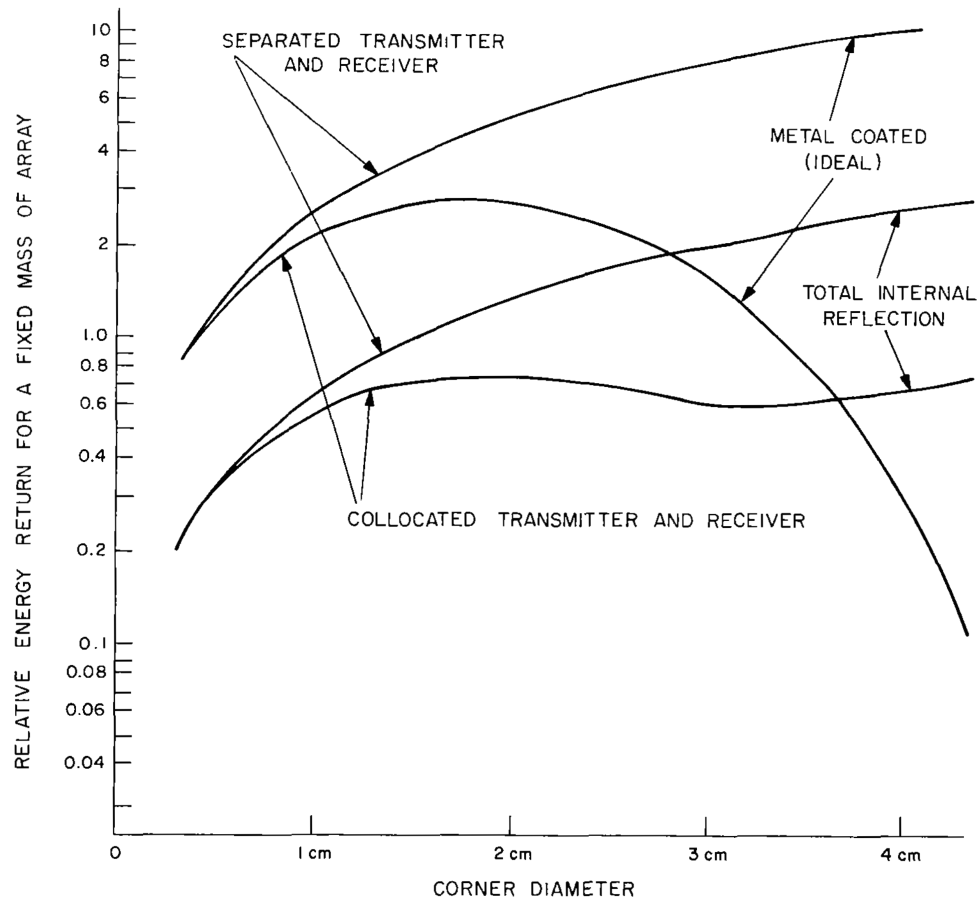

Figure 2-1. The energy of the laser signal reflected from an array of diffraction-limited corners as a function of corner size, for a fixed weight of array on a geosynchronous satellite.

The Apollo 11 crew reported a successful emplacement of the Laser Ranging Retroreflector (LR^3) on the lunar surface with east-west and leading alignments each better than 1°. Acquisition of laser pulse reflections by the 120-in. telescope at the Lick Observatory of the University of California on August 1 confirms the crew report and indicates that apparently no serious degradation of the reflector occurred from debris coverage during takeoff. No adequate quantitative analysis has been made of the signal strength, although it appears to consist of several photoelectrons per shot, in agreement with calculation. Precise timing to 1 nsec by use of the sophisticated electronic equipment at the 107-in. telescope of the McDonald Observatory of the University of Texas was realized within weeks after the initial measurement at McDonald to 4 m on August 19.

The design of the LR^3 experiment to accomplish the scientific aims[4,5] has been the responsibility of the following group of scientists: C. O. Alley, P. L. Bender, D. G. Currie, R. H. Dicke, J. E. Faller, W. M. Kaula, G. J. F. MacDonald, J. D. Mulholland, H. J. Plotkin, S. K. Poultney, and D. T. Wilkinson. Tables 2-1, 2-2, and 2-3 show the estimated uncertainty in the measurement of many quantities. The estimates were made by P. L. Bender. Similar results were obtained in an error analysis carried out by W. M. Kaula.

2.4.3 Very Long-Baseline Interferometry (VLBI)

The technique of "Atomic Clock Interferometry" (with local frequency standards and tape recorders replacing microwave links or coaxial cable interconnections) has recently been applied to the problem of estimating the angular diameter of distant radio sources. The highest resolution obtained so far is 0.''0006. This was accomplished over the intercontinental distance of 6319 km (between the US and Sweden) at a wavelength of 6 cm.[6] A number of compact, distant radio sources remain unresolved at this

[4] Alley, C. O., P. L. Bender, D. G. Currie, R. H. Dicke, and J. E. Faller, Some implications for physics and geophysics of laser range measurements to a lunar retroreflector. In "Proceedings of the NATO Advanced Study Institute on the Application of Modern Physics to the Earth and Planetary Interior," ed. by S. K. Runcorn, John Wiley & Sons, London, 1969.

[5] Alley, C. O. and P. L. Bender, Information obtainable from laser range measurements to a lunar corner reflector. In "Symposium No. 32 of the International Astronomical Union on Continental Drift, Secular Motion of the Pole, and Rotation of the Earth," ed. by Wm. Markowitz and B. Guinot, D. Reidel Publishing Co., Dordrecht, Holland, pp. 86-90, 1968.

[6] Cohen, M. H., D. L. Jauncey, K. I. Kellermann, and B. G. Clark, Radio interferometry at one-thousandth second of arc. Science, 162, pp. 88-94, 1968.

TABLE 2-1. Lunar Orbit

Quantity	Present Accuracy ±	1.5-m Range Uncertainty Accuracy	Time	0.15-m Range Uncertainty* Accuracy	Time
Mean distance	500 m	250 m	1 yr	75 m	0.5 yr
				25 m	1 yr
Eccentricity	1×10^{-7}	4×10^{-8}	1 yr	1.5×10^{-8}	0.5 yr
				4×10^{-9}	1 yr
Angular position of moon with respect to perigee	2×10^{-6}	4×10^{-7}	1 yr	1.5×10^{-7}	0.5 yr
				4×10^{-8}	1 yr
Angular position of moon with respect to sun	5×10^{-7}	4×10^{-7}	1 yr	1.5×10^{-7}	0.5 yr
				4×10^{-8}	1 yr
Time necessary to check predictions of Brans-Dicke scalar-tensor gravitational theory	-	25 yr		8 yr	

*3 observing stations are assumed for periods longer than 1/2 year.

TABLE 2-2. Lunar Properties

Quantity	Present Accuracy ±	1.5-m Range Uncertainty Accuracy	1.5-m Range Uncertainty Time	0.15-m Range Uncertainty* Accuracy	0.15-m Range Uncertainty* Time
Libration parameters					
$\beta \equiv \frac{C - A}{B}$	1×10^{-5}	3×10^{-7}	4 yr	3×10^{-7}	0.5 yr
				3×10^{-8}	4 yr
$\gamma \equiv \frac{B - A}{C}$	5×10^{-5}	2×10^{-6}	1.5 yr	1.5×10^{-6}	0.5 yr
				2×10^{-7}	1.5 yr
Coordinates of retroreflector package with respect to center of mass					
X_1	500 m	250 m	1 yr	75 m	0.5 yr
				25 m	1 yr
X_2	200 m	70 m	1 yr	40 m	0.5 yr
				7 m	1 yr
X_3	200 m	50 m	3 yr	50 m	0.5 yr
				5 m	3 yr

*3 observing stations are assumed for periods longer than 1/2 year.

TABLE 2-3. Geophysics

Quantity	Present Accuracy ±	1.5-m Range Uncertainty	0.15-m Range Uncertainty
Rotation period of earth	5×10^{-3} sec	10×10^{-3} sec	1×10^{-3} sec
Distance of station from axis of rotation	10 m	3 m	0.3 m
Distance of station from equatorial plane*	20 m	6 to 20 m†	0.6 to 2 m†
Motion of the pole*	1 to 2 m	1.5 m	0.15 m
East-west continental drift rate observable in 5 yr*	30 to 60 cm/yr	30 cm/yr	3 cm/yr
Time for observing predicted 10 cm/yr drift of Hawaii toward Japan*	15 to 30 yr	15 yr	1.5 yr

*3 or more observing stations are required.

†Depending on latitude of station.

interferometer spacing of more than 10^8 wavelengths. With better clocks (hydrogen masers) and adequate attention to the removal of systematic errors, long-baseline interferometry shows promise of solving the following general problems:

1. Determination of the magnitude and direction of continental drift over periods as short as 1 yr if the rate exceeds 2 cm/yr.

2. Routine international comparisons of time and frequency to parts in 10^{13}.

3. Systematic study of the irregularities in the earth's rotation. Correlation of these irregular motions with earthquakes,[7] magnetic storms, seasonal and shorter term meteorological effects, and tidal phenomena.

4. Performance of more precise tests of general relativity.

It is well to state at the outset a few useful and not immediately obvious facts. The systematic errors and new geophysical phenomena to be examined by really high-precision interferometry are sufficiently numerous and intertwined to warrant much cross checking and duplication. A sizable number of baselines will be required. This does not mean that a large number of stations need be established. The number of possible baselines for N stations is $N(N-1)/2$, so that for as few as 9 stations there are 40 possible baselines. One should also keep in mind that the sensitivity of an interferometer is proportional to the geometric mean of its antenna areas. Accordingly, the penalty for using a smaller dish in conjunction with a larger one is a linear function of the dish diameter, not area. This makes it possible to use a small, transportable dish for certain experiments of particular interest such as studying the rate of drift of Baja, California, away from mainland Mexico.

The response of a two-element correlation interferometer as a function of θ, the direction of a plane (monochromatic) radio wave of radian frequency ω_0, is

$$P(\theta) = \cos\left(\frac{\omega_0}{c} D \sin\theta\right) , \tag{1}$$

where D is the antenna separation, and c the velocity of light. This is identical in form to the equation for a very long-baseline interferometer used to observe a distant "point" source of radio noise, provided the receiver bandwidth is a small fraction of the operating radian frequency ω_0.

[7] Smylie, D. E. and L. Mansinha, Earthquakes and the observed motion of the rotation pole. J. Geophys. Res., 73, pp. 7661-7673, 1968.

Let us inquire what happens if the system bandwidth is not a small fraction of ω_0. Fringes well away from the central maximum are now reduced in amplitude because of destructive interference. One can describe this by rewriting (1) as

$$P(\theta) = \Gamma_{12} \cos\left(\frac{\omega_0}{c} D \sin\theta\right) \quad , \tag{2}$$

where ω_0 is now the mean radian frequency and Γ_{12} is the mutual-coherence function. If we restrict our analysis to that of observing a distant "point" source of radio noise with omnidirectional antennas, a wide-bandwidth system will exhibit a certain directivity (i. e., fringes will be obtained over only a narrow range of θ). To show how this comes about, note that

$$\Gamma_{12}(\vec{r}, \tau) = \langle V_1(\vec{r}_1, \tau_1) V_2^*(\vec{r}_2, \tau_2)\rangle \quad , \tag{3}$$

which expresses mutual coherence as the correlation of the wavefield at the antennas 1 and 2.

Unambiguous determination of the angle θ to a point radio source is equivalent to the problem of determining the delay time, $\tau = D \sin\theta/c$, that maximizes the correlation (i. e., fringe amplitude). In the simple case that the signal incident on antenna 1 is the same as that incident on antenna 2 (except for the time delay), the cross-correlation function is identical to an autocorrelation:

$$\rho(\tau) = \langle V_1(t) V_1^*(t + \tau)\rangle \quad , \tag{4}$$

and by the Wiener-Kinchine theorem we can write

$$\rho(\tau) = \int_{-\infty}^{\infty} F(\omega) \cos\omega\tau \, d\omega \quad , \tag{5}$$

where $F(\omega)$ is the received power spectrum.

Thus, from the Fourier transform relationship expressed by (5), we immediately appreciate that a wide-band interferometer will have a narrow response function, and vice versa. With a system operating over a sufficiently wide frequency range, one can unambiguously determine delay time and, from it, the baseline parameters.[8, 9]

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[8] Hinteregger, H. E., A long baseline interferometer system with extended bandwidth. 1968 NEREM Convention Record, 10, pp. 66-67, 1968.

[9] Burke, B. F., Long baseline interferometry. Physics Today, 22, No. 7, pp. 54-63, 1969.

Although VLBI measurements have demonstrated exceptional angular resolution, the accuracy has not yet been determined, and clearly it is accuracy that is relevant in assessing the value of the VLBI to our system. Ionospheric and tropospheric propagation errors will be of basic importance. Although these errors can be avoided with VLBIs on high-altitude satellites, this solution may not be practical in view of the large antenna apertures needed for observing celestial radio sources.

Ionospheric errors can be controlled by use of two-frequency reception. A frequency pair with a ratio of 2:1 or more and in the region between 2 GHz and the atmospheric cutoff at ~15 GHz would be suitable

Tropospheric errors are more difficult to correct and are larger than at optical frequencies, but accuracies of 0.''001 may be obtained if, for example, radiometer observations are made along the propagation path simultaneously with the VLBI measurements to determine the water-vapor content of the atmosphere.

Finally, it has not yet been established that a suitable collection of point sources can be assembled in sufficient number and properly distributed to form a radio-star catalog that can be used to define a satisfactory inertial reference frame.

2.4.4 Satellite Altimetry

Our objective is to map the dynamic topography of the sea surface to an accuracy of 10 cm for wavelengths of the order of 1° (100 km) and larger. Time variations ranging from 2 cpd to 1 cpy are of prime interest, and long-term secular changes would be useful.

Radar scatterometry at angles off the vertical would provide useful data on sea state that may be necessary to exploit fully the altimeter measurements. That is, if we make the pessimistic assumption that we will not be able to find a unique relationship between sea state and sea-state altitude bias (as discussed in detail in Section 3.2), scatterometry measurements may be the most efficient means of identifying altimeter measurements that have been made under "unacceptable" sea-state conditions, so that these data can be edited out of the data sets used for topographic analyses.

It is evident from the detailed discussions in the chapter on oceanography that we must end up with dense sets of data extending over at least 2 yr if we are to be able to sort out and quantitatively assess the various forces acting on the ocean surface. From this we deduce that we need a total of some 10,000 hr of observations.

We should not overlook a very important interim objective: refining our knowledge of the geopotential. We can now define the geoid to an accuracy of 10 to 20 m. The most conservative estimate of the accuracy that will be attained on the first (GEOS-C) satellite altimeter is 5 m, so that a substantial improvement to the geoid could be expected from initial altimeter experiments.

It is possible to build a space-qualified altimeter with available components in which the error contributed by the altimeter does not exceed 1 m for averaging times of 10 sec.

To attain altitude measurements with an accuracy of 10 cm, it will be necessary to solve problems in three general areas: 1) propagation, 2) electromagnetic wave scattering by the sea surface, and 3) instrumentation.

Propagation problems are alleviated to a considerable degree by the fact that all observations are made along a vertical path, thereby minimizing the tropospheric and ionospheric path lengths. They are aggravated by the practical difficulty in getting detailed ancillary data for accurate correction of each data sample. The best solution would be to find some means of using available global meteorological and ionospheric data to compute a correction, but there is some question as to whether adequate data are available. Here again, the troposphere is the more serious problem, since a two-frequency system can be used to correct ionospheric errors. The latter are also smaller in magnitude. At 10 GHz, for example, the ionospheric error should be less than 50 cm under severe ionospheric conditions and less than 30 cm under most conditions.

Propagation errors have one unfortunate characteristic: they vary with sunlight and thus have systematic variations at orbital period and orbital precession rates that could result in problems with aliasing.

The problem of radio wave scattering by the sea surface should not be a serious obstacle to accurate altimetry. It is true that we have no sufficiently accurate theory that relates the indicated "altitude" to a "mean" sea-level surface for all sea states. However, there are two empirical ad hoc solutions that seem quite practical. One solution is to calibrate this relationship by means of simultaneous ground-truth and satellite-altitude measurements. (A similar experiment must be performed in any case to calibrate the satellite instrumentation.) The other solution is simply to discard data when the sea state exceeds a specified roughness. It is generally agreed that for moderate wave heights, sea-state bias is not a serious problem, so that less than one-fourth of the data would need to be discarded. This is not to say that the functional relationship between sea state and the reflected radar signal should not be further investigated. On the contrary, such a relationship would be quite valuable — both to avoid loss of altimeter information and, more important, to provide a means for getting synoptic sea-state data from satellite observations.

A substantial development program will be needed to obtain satellite instrumentation that can measure altitude to the desired accuracy, viz., an instrumentation error of 3 cm or less. Particular emphasis should be given to the following specific areas:

1. Transmitter development. This is a long-leadtime item because of the need to develop a source of radio-frequency power that meets rather stringent requirements with respect to operating life (20,000 hr), fast rise time, short pulses of very high stability, etc. for pulse-type transmitters. The use of pulse-compression or related techniques would be advantageous in this application.

2. High-precision timing techniques. Propagation time should be measured to 0.1 nsec.

3. Self-calibration techniques. Even with an active program of component development and improvement, it is not likely that system phase delays can be held stable to the subnanosecond level in the face of temperature and aging effects on components. A means of self-calibration to 0.1 nsec or so would be a great comfort.

4. Signal-processor development. It will be necessary to implement specific signal-processing techniques that result from signal analysis (sea reflection characteristics, etc.) studies. This effort should result in the design of satellite-borne adaptive signal and data processors.

To ensure the success of an altimetry program, it will be necessary to develop the instrumentation within the context of a flight program supported by a substantial oceanographic and meteorological effort to establish ground truth. This "calibration" program should receive considerable emphasis throughout the periods when the orbiting altimeters are operating, because we will not be able to extract all the information on ocean dynamics that is available from the altimeter data until we fully understand how the ocean surface influences the observed return signal. The predicted performance levels for an altimeter development program are

CY	Instrumentation error	Overall accuracy
1970	1 m	2 to 5 m
1973	30 cm	1 m
1976	10 cm	50 to 100 cm
1978	5 cm	20 cm
1980	3 cm	10 cm

2.4.5 Drag-Free Satellite Techniques[10,11,12]

A drag-free satellite in its most elementary form consists of a main satellite body and a small proof mass contained within a cavity at the mass center of the satellite. The reference for drag-free satellite control is the unsupported proof mass, which is shielded by the satellite from external nongravitational forces. Since only gravitational forces act on the proof mass, it follows a purely gravitational orbit. A control system in the satellite senses relative motion of the satellite with respect to the proof mass and actuates translational control thrustors, forcing the satellite to follow the proof mass without touching it. The satellite therefore also follows a purely gravitational orbit.

The design and mechanization of the control system of a drag-free satellite draws upon techniques and components that have been in widespread application in inertial navigation and satellite-attitude control since 1964; it is well within current state of the art. For instance, proof-mass position sensing can be accomplished with a differential capacitance scheme similar to that used in electrostatically suspended gyros and accelerometers. Thrusting can be accomplished with a cold gas thrustor modulated by any one of a number of pulse-modulation techniques (e.g., "pseudo rate" or "derived rate"). The entire drag-free subsystem, including proof mass, capactive position sensor, control electronics, gas lines, and valves (exclusive of propellant and tanks) can be held within a weight budget of 10 kg and power budget of 5 W. Such a system in fact will be built and flown in late 1970 on a gravity gradient-stabilized experimental navigation satellite.

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[10] Lange, B. O., The drag-free satellite. AIAA Journ., 2, 1964.

[11] "Proposal to Develop and Operate a Sustaining Earth Satellite in Two Orbital Flights," submitted to NASA by Stanford University, February 1966 (with Addendum added August 1966).

[12] "Final Technical Report on a Preliminary Design of a Drag-Free Satellite and Its Application to Geodesy," Stanford University, NASA Contract NAS 12-695, May 1969.

The drag-free device very effectively cancels the disturbing accelerations due to surface forces such as atmospheric drag and solar radiation pressure. However, the satellite will not exactly achieve a purely gravitational orbit because of several other very small perturbing accelerations. The largest of these effects is definitely the acceleration of the proof mass by mass attraction of the satellite. By careful management and accounting of the mass distribution within the satellite (particularly masses very near the proof mass), it is possible to compensate this effect to an uncertainty of about 10^{-11} g or smaller, depending on satellite configuration. Since this acceleration is fixed relative to the satellite, an along-track component can be attenuated even further (factor of 10 to 100) by spinning the satellite either about the normal to the orbit plane or about the local vertical. Worst-case upper bounds of the remaining perturbations are position sensor/proof mass interaction, $< 3 \times 10^{-13}$ g; leakage electric field in the cavity, $< 3 \times 10^{-13}$ g; image attraction of cavity for a charged proof mass, $< 3 \times 10^{-13}$ g; divergence of satellite magnetic moments within cavity, $< 10^{-14}$ g; and other effects, $< 10^{-15}$ g.

The propellant required for a given lifetime depends almost entirely on the orbit perigee altitude and eccentricity for close orbits. Figure 2-2 is representative of the cold-gas propellant tradeoff with orbital parameters for a drag-free lifetime of 1 yr, using a reasonable projection of $I_{sp} = 100$ sec for propellant plus tankage.

Ion-engine thrustors[13] rather than gas propellant may provide a better technique for achieving a longer lifetime at a lower altitude if the large amount of electrical power required can be made available. For example, an ion engine having the following properties has been built and tested in vacuum: thrust, T = 1900 dyne; power required, P = 500 W; specific impulse, $I_{sp} = 4330$ sec.

To determine at what atmospheric density this ion engine could overcome the drag, calculate from

$$D = \frac{1}{2} C_D \rho A v^2 \quad ,$$

where

$$D = \text{drag} = T = 1900 \text{ dynes, and}$$

$$C_D \doteq 2.4 \quad .$$

[13] Worlock, R., Informal communication, Electro-Optical Systems Inc., Pasadena, Calif., October, 1969.

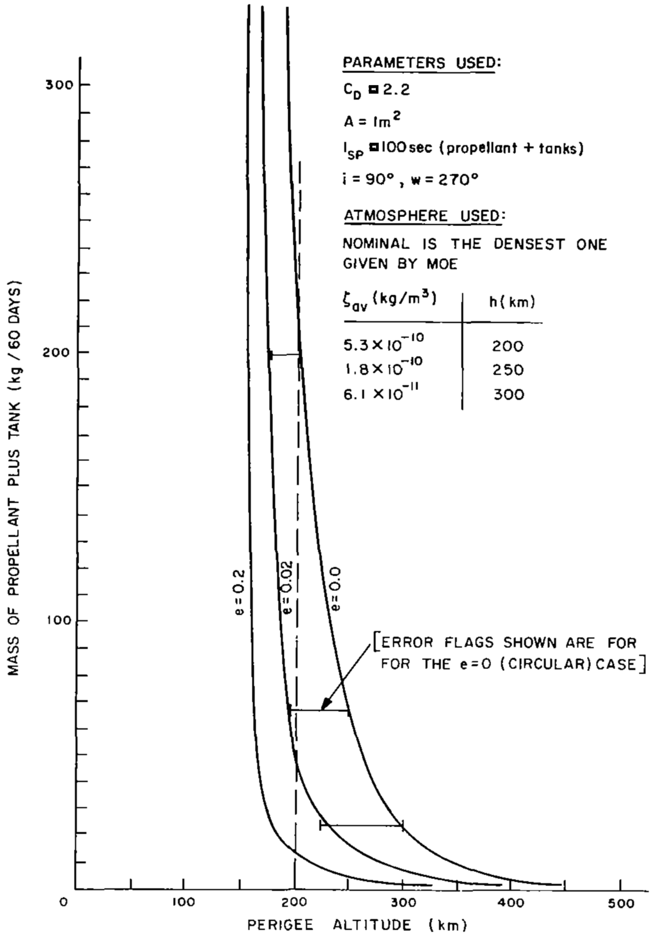

Figure 2-2. Drag-free satellite propulsion system mass as a function of perigee altitude and eccentricity for a cold-gas thrustor.

Assume

$$A \doteq 1\ m^2 = 10^4\ cm^2 \quad ,$$

$$v \doteq 7 \times 10^5\ cm/sec \quad ,$$

and

$$\rho = \frac{D}{1/2\ C_D\ A\ v^2} = \frac{1900}{2.4/2 \times 10^4 \times 49 \times 10^{10}} = 3 \times 10^{-13}\ g/cm^3 \quad .$$

This atmospheric density will occur at an orbital altitude of about 200 km. At a slightly higher altitude of about 240 km, the 1-yr lifetime would be extended to 2 yr.

2.4.6 Satellite-to-Satellite Range-Rate

In order to exploit the satellite altimeter measurements to the full, it is necessary to separate the effects of variations in gravity from the observed altitude. The only way this can be accomplished unambiguously is to determine the geoid independently. Because of the enormous number of coefficients needed to describe the geoid to this accuracy, possibly as many as 10^4, it is not practical to calculate spherical harmonic coefficients through an analysis of orbital dynamics. The number of independent geodetic satellite orbits needed would be greater than 50, possibly in excess of 100. Furthermore, the amplitudes of the orbital perturbations associated with harmonics of degree greater than 50 are well below 0.1 mm and cannot easily be observed.

As noted in Section 5.6, the method used successfully by Muller and Sjogren[14] to obtain the gravitational field of the front face of the moon should be applicable to this problem. The method is to deduce the acceleration of a satellite from doppler measurements, which provides a direct measure of the component of force acting on the satellite parallel to the propagation path. By observation of the doppler shift over a sufficient number of orbits, it is possible to obtain a very detailed gravimetric map through direct observation.

Assuming that variations in kinetic energy can be translated into variations in potential energy, doppler measurements with an accuracy of 0.1 mm/sec between a stationary satellite and a satellite in a low orbit will be adequate to map variations in the equipotential at satellite altitude to 10 cm. The accuracy with which this can be translated into geoidal variations depends on satellite altitude, the analytical techniques available, and how long an averaging time is acceptable. We estimate that a doppler measuring accuracy of 0.03 to 0.05 mm/sec for averaging times of 10 sec will be needed to determine the geoid to an accuracy of 10 cm.

The data used by Muller and Sjogren were obtained with a two-way doppler system using earth-based transmitters and receivers and a transponder in the Lunar Orbiter. The uplink frequency of ~2115 MHz was controlled by a rubidium frequency standard. The transponder multiplied this frequency by 240/221, resulting in a downlink frequency of 2300 MHz. The doppler shift was then obtained by beating the received downlink signal with the rubidium standard. The accuracy of the doppler measurements was in the neighborhood of 2 mm/sec.[15]

[14] Muller, P. M. and W. L. Sjogren, Mascons: lunar mass concentrations. Science, 161, pp. 680-684, 1968.

[15] Muller, P. M. and W. L. Sjogren, Information from deep-space tracking. Physics Today, 22, pp. 46-52, 1969.

Using an identical system for the synchronous-to-low-altitude satellite measurement should result in doppler-shift accuracies of at least 0.3 mm/sec. The improvement results from three factors: elimination of tropospheric propagation effects, reduction by a factor of about 2 in the ionospheric effects, and reduction of the total propagation time by a factor of 10, improving the "coherence" of the signal that has made the round trip with the signal it is compared with in the receiver.

Further improvement can be obtained by use of either a two-frequency pair at or above 1000 and 2000 MHz or a single frequency above 20 GHz* to eliminate ionospheric errors. If the doppler shift were integrated over 10-sec intervals and the number of cycles were measured to a precision of 5 nsec, which is quite reasonable, the counting error would be equivalent to 0.015 mm/sec. (Errors such as this can be further reduced by taking account of their well-defined statistical properties.) We estimate such a system should produce a range-rate accuracy of 0.1 mm/sec. We believe it is possible within the time scale of the Earth Physics Program to achieve accuracies at a level of 0.03 mm/sec.

2.4.7 Radio Ranging

High-accuracy radio ranging is an established technique in satellite tracking. Two distinct types of systems are currently used in this application, pulsed radars and CW systems using ranging tones or pseudo-random range codes. Although satellites have been "skin-tracked" by radar, higher accuracy and more efficient operation are obtained with active repeaters or transponders. CW range tone systems, e.g., the Army's SECOR and the Goddard Range and Range Rate (GRARR) and the JPL Deep Space Network (pseudo-random range code) system all use satellite transponders.

The accuracy of these systems at present is 5 to 15 m. The main sources of error are propagation uncertainties, uncertainty in transponder time delay, finite rise time and jitter of radar pulses, errors in detecting the time of arrival of radar return pulses, and errors in measuring the phase of ranging tones in the CW systems. It is possible to design radio range systems with currently available components that have instrumentation errors of less than 50 cm. This residual error results primarily from transponder time-delay uncertainties that can be further reduced by self-calibration techniques and modifications in transponder circuitry. Aside from propagation errors, radio range accuracies should be competitive with laser ranging.

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*It is of interest to note that selecting a frequency above 20 GHz, which is absorbed in the troposphere, could solve a frequency-allocation problem, since these signals would not be detected on the ground.

In a geosynchronous constellation, the minimum altitude of the satellite-to-satellite propagation paths is about 12,000 km, obviously above the troposphere and most of the ionosphere; hence, it is of interest to examine the possibility of using radio ranging to measure satellite-to-satellite range in our constellation of three high-altitude satellites.

With current techniques, radio systems have a considerable advantage over laser systems in this application. The overall efficiency of generating laser output energy from a primary source of power is less than 0.02% (for a ruby laser). For a solid-state 2-GHz radio system, the efficiency is at least 20%, a factor of 10^3 better than the laser. A further advantage is gained from the applicability of extremely narrow-bandwidth techniques in radio systems.

As an example, it is a straightforward matter to calculate the parameters of the GRARR S-band (2-GHz) system as modified to measure satellite-to-satellite range in the geosynchronous constellation. In this case, the changes in range should be quite slow — the maximum range-rate will certainly be less than 1 m/sec. Thus, we can conservatively use a bandwidth of 10 Hz and averaging times of 100 sec and obtain the following system parameters:

Carrier frequency	2 GHz
Antennas	100-cm diameter parabolas
Beamwidth	10°
"Fine" range tone	15 MHz
Precision	2 cm (0.001 at 15 MHz)
Effective bandwidth for fine range tone	10 Hz
Effective S/N ratio for fine range tone	30 db
Transmitter power	500 MW
Estimated primary power consumption for each satellite	10 W
Weight per satellite including antennas	30 lb

A pulsed ruby laser for this same application would have roughly the following characteristics:

Energy per pulse	5 joules
Beamwidth	1'
Pulse rate	1 per 10 sec
Area of corner-cube reflector array	2500 cm^2
Primary power consumption	2500 W
Weight of transmitter and receiver	500 lb
Weight of reflector array	10 lb

The rough estimates given above indicate a clear advantage for radio range systems in satellite-to-satellite applications based on the present state of the art. It is important, then, to improve the measuring accuracy of such systems — mainly by reducing transponder time-delay uncertainties.

Radio ranging systems may also be useful in ground-to-satellite links if tropospheric errors can be controlled. The main advantage over lasers in this case would lie in their all-weather capability. It is also of interest to note that it is a simple matter to obtain range-rate data from a CW radio range system.

2.4.8 Tropospheric Propagation Errors

Tropospheric propagation errors present a fundamental limit to the accuracy of satellite observation by earth-fixed stations. Bean and Thayer[16] have shown that the ultimate accuracy of single-wavelength optical ranging to satellites or the moon, using surface measurements of refractive index to estimate these corrections, appears to be limited to about 6 cm, or 2.5% of the total correction at zenith. The range error increases approximately by sec Z as zenith angle increases. Radio systems are worse by a factor of about two because of the increased influence of water vapor in the radio spectral region. For a VLBI with a baseline of about the radius of the earth, say 6×10^6 m, this tropospheric error, when observing a radio star, amounts to at least 12 sec 30° $\cong$ 14-cm uncertainty in the propagation path to each antenna. This causes a range-difference uncertainty in the two propagation paths of about $14\sqrt{2} \cong 20$ cm,

[16] Bean, B. R. and G. D. Thayer, Comparison of observed atmospheric radio refraction effects with values predicted through the use of surface weather observations. J. Res. NBS, 67D, pp. 273-285, 1963.

resulting in an angular uncertainty in the VLBI observation of $\Delta\theta \sim 20/6 \times 10^{-8}$ radians $\cong 0\overset{''}{.}007$. Applying the same 5% tropospheric uncertainty factor to the total radio doppler refraction error yields a limit of about 0.05×10 mm/sec = 0.5 mm/sec at 45° zenith angle.

By use of dispersion effects, the uncertainty in range measurements through the atmosphere can be reduced by a factor of 20 to 30 by the use of simultaneous measurements at two optical wavelengths, assuming that sufficiently precise instrumentation is available.[17] A further reduction by a factor of 40 more could probably be gained by adding one or two radio wavelengths, depending on the wavelengths chosen, to reduce the effects of tropospheric water vapor and of the ionosphere.

Some improvement in the accuracy of single-wavelength ranging might result from more accurate measurements of the tropospheric refractivity profile. However, horizontal inhomogeneity of the atmosphere will probably prevent significant improvements in the figures given above, and unknown short-term variations may make the uncertainties worse. Hence, it will be necessary to go at least to single-wavelength optical techniques or to radio methods supplemented by radiometry, and very possibly to multiple-wavelength methods, in order to achieve 10-cm accuracy.

This is true even for the case of satellite-to-satellite tracking of a minimum-altitude drag-free satellite by a synchronous satellite, because at an altitude of 200 km, the satellite will be below the altitude of maximum ionospheric density and the propagation path will traverse more than half of the ionosphere. In addition, the synchronous satellites must still be observed from the ground through the troposphere.

2.4.9 Ionospheric Propagation Errors

In the context of the Earth Physics Program, the effects of the ionosphere on electromagnetic wave propagation can be adequately discussed in terms of the simplified Appleton-Hartree equation for the equivalent index of refraction

$$n \cong \sqrt{1 - \frac{f_N^2}{f^2}} \quad ,$$

[17] Thayer, G. D., Atmospheric effects on multiple-frequency range measurements. ESSA, Tech. Rept. IER 56-ITSA, 53, US Gov't. Printing Office, Washington, D. C. 1967.

where

f_N = electron plasma resonance frequency,

$\cong 9000 \sqrt{N}$ Hz ,

N = electron density per cm^3 ,

f = transmitted frequency.

Because we are interested only in measurements of the highest accuracy, we shall always select frequencies such that

$$\alpha^2 = \frac{f_N^2}{f^2} << 1$$

and

$$n \cong 1 - \frac{1}{2} \alpha^2 \quad .$$

In systems that measure range by observing the total accumulated phase shift between a transmitter and a receiver — such as the GRARR system — the apparent range R_a will be related to the true range R by the relationship

$$R_a = \int n \, dR \cong R - \frac{1}{2} \int \alpha^2 \, dR \quad ,$$

where the integral is taken over the propagation path. For the frequencies of interest here, that is for $\alpha^2 << 1$, the propagation path can be assumed to be a straight line, the range error $\delta R = - 1/2 \ \alpha^2 \ dR$ being primarily the result of the changed phase velocity, $v = c/n$, so the integral can be evaluated along a straight line between transmitter and receiver. Figure 2-3 depicts representative daytime and nighttime variations of electron density with altitude. For a vertical path through the ionosphere, we can evaluate the integral

$$\int_0^h f_N^2 \, ds \cong 81 \times 10^6 \int_0^h N(s) \, ds$$

from these curves, with the result that at vertical incidence,

$$\delta R \sim -\frac{25 \times 10^{20}}{f^2} \text{ cm} \qquad \text{day}$$

$$\delta R \sim -\frac{5 \times 10^{20}}{f^2} \text{ cm} \qquad \text{night} \quad .$$

The ionospheric electron densities vary considerably with solar activity, geography, and — as shown above — with time of day. The variations are complex and difficult to predict, so that in the absence of measurements along the appropriate propagation path at the actual time of a range measurement, we can assume that an ad hoc correction will reduce δR only by a factor of about five. For range measurements at nonvertical incidence, δR will be increased. At 20° elevation, δR is greater by about a factor of three. Thus, the equation above for a daytime ionosphere can be rewritten as

$$|\delta R| \sim \frac{3 \times 10^{21}}{2f^2} \quad \text{cm} \quad ,$$

for use as a rough guide to frequency selection. Thus, for $\delta R = 3$ cm, $f_{min} = 22$ GHz. A similar analysis for pulse-type systems leads to identical results except that the algebraic sign of δR is reversed.

The dependence of the ionospheric error on $1/f^2$ can be exploited by use of a two-frequency system. This provides an explicit evaluation of δR along the propagation path at the time of measurement. For practical reasons, it is convenient to use a frequency pair with a simple integer ratio. The use of two frequencies does not provide an exact correction for ionospheric effects, since there are higher order terms omitted in the above analysis. These higher order terms can be developed as a series in $1/f^n$, $n > 2$, so they exhibit an even stronger attenuation with increasing frequency than the δR shown above. To keep the ionospheric error below 3 cm, the lower frequency of a pair should be 1000 MHz or greater.

Finally, it is of interest to note that 75% of the ionosphere is above 300 km and 90% above 200 km (see Figure 2-3). Thus, the satellite-to-satellite radio link used for tracking the low-altitude gravity-field mapping satellite (Section 2.3) will traverse most of the ionosphere.

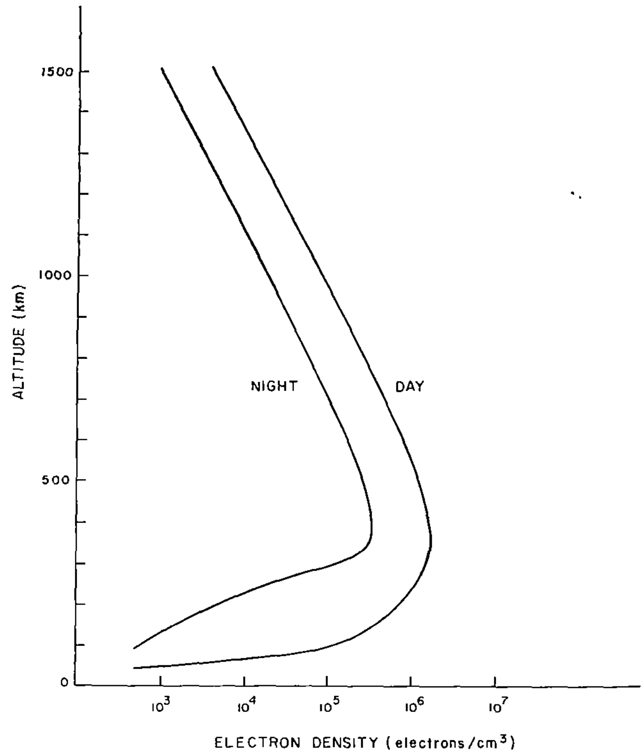

Figure 2-3. Representative ionospheric electron density as a function of altitude.

2.4.10 Epoch Timing

Time must be considered in two ways in our measuring system: as a means of determining range by time-of-flight measurements and as the independent variable in the equations of motion of a satellite.

In range determinations, we should like to obtain accuracies of 0.1 nsec in measuring intervals of the order of 0.25 sec or less, or 4 parts in 10^{10}. Time standards of this accuracy are readily available now, so the only problem is to attain 0.1-nsec resolution in the instrumentation.

There are two considerations associated with the experimental determination of time for use in satellite equations of motion. The first relates to the question of the "uniformity" of a primary time base. This raises some rather subtle problems, since unlike the situation of a length standard, one cannot superpose measured time intervals from different epochs to obtain a direct comparison. The problem has been "solved" by the tacit assumption that atomic time is suitably uniform as the argument in satellite equations of motion. The validity of this assumption rests on the absence of any apparent contradictions between observation and orbital theory. This assumption should not have any impact on geophysical measurements per se, but would be a point of scientific interest in itself as the accuracy (reproducibility is perhaps a more apt term) of atomic standards increases. That is, it would be of great interest to observe whether time in the microscopic domain — atomic time — shows a secular drift with respect to time in the macroscopic domain of astronomy, as has been suggested by theoretical considerations.

The second consideration is the more pragmatic problem of synchronizing geographically separated clocks that are used to establish the epochs associated with satellite-tracking measurements. The required epoch accuracy must be consistent with satellite velocity and the desired spatial resolution. The velocity of a near-earth satellite is roughly 7.5 km/sec. If the spatial resolution is to be 3 cm, our clocks should be synchronized to within 4 μsec.

This accuracy can be achieved through several techniques now in use.

1. LORAN-C. Accuracies of 1 μsec are achieved consistently within the region of ground-wave coverage. The difficulty is that adequate geographic coverage is not now available.

2. Transport of atomic clocks: Accuracy is 0.1 μsec at time of measurement and closing error is 0.9 μsec for a 20-day trip. The main drawback is that frequent calibration of remote clocks is difficult and places the burden on stability and reliability of standards in tracking stations.

3. Artificial satellites. Accuracies of 0.1 μsec have been obtained experimentally by two-way signal exchange, and of 10 μsec by means of satellite-borne clocks. It is feasible to obtain 10-nsec accuracies with present instrumentation.

4. VLBI. In principle, it appears that synchronization to 0.1 nsec should be achievable.

It is apparent that there are already available several means for synchronizing clocks with all the accuracy we might need. Artificial satellites would be the preferred technique because they readily provide frequent (at least daily) global calibrations with modest equipment. In particular, the three-satellite geostationary constellation could provide essentially continuous access to a central master clock from all the ground stations in the system. This ready access would impose minimal requirements on each station clock.

Given below are typical stability characteristics of several time and frequency standards. The tabulated values represent the best state of the art currently available.

Type of Standard	Stability	Averaging Time
Quartz crystal	2 to 4×10^{-12}	100 to 1000 sec
	1×10^{-11}	per day
Rubidium	5×10^{-13}	100 to 1000 sec
	5×10^{13}	per day
Cesium	2×10^{-12}	100 to 1000 sec
	Used as primary standard. Long-term accuracy of the order of few parts in 10^{13}.	
Hydrogen maser	1×10^{14}	100 to 1000 sec
	Reproducible to 1 part in 10^{14}.	

2.4.11 Gravimeters and Gradiometers

In contrast to the situation in satellite measurements, surface gravimeters can readily observe short-wavelength geoid features but pose serious difficulties in obtaining synoptic wide-area coverage. This suggests that surface gravimeters be used to supplement satellite measurements through detailed measurements of localized gravity anomalies such as those in the vicinity of trenches, etc.

A large amount of gravimeter data is now available, though the coverage is sparse or nonexistent over more than half of the earth. In addition, an important factor is that the at-sea measurements are accurate to only 5 to 10 mgal. This is not a fault of the gravimeters per se, but rather the result of errors in our knowledge of ship's velocity. If this factor could be eliminated, existing gravimeters could provide accuracies of 0.5 to 1 mgal. This can be attained by measuring ship velocity (over the ground) to an accuracy of ± 5 cm/sec.

Detailed measurements of local anomalies to an accuracy of 0.5 to 1 mgal are essential to the attainment of a complete geoid map to ± 10 cm.

The use of satellite-borne gradiometers has been suggested as a means of obtaining the harmonics in the earth's gravitational field in the 20th- to 100th-degree range (400- to 4000-km wavelength). At an altitude of 200 to 300 km, it appears that an instrument of the accuracy of 0.1 Eotvos unit ($1E = 10^{-9}$ m/sec^2 m) would be able to make some contribution to this goal. A space-qualified instrument of this accuracy is under development.[18] This is, however, some two orders of magnitude short of what would be required to map the geoidal surface to 10 cm. In addition, extremely precise orientation control (10") is required to obtain meaningful results. Development of other instruments[19,20] with different characteristics may provide relief from this condition. Until more definitive data are available on these instruments, it would seem desirable to base present plans for satellite observations on satellite-to-satellite doppler data, where the required accuracy is already available from current technology.

2.5 CONCLUSIONS AND RECOMMENDATIONS

The main conclusion with respect to technology is that the measuring accuracies needed to meet the objectives listed in Section 2.2 are either available now or can be attained in the near future.

Nonetheless, some specific areas of technology where additional research and development are needed can be identified now:

1. Tropospheric refraction in both the radio and optical regions. A better statistical picture of atmospheric height profiles versus geography and time of year is needed, as well as better information on high-frequency fluctuations in the refractive index. Development of simpler methods of correcting for refraction would be very useful.

2. Laser ranging. Photodetectors with better time resolution are needed. The current capability of 1 nsec should be improved to 0.1 nsec at the single-photoelectron level.

3. Engineering design of a satellite-to-satellite range-rate tracking system.

4. Engineering design of a satellite-to-satellite ranging system with an accuracy of 3 cm.

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[18] Forward, R. L. and L. R. Miller, Generation and detection of dynamic gravitational-gradient field. J. Appl. Phys., 38, No. 2, pp. 512-518, 1967.

[19] Savet, P. H., Gravity field exploration by a new gradient technique. J. Spacecraft, 6, No. 6, pp. 710-716, 1969.

[20] Wilk, L. S., A gradiometric instrumentation concept — the centrifugal balance. MIT Meas. Syst. Lab. Rept. RN-49, 1968.

5. Engineering design of two-frequency satellite beacons for use by ground-based VLBIs.

6. Engineering design of long-life satellite radar altimeter of 10-cm accuracy.

7. Theoretical analysis of the relationship between satellite altimeter observations and ocean-surface parameters, and parallel experimental measurements of these relationships.

8. Engineering development of an ion-engine thrustor or some alternate device for achieving extended lifetime drag compensation in a low-altitude (200-km) satellite.

It will be necessary to support the technological research and development outlined above with a number of satellite experiments. The most effective way to accomplish this would be through an integrated flight program. However, there are some experiments that need not wait for the formulation of a detailed program and that should be implemented as soon as possible. These experiments include, but should not be limited to, a lunar VLBI beacon, an ATS-F-GEOS-C satellite-to-satellite tracking experiment, the GEOS-C altimeter, and the installation of laser retroreflectors and VLBI beacons on the ATS-F and G spacecraft.

In addition to these particular technological problems, a comprehensive systems study should be undertaken to determine just how the totality of observations can best be obtained. In this chapter, we have described a unified system for the program. This system was intended only to provide a means, first, for testing the feasibility of the measurements per se and, second, for emphasizing the fact that from the point of view of instrumentation many of the seemingly disparate geophysical objectives cannot be distinguished from one another and so should be served by common instrumentation.

It should also be emphasized that when we speak of a unified system for earth-physics measurements, we do not mean to imply that this must be comprised of satellites or other system elements that are the exclusive possession of the earth-physics system. On the contrary, it seems clear to us that, for example, early or intermediate earth-physics observations should be obtained with the aid of currently programed spacecraft such as the ATS satellites and that the function of the high-altitude satellites used for tracking the low-altitude geodetic satellite could be most economically performed by a system of satellite-tracking stations designed for general tracking purposes, such as the SCOTT Network. Further, many of the characteristics of the geosynchronous constellation we describe here are identical to those needed for a satellite system for navigation and traffic control. It is important that considerations such as these not be overlooked when overall system design is examined.

2.6 SCHEDULE TO ACHIEVE INSTRUMENTATION ACCURACIES

1. The current status of instrumentation accuracies is as follows:

Laser and radio ranging:	1-10 m
Doppler range differences:	0.1-10.0 cm/sec
Optical camera angles:	1-4''

The accuracy of orbits, survey, and gravity solutions obtained with these accuracies corresponds roughly to ± 30 m with respect to the center of mass of the earth.

2. Improvements of approximately one order of magnitude in laser ranging and two or three orders of magnitude in VLBI angles are expected within the next several years. Also, a new measurement, namely, satellite altitude to ±5 m, is expected within the same time. These improvements should provide within about 5 yr an order-of-magnitude improvement in the accuracy of the current geodetic surveys and gravity fields. They will also bring many of the oceanographic application measurements within reach for the first time.

3. To achieve the instrumental accuracies listed as goals for oceanographic and other geodetic applications will require an improvement of another order of magnitude in measurement accuracy, along with an order-of-magnitude improvement in our ability to correct tropospheric refraction errors, station location variations due to earth tides, etc. These improvements are expected to take at least 10 yr.

CHAPTER 3

OCEAN PHYSICS

3.1 INTRODUCTION

The long-established practice of studying the ocean from surface ships (and more recently from submersibles and aircraft) has one frustrating aspect: the world ocean is so big that even aircraft can sample only a small part of the whole in a day. The possibility of using sensors in satellite vehicles to examine the world ocean twice each day is a very exciting prospect indeed.

In this chapter, we present some ideas about sensors and systems for measuring the properties of the ocean from satellites and of the peculiar suitability of certain orbit configurations to meet special scientific needs. The variety of sensors considered has been limited to those having immediate use. As experience teaches us more about their actual capabilities in flight and as oceanographers themselves become accustomed to thinking and planning in terms of orbiting sensors, many other possibilities may be expected to emerge.

It is important to remember when reading this chapter that the physical sea surface is not equipotential. It is the difference of a few dynamic meters between the physical sea surface and the geoid that is the oceanographer's concern.

3.2 THE ORBITING ALTIMETER

3.2.1 Introduction

The geocentric radius to the surface of the land and sea is a changing quantity at each point of the earth. Tidal forces, wind stress, and barometric pressure constantly remold the sea surface. Erosion, tectonic events, glacial accumulations, and internal mass adjustments remold the surface of the land. These changes can be progressive, cyclic, or intermittent, but each has an explanation and significance in furthering understanding of physical processes at work within the solid earth, oceans, and atmosphere.

It is suggested that worldwide surveillance of these effects might be provided by an orbiting altimeter. Given experience in the analysis and interpretation of remotely sensed events, the technique should prove especially valuable in the rapid survey of oceans.[1]

With an orbiting height sensor we might hope to measure:

1. the patterns and transports of primary ocean currents;
2. tides, ocean-surface waves, and possibly tsunamis;
3. the gravity field and figure of the earth;
4. the atmospheric pressure (and winds) over oceans;
5. eustatic changes of sea level; and
6. volumes and motions of sea ice.

A satellite altimeter in near-earth polar orbit would provide a coarse-grained topographic map of the sea surface every 12 hr. A time series of such maps would provide evidence of change in the oceans that may easily reveal unexpected phenomena in the sea for scientific observation. To those who have worked from ships, aircraft, and submarines covering small patches of ocean each day, the prospect of quantitative semi-diurnal observation of the whole world ocean is a bright one indeed.

How good these opportunities may be depends upon the height resolution technically possible. It is expected that a resolution of ±5 m would provide usefully detailed information concerning the shape of the geoid, but very little oceanographic information. A resolution of ±1 m would permit the detection of tides on continental shelves, storm surges, and possibly the surface elevations associated with western boundary currents. A resolution of ±0.1 m or less would permit detection of the general circulation and greatly augment the scientific significance of all other observations.

3.2.2 The Geoid

Each part of the ocean is equilibrated to the gravity field of whole earth except for effects of order 10^{-7}g due to wind stress, barometric pressure gradients, tides, and barotropic or steric relief. The geometrical topography of the sea surface is essentially that of a level surface to an average accuracy of better than ±1" in most areas. Geoidal relief is of order ±100 m, whereas ocean relief is of order ±10 m at most. Therefore, a direct acceptance of ocean surface topography as equipotential would be a fairly accurate map of geoidal undulations.

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[1] Greenwood, J. A., A. Nathan, G. Neumann, W. J. Pierson, F. C. Jackson, and T. E. Pease, Oceanographic applications of radar altimetry from spacecraft. In "Remote Sensing of Environment," American Elsevier Publ. Co., pp. 71-80, 1969.

A closer approach to the geoidal figure could be obtained by correcting observed sea-surface topography to that of the "standard ocean," namely, by using the equation of state to reduce the observed sea-surface elevations to that of an ocean with 35‰ salinity, 0°C temperature, and 1-atm surface pressure.[2] Sufficient oceanographic information already exists for all depths to allow this to be done. Such correction for the specific-volume anomaly would involve height increments of a few meters, but would only remove the baroclinic relief of the ocean surface. The barotropic relief due to the climatological mean setup resulting from windstress and barometric loading would remain uncompensated. These effects are believed to cause height anomalies of less than 1 m. Ocean circulation models currently under study at the Geophysical Fluid Dynamics Laboratory of ESSA may permit correction for even these effects.[3]

3.2.3 The General Circulation

Of fundamental importance to physical oceanography is the measurement of the difference between the topography of the sea surface and the geoid. Given the geopotential of the sea surface and knowing from ship observations the internal distribution of water density, we would then be able to compute the dynamic topography of all isobaric surfaces and the values of the global geostrophic transport of mass and heat by ocean currents at all depths. The great advantage in this approach is that oceanographic calculations of geostrophic mass and heat transports by ocean currents could be made on the basis of facts, avoiding the traditional and invalid assumption[4, 5, 6] that somewhere deep in the ocean the water is motionless.

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[2] LaFond, E. C., Processing Oceanographic Data. H. O. Publ. No. 614, US Navy Hydrographic Office, 1951.

[3] Bryan, K. and M. D. Cox, A non-linear model of an ocean driven by wind and differential heating: Part I. Description of 3-dimensional velocity and density fields. Part II. An analysis of the heat vorticity and energy balance. J. Atmos. Sci., 25, pp. 945-978, 1968.

[4] Sverdrup, H. U., On the explanation of the oxygen minima and maxima of the oceans. J. Conseil Intern. Explor. Mer, 13, pp. 163-172, 1938.

[5] Riley, G. A., Oxygen, phosphate and nitrate in the Atlantic Ocean. Bull. Bingham Oceanogr. Coll., 13 (1), 126 pp., 1951; see pp. 110-121.

[6] Stommel, H. M., "The Gulf Stream." Univ. California Press, Berkeley, 248 pp., 1965; see pp. 19, 158-172, 177.

These measurements would be not only of basic scientific interest, but also of practical value. For example, the atmosphere overlies the world ocean and is nourished by oceanic water vapor and heat. Detailed observation of the structure of the oceanic general circulation on a day-by-day basis would surely advance knowledge of the energy exchanges between the ocean and the lower atmosphere[7] and improve capabilities to predict weather by numerical forecasting techniques.

For dynamical interpretation of calculations of mass transports, measurements of sea-surface relief would be most valuable if made with reference to the geoid. (In this case, we must define the geoid as that equipotential defined by the surface of a motionless ocean, under uniform atmospheric pressure, in which density is a function of pressure alone.) There is at present no method that permits the potential or gravity at the sea surface to be determined to high spatial resolution from satellite measurements.

Spherical harmonic analysis of the geopotential topography of the sea surface would have to be carried to at least 360th degree to resolve the topographic changes associated with such important features of the ocean circulation as the Gulf Stream. The most optimistic estimates of spherical harmonic resolution from present methods of orbital perturbation analysis suggest that 20th-degree coefficients may be evaluated, but this is too coarse for oceanographic purposes. Hence a more sensitive technique, such as continuous satellite-to-satellite range-rate, is needed to obtain the required resolution.

The altimeter senses variations in the height of ocean surface. To distinguish the ocean surface from the geoid, variations in the gravity field must be sensed. In principle, this sensing can be done by continuous tracking of the satellite orbit variations, as recommended in Section 5.6. This technique should be adequate for averages over extents of 100 km or more. However, the satellite orbit tracking probably would not be accurate enough to pick up the variations of less than 100-km wavelength, which are appreciably damped at satellite altitude (see Figure 5-7). In a few areas, shipborne gravimetry (measurement of acceleration, the vertical derivative of potential $\partial V/\partial r$), may be accurate enough and dense enough to resolve geoid height changes over a few tens of kilometers (by use of the Vening Meinesz formulas). However, further investigation should be made of surface techniques to determine variations in geoid height: i. e., the deflection of the vertical (the slope of the geoid, and hence the horizontal derivative of potential $\partial V/\partial s$, referred to the fixed stars). The accuracy desired is $\pm 0''.5$ for an averaging distance of 15 km. At present, shipborne observations of the deflection

[7] Phillips, O. M., "The Dynamics of the Upper Ocean," Cambridge Univ. Press, London, 261 pp., 1966.

of the vertical (GEON) appear to offer the most hope. Gravity gradiometry (measurements of the second derivatives of potential $\partial^2 V/\partial x \partial y$), both shipborne and satelliteborne, should continue to be examined.

A difference of the slope inferred from the altimetry from that derived from the deflections of the vertical would indicate a slope of the sea surface with respect to the geoid, i. e., the presence of a current. The observed slope would be very close to the slope of an isobaric surface (1 atm) and, with 0.1-m resolution in the altimetric data, yield a measurement of the dynamic slope accurate to 0.1 dynamic meter. Such resolution in the dynamic topography of an isobaric surface would permit the internal field of pressure and currents at all other depths in the ocean to be computed with an error of only 20% or so[8] wherever measurements have been made of the vertical specific-volume gradient in the underlying water column.

In the several phases of this orbiting-sensor concept, it is to be expected that additional information will be incorporated in the interpretation and analysis of height measurements. For example, one would certainly wish to interpret the barometric load on the ocean with reference to synoptic weather maps and take into account the steric relief of the sea surface due to regional differences of sea-water density and steady-state currents. Similarly, where sea-level barometric pressure systems are clearly established, there should be accompanying geostrophic windfields and well-developed sea states.

While the western boundary currents, such as the Gulf Stream and Kuroshio, will provide sharply defined relief, altimetric changes over the broad Equatorial Current systems will be difficult to detect through the "noise" due to long waves, tides, and barometric pressure changes. For this reason, an altimeter should be accompanied by thermal, spectrophotometric, and possibly other ancillary sensors.

The data rate desirable for altimetry depends upon the ground speed of the satellite and the ocean features under investigation. Major western boundary currents tend to be narrow — about 100 km wide — and present the highest data rate requirement. For a satellite at 200- to 500-km altitude, the data rate would be once every 5 sec as a minimum — once every 2 or 3 sec would be better. Features outside the western boundary zones are broader, in which case one measurement every 10 to 20 sec would suffice. If highly detailed maps of the geoid are also to be realized, features such as the trenches along island arcs would demand a higher data rate, again in the once per 2- or 3-sec range.

[8]Worthington, L. V., 1969 (personal communication) reports that present methods based on the "level of no motion" concept can fail to satisfy the mass-continuity condition by as much as a factor of three.

3.2.4 Low-Frequency Phenomena

The spectral density of sea-level variations at frequencies below 1 cph only exceeds the order of 1 cm^2/cph around the tidal clusters at 1 and 2 cpd and at the low-frequency peak going toward 0 cpd. It is most sharply peaked at 1 and 2 cpd.[9] These variations, combined with astronomically derived knowledge of the frequencies of the discrete-line part of the spectrum, make feasible, at 10-cm height resolution, the exploration of the tidal portion of sea-surface elevation by satellite altimetry.

To what precision would oceanographers and geophysicists like to measure the tide? To compute from the global field of sea level elevation the work done by the moon and the sun on the water of the sea (oceanic tidal dissipation), very precise observations — precision of $\pm 1/2°$ in phase and ± 2 cm in amplitude — might allow detection of some significant tidal dissipation outside the ocean. In another case, the US Coast and Geodetic Survey has found that for purposes of tidal prediction at ports, 0.1-hourly values read with a precision of about 3 cm are more than sufficient. For various geophysical purposes (computing the ocean-loading contribution to solid-earth tides, computing the oceanic contribution to tidal fluctuations of the terrestrial magnetic field, etc.), knowledge of the deep-sea tidal elevation field to within 10% of its local value would enable progress to be made. These are problems of enduring geophysical interest, having been under study for centuries.

Excluding noise, bias, and orbital effects, the altimeter signal is a sum of three terms:

time-invariant equipotential topography	+	dynamic topography of ocean	+	tidal elevation	.

Rather than attempt to untangle the global tidal field from a long series of altimeter results, we may use numerical models of the tide that are now under construction to <u>calculate</u> the global tide as a function of geographical location and time, and we may then <u>remove</u> the tidal contribution in each altimeter reading. Any periodic time variability of subsequent altimeter readings points to a nonzero error in the tidal prediction. The tidally periodic components of this error term can then be evaluated at special geographic locations in order to improve global prediction. The quality of prediction projected 2 yr into the future is sufficiently good so that we may expect this procedure to converge to errors that reflect the nongravitational part of the tidal spectrum after one or two cycles. The long-period ocean tides (annual, semiannual, even to a large extent the fortnightly) are largely meteorological. In a scheme such as that outlined above, one would certainly want to include meteorological (inverse barometer) and radiational (thermal expansion and contraction) tides at some point in the data reduction.

[9] Munk, W. H. and D. E. Cartwright, Tidal spectroscopy and prediction. Phil. Trans. Roy. Soc. London, A259, pp. 533-581, 1966.

Several procedures for analyzing the error signal can be imagined. All are equally good in the total absence of noise. But there will be noise in the error signal. It will consist of uncertainties in orbital position, systematic propagation effects, and instrumental noise (including nonsystematic propagation effects). The first has a fairly well-defined and predictable frequency spectrum, the third is probably random from one pass over a given location to the next. In whatever manner one combines data from passes over neighboring subsatellite points (in order to make use of spatial continuity of the tidal field in overcoming insufficient sampling of a given small area), one ought to choose a method that does not alias the error of orbital location into near-tidal frequencies. For example, sun-stationary orbits would emphasize the lunar tide, while moon-stationary orbits would emphasize the solar tide. For complete coverage of the tides, both orbits should be avoided.

Specifically, orbits that avoid periods of 24 and 24.84 hr would, over the course of time, ensure that all important diurnal and semidiurnal tidal components would be viewed over all possible phase interrelationships. The fortnightly tides, the monthly tides, and the annual tides require other orbital configurations. Special consideration must also be given to sporadic events such as tsunamis.

A tsunami originating on the rim of the Pacific Ocean takes about a day to travel across the Pacific to the other side. Owing to the shape of the earth, originally divergent waves can converge and increase in amplitude as they approach an antipodal point. The most prominent waves are present for the first day or so. If a satellite makes 14 orbits a day consisting of 14 north-bound and 14 south-bound passes, there is a high probability that 5 or more orbits will pass over a tsunami wave train as it progresses across the Pacific. But tsunamis are ephemeral. For this reason, it seems unlikely that an altimetric warning would precede tsunami detection by ground-based sensors. However, the open-ocean amplitude and progress of a tsunami wave train might best be determined by spacecraft altimetry. Such observations would also provide fresh information on the directional characteristics of each type of source.[10,11]

[10] Van Dorn, W. G., Impulsively Generated Waves. Scripps Inst. Oceanogr., Rept. 11, 1959.

[11] Kranzer, H. C. and J. B. Keller, Water waves produced by explosions. J. Appl. Phys., 30, pp. 398-407, 1959.

3.2.5 Waves

Wind-generated waves are both a source of bias in precise altimetry and an oceanographic feature that is of scientific and practical interest to monitor from space.[12] Unfortunately, the statistical properties of the sea surface cannot be described by a single "sea-state" parameter. Furthermore, the dynamics governing wave motion are not linear and consequently the statistics are not gaussian. These factors complicate the analysis and calibration of radar altimeters and sea-state sensors.

The wind-wave spectrum can be loosely divided into three regions:

1. capillary and short gravity waves;
2. energy-containing waves generated locally; and
3. swells propagated from distant generation regions.

Because there is no unique relation between these spectral subranges, the sea state cannot be characterized by a single parameter.[13] The energy-containing waves are of greatest practical importance.[14] The higher frequency waves are expected to be closely related to local surface winds and apparently are the part of the spectrum sensed by scatterometers. The relation between surface roughness and wind speed is influenced by surface film contamination that cannot now be determined from space. The effects of surface contamination on the radar altimeter signal need investigation.

The analysis of the radar return from a wave-disturbed sea is dependent on a detailed knowledge of the statistical properties of the surface. Available experimental data are adequate only to demonstrate that gaussian statistics are not appropriate for ±10-cm accuracy in the definition of sea level in most sea states. This makes an a priori estimate of radar-altimeter performance and the interpretation of radar returns somewhat difficult.

Present attempts to calculate radar sea return and the shape of the return pulse are dependent on linear theories about the shape and statistics of the sea surface. Higher quality ocean-wave time histories whose nonlinear features, especially at very

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[12] Kinsman, B., "Wind Waves." Prentice-Hall, Englewood Cliffs, N. J., 676 pp., 1965.

[13] Proceedings of a Conference, "Ocean Wave Spectra." Div. of Earth Sci., Nat'l Acad. Sci. — Nat'l Res. Counc. Pub. Prentice-Hall, Englewood Cliffs, N. J., 357 pp., 1961.

[14] Moskowitz, L., Estimates of the power spectrums for fully developed seas for wind speeds of 20 to 40 knots. J. Geophys. Res., 69, pp. 5161-5179 (see also pp. 5181-5204), 1964.

short wavelengths, were accurately preserved could provide additional insight into the complicated structure of the surface and thus yield better models. These may be available from current research programs and should be investigated in this context. There are no conceptual difficulties in working out expected value statistics on nonlinear properties.

The value of σ° (the radar scattering cross section) for straight-down propagation is a design parameter for a radar altimeter. Measurements from NASA aircraft apply only to within 5° of the vertical, and some radar scientists suggest that σ° is much larger at the vertical. A program to measure σ° precisely at the vertical would provide this much-needed design parameter. At present, σ° is probably underestimated, and therefore the estimated power requirements for an orbiting radar altimeter may be excessive.

Since the mean sea surface is everywhere convex upward, the problems of radar scatterometry at other angles than the vertical do not appear to enter into the problem of the optimum design of an altimeter. Scattering data useful in describing wave conditions might be contained in a simple record of return-signal strength in the vertical. It is probable that information on wave height can be obtained by processing the return altimetry signal so as to remove the bias.

The radar altimeter design capable of 10-cm rms random error is based conceptually on very high ambiguous pulse-repetition frequencies of the order of many thousands of pulses per second. For averages based on such prf's, the sampling variability problem virtually vanishes. Expected value theory then permits the investigation of a wide variety of possible wave-elevation distributions and of variations in signal return at crests and troughs so as to determine the range of biases that could occur.

The uncertainties in altimeter performance associated with sea-surface roughness are not critical at the 1- to 5-m level of resolution, but the 10-cm level will not be reached until the bias in radar returns from a wave-disturbed sea is understood. Toward this end, the research programs in progress should be continued and others formulated:

1. laboratory and theoretical studies of electromagnetic reflection from wavy surfaces with the aim of determining the relevant statistical properties of the surface;

2. field measurements to determine the ocean wave statistics relevant to electromagnetic reflection; and

3. field testing of radar systems.

Such programs are needed to determine what sea-state information will be required for accurate altimetry as well as what properties of the ocean wave field are measured by radar altimeters.

3.2.6 Ocean Verification Site

The first experiment using a satellite altimeter (presumably aboard GEOS C) will require verification in a very well-surveyed region and the placement of ships in that region to monitor oceanographic and meteorological changes. Such a site should have conspicuous and well-known geophysical, meteorological, and oceanographic features.

The Caribbean Sea area fulfills these requirements. It contains significant gravity anomalies that have been carefully surveyed.[15] The tidal regimes and dynamical topography are known from existing oceanographic observations.[16,17] The site would also provide an opportunity to study sea-surface slopes due to trade winds and the circulation of major current systems. If the Pacific west of the Isthmus of Panama is added, as well as perhaps the Gulf of Mexico and Gulf Stream as far north as Cape Hatteras, all significant features desirable in a first experiment will be present.

The choice of a test site is intimately connected with the choice of orbit. An orbit of at least 30° inclination would be preferable to a lower inclination since it would sweep over strong currents such as the Gulf Stream. However, the greatest benefit to both geodesy and oceanography would come from a high-inclination orbit given essentially global coverage of well-known ocean areas.

The lifetime of GEOS C or an equivalent satellite carrying the altimeter experiment should be 6 mo to 1 yr. Subsequent satellite altimeters in polar orbit should have a lifetime of years, if possible, with standby equipment ready for immediate replacement launch.

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[15] Bowin, C. O., Some aspects of the gravity field of the northern Caribbean. In "Transactions of the Fifth Caribbean Geology Conference," July 1-5, 1968, St. Thomas, V.I. 1969 (in press).

[16] Wüst, G., "Stratification and Circulation in the Antilles-Caribbean Basins." Columbia Univ. Press, New York, 201 pp, 1964.

[17] Worthington, L. V., Recent oceanographic measurements in the Caribbean Sea. Deep-Sea Res., 13, pp. 731-739, 1966.

3.3 PRECISE POSITIONING AND TRACKING

3.3.1 Introduction

A long-standing problem in deep-sea oceanography is that of adequate horizontal positioning. Many quite proper scientific questions are simply not asked because off-shore navigation, even by TRANSIT satellite, is not accurate enough. Continuous vehicle location to ±100 m or better and a determination of 5-min average vehicle velocity to ±5 cm/sec or better can be achieved by radio navigation within 100 miles of land, but off-shore navigation is only one-tenth as accurate at best. Removal of this limitation would produce a quantum jump in open ocean research and survey opportunities.

There are basically two types of measurement requirements:

1. positioning of fixed points on the ocean floor where several repeated measurements can be made; and

2. positioning while the vehicle is under way so that only a single measurement can be made at one place.

It is desirable that the accuracy achieved with type-1 measurements be an order of magnitude higher than with type-2 to permit precise station-keeping and to provide "reference points" for survey operations.

3.3.2 Marine Geodetic Reference Points and Standards

Marine geodetic reference points are needed to serve as sites in the open sea and for navigation and mapping control for the calibration of positioning and surveying systems. It is desirable that these reference points be located in an ocean-wide geodetic coordinate system and that standards of gravity be known at each station to ±0.1 mgal, magnetic dip to ±1', magnetic intensity to ±1 gamma, and water depth to ±0.5 m (referred to mean sea level). It has been shown that such reference points can be marked by an acoustic transponder array on the sea floor.[18]

It is intended that these marine reference points be moved about to meet existing research and survey requirements. Apollo tracking ships appear to be suitable vehicles for locating these stations to the required accuracy. But the full capability of these ships can be achieved only when a satellite is equipped with either a C-band or S-band radar transponder and a doppler system.

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[18] Mourad, A. G. *et al.*, New geodetic marker. EOS, Trans. Amer. Geophys. Union 50 (4), p. 104, see also p. 119, 1969.

3.3.3 Marine Gravity Measurements

Gravity measurements on a worldwide basis are needed to further understanding of the earth's figure and mass distribution. The largest errors in gravity measurements at sea, whether the measurements were obtained from shipboard or in airborne systems, are caused by navigational uncertainties. It is necessary that the E-W component of velocity of the surveying vehicle be known to 1.0 knot (5 cm/sec) to reduce observed gravity to rest with an accuracy of 1 mgal.

The proposed open-ocean reference points would be valuable in this connection for navigational control. Electromagnetic or acoustic positioning relative to these stations could fill in the gaps between satellite fixes and would thus provide a much needed improvement in the measurement of ship velocity for the reduction of gravity observations to rest.

3.3.4 Marine Mapping and Charting

Effective exploration and exploitation of the oceans and their resources are dependent upon the availability or construction of accurate maps and charts. Accuracy requirements[19] for detailed mapping range from ±20 to ±200 m for bottom exploration, and from ±300 to ±1000 m or more for descriptive oceanographic or biological charting. Systematic mapping of ocean topography is usually carried out on "plotting sheet" (about 1:1,000,000) scale because of navigational uncertainties. On the continental shelf and slope areas, mapping on a 1:250,000 scale is practicable,[20] but larger scales are appropriate for many proposed research and engineering programs.[21] A combination of satellite and radio navigation methods has been utilized in small-scale deep-sea mapping. For large-scale deep-sea mapping, continuous, high-precision positioning techniques must be developed. A satellite navigation system should be considered.

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[19] Adams, K T., Hydrographic Manual. Special Pub. No. 143, US Coast and Geodetic Survey, US Gov't. Printing Office, Washington, D. C., 940 pp., 1942.

[20] Taylor, L. G., Bathymetric maps for continental shelf development. In Proc. 1st. Marine Geodesy Symposium, US Gov't. Printing Office, Washington, D. C., 1966.

[21] Stratton, J. A. et al., "Our Nation and the Sea." Report of the Commission on Marine Science, Engineering and Resources, US Gov't. Printing Office, Washington, D. C., 305 pp., 1969.

3.3.5 Marine Surveys

The periodic positioning capability of the TRANSIT system can provide the accuracies required for deep-sea marine surveys, but it is not a substitute for the ultimate requirement of continuous position information, physically and economically adapted to research and survey vessels.

If satellite observations are to be used in surveying environmental features, it is essential that the location of the satellite viewing area be known to within ±1 km. This would permit reconnaissance maps (at 1:1,000,000 scale or smaller) to be made on the basis of useful overlap, junctioning, and repetitive measurements from different spacecraft or from successive orbits of the same spacecraft, or with observations made from surface vehicles.

3.4 OCEAN TRANSPORT AND DIFFUSION

3.4.1 The Problem

The elucidation of the general circulation is a fundamental problem in physical oceanography.[22] Interest in the results ranges from simple scientific curiosity to very practical and topical concerns such as the spread of nutrients or of pollutants that have been released in the deep sea deliberately or by accident. After a century of study, oceanographers are still unable to answer such questions as "How long will any leakage of supposedly sealed reactor waste take to reach the surface from a deep dumping ground?" or "Where will any leakage first make its appearance at the surface?" When dealing with the surface circulation, which has been by far the most fully explored, oceanographers are hard put to predict the motion of a Santa Barbara oil slick, to name another practical example. Some of the most important questions asked of oceanographers concern the distribution and transport of substances in the ocean. The answers to these questions have as their starting point statements about mixing and flow in the sea. Such questions must be answered if disasters are to be avoided in the exploitation of the oceans.

Oceanographers may answer these questions only if they can understand the motion of the water of the sea. The amount of knowledge necessary depends upon the detail to which a prediction of the spread of any substance is required: studies of offshore pollution by city sewage require more detail (seasonal at least, and in length scales of several

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[22] Stommel, H. M. et al., Summer Study Program in Geophysical Fluid Dynamics. Woods Hole Oceanographic Institute, Ref. No. 68-72, 1968.

miles) than studies of phosphate distribution in the deep ocean. No typical scales are applicable to the deep ocean because too little is known about the deep circulation to suggest appropriate ones, especially if the escape of small amounts of material is of concern. Enabling oceanographers to answer such questions is surely one of the most important practical objectives from the viewpoint of general ability and benefit.

3.4.2 Method

What is the simplest program that would lead to substantial improvement in the ability to answer these questions? Without knowing any more than is now known about the statistics of the flow, it is not possible to specify how many measurements will result in a specified improvement of predictive ability. It cannot even be said how many measurements will improve present knowledge of the statistics by a significant amount. Nevertheless, a beginning must be made from the present state of ignorance.

Mixing and transport are determined directly from the motion of Lagrangian tracers. Investigation of the transport of substances using Lagrangian tracers therefore appears the most suitable method when it is realized that an Eulerian description of the flow sufficiently dense in space and time to reconstruct the Lagrangian description is extremely difficult to obtain even in the laboratory. A Lagrangian study would be in no way competitive with or redundant of existing and proposed studies of the flow from moored buoys. Those kinds of studies give a wealth of information about the time variation of the flow, but they would have to be run for years at closely spaced but widely distributed geographical locations in order to predict where a fluid parcel would drift in a month or a year.

The only practical way such a study could be realized is by monitoring from space the location of free-drifting beacons. Such beacons, housed either in surface buoys or in subsurface floats that periodically rise to the surface to be located, would allow direct measurement of fluid motions on many scales. For example, the general circulation that is intimately related to the distribution of ocean resources, or oceanic mixing, which is crucial to waste disposal at sea, could be examined. Such a location system might also prove useful in meteorology or the study of wildlife migration.

The principal sources of information regarding surface currents are 1) ship's drift observations, 2) geostrophic estimates relative to a hypothesized level of no motion, 3) drift-bottle observations, and 4) a tiny number of direct current determinations, many in special locations where the flow is intense (Gulf Stream, Cromwell

Current, etc.). This evidence suggests the energy of the flow at all scales of length and time but is totally inadequate to an examination of even the gross features of mixing between adjacent current gyres.

Knowledge of the deep flow is far less extensive than that of the surface flow. There are some 1) tracer studies of the global distribution of properties (temperature, salinity, oxygen); 2) studies of the motion of neutrally buoyant floats; 3) radiocarbon dating of deep-water samples; and 4) results from numerical models. Of these, only 2) offer any suggestion of how long it is necessary to allow a deep float to average the deep flow if individual segments of its track are to reflect more than the transient eddy structure of the flow. The result seems to be that averaging periods far longer than a week are essential.

Mean surface flows of 50 cm/sec lead to buoy drifts of 40 km in a day, 300 km in a week. The length scales over which detail would appear in the path of a continuously tracked float range from millimeters to earth radii: for investigations especially concerned with mixing, the best averaging intervals (between successive float position fixes) are those that remove the effect of the various long wave motions resulting in appreciable instantaneous particle velocity but in little net mass transport (tides, inertial motions).

If the mean deep flow is 0. 1 to 1 cm/sec, the corresponding buoy drift in a week is 0. 6 to 6. 0 km. When the float surfaces, it must be ranged by satellite before it has drifted more than perhaps 20% of its deep drift if the deep flow is to emerge from the measurements. Perhaps one might begin with deep drifts of a month (2 to 20 km). If the surface-residence time of the float awaiting acquisition results in drifts 20% of these values, then the float should stay at the surface long enough for a measurement of mean surface current by the same method.

How many floats must be used? "The more the better" is not a sufficient response. There must be enough floats to provide a guess at how representative subsequent single measurements may be. A cluster of 10 to 20 floats initially at the same point seems intuitively the proper minimum starting point, although there are no firm results regarding eddy-length scales to support this. Most oceanographers would be wary of drawing conclusions from one, two, or five floats. The amount by which such a clump of floats spreads depends upon the spatial coherence and eddy structure of the flow. Mixing coefficients of 10^4 to 10^6 cm^2/sec lead to spreading scales of 1 to 8 km over a day, 4 to 40 km over a month, and 16 to 160 km over a year. These are, of course, not rigorous estimates. They merely suggest appropriate tracking scales.

3.4.3 Programs

Given a global satellite system for tracking drifting floats, then perhaps a reasonable first program of surface observations would involve placing 6 clumps of 12 floats, with 1 clump each at the following locations:

1. the Gulf of Mexico in the Yucatan Channel;
2. the Gulf Stream off Cape Hatteras;
3. the central equatorial Atlantic, at one's best guess at the boundary between gyres;
4. the California current;
5. the north-central Pacific near the boundary between subtropical and subpolar gyres;
6. the equatorial Pacific.

The floats should be tracked at intervals of 1 day to 1 week for 6 months or 1 year.

An analogous deep-sea program would perhaps begin with 6 clumps of 12 deep floats each at the following locations:

1. the deep North Atlantic;
2. the deep mid-Atlantic;
3. the Tonga Trench;
4. the Antarctic Circumpolar Current north of the Weddell Sea;
5. the Central North Pacific;
6. the Central Indian Ocean.

The floats should be followed for 2 yr at monthly or bimonthly intervals.

These are only examples of possible programs. Other interesting locations and combinations of deep and surface programs are easily imagined. Certainly these two sample programs would not by themselves provide all the information that will be required eventually.

3.5 RECOMMENDATIONS

3.5.1 Satellite Altimeter

Prove in an early flight the capability of a single satellite, in near-earth (polar) orbit and equipped with a suitably designed radar altimeter, to find the topographic relief of the physical sea surface; test such observations against "ground truth" in an area where geodetic, gravimetric, and oceanographic variables are well known; plan for and design a more advanced satellite for physical surveillance of the world ocean, its mass transports, heat fluxes, tidal regimes, surface-wave characteristics, and sporadic phenomena such as storm surges and tsunami wave trains.

3.5.2 Downward Continuation of Potential

Support theoretical research in the determination of the geoid from measurements of satellite range-rate, to include both the mathematical problem arising from the need to generalize Stokes' theorem and the statistical problem arising from the damping of the short-wavelength variations at satellite altitude.

3.5.3 Scattering of Reflected Electromagnetic Waves

Support research into the problem of electromagnetic wave scattering from a non-linear sea as a necessary step toward 10-cm resolution of sea-surface heights. (The 10-cm level of resolution will not be reached until this source of bias in radar returns from a wave-disturbed sea is well understood.)

3.5.4 Ancillary Sensors

Require that any advanced version of the altimetric satellite be equipped with sea-surface temperature and spectrophotometric sensors (scanning or imaging at the same resolution as the altimeter spot) to aid in the interpretation and confirmation of marine altimetric observations.

3.5.5 Buoy-Tracking Capability

Provide a satellite, to be flown in a year with a mission duration of 2 to 4 yr, that is capable of tracking 50 to 500 expendable drift-indicator floats that do no more than broadcast a continuous signal for tracking purposes. (Attempts to telemeter additional data or to query individual floats from the satellite should not be undertaken.)

3.5.6 Position and Velocity Measurements

Develop systems that will provide, on a global basis, continuous running average position of moving vehicles to ±100 m in a worldwide geodetic or geocentric coordinate frame, velocity to an accuracy of ±0.05 m/sec or better (5-min average), heading to an accuracy of 10 mrad with reference to the geographic north point, and daily position of drifting instruments to an accuracy of 1 km.

3.5.7 Standard Stations

Provide acoustically activated, sea-floor, geodetic control stations, located on the world datum to ±10 m horizontally and ±0.5 m vertically (referenced initially to local mean sea level) as required for basic oceanographic and geophysical research or survey operations, and provide at these stations standard values of gravity (±0.1 mgal), mean magnetic intensity (±1 gamma), magnetic dip (±1'), and water depth (±0.5 m) at mean tide.

3.5.8 Improvement of Research-Vessel Capabilities

Contribute to the improvement of existing research vessels by encouraging or supporting the acquisition of ±1-mgal gravity data; provide engineering support to the oceanographic community in the fields of automatic data acquisition and processing; and improve the efficiency of research vessels by providing support for on-board real-time reception of remote sensor outputs (navigation, tracking, imagery) applicable to certain phases of research at sea. (As a general rule, it is better to provide complex systems in the satellite in order to simplify real-time shipboard reception and analysis of satellite observations.)

3.5.9 Relay Communications

Develop a reliable and inexpensive shipboard receiver for real-time readout on surface vessels of local cloud cover and IR image frames and altimeter tracks; provide sufficient on-satellite memory so that shore stations can collect all the altimeter data generated since the satellite's last pass within transmitting distance; provide, upon interrogation, continuously updated summaries of position and acquisition times of satellite-tracked drifting objects.

3.5.10 Apollo Tracking Ships

Investigate the feasibility of retaining or having access to at least two Apollo tracking ships (one in the Atlantic and Indian Oceans and another in the Pacific) for integrated support of the satellite/marine sciences program, to assist in the determination of orbits with greater precision over oceans and to provide the measurement capabilities needed to locate and calibrate the standard stations described in Section 3.5.7.

CHAPTER 4
SHORT-TERM DYNAMICS OF THE SOLID EARTH

4.1 INTRODUCTION

4.1.1 The Earth as a Mechanical System

The planet earth is a mechanical system embracing, as major subsystems, the atmosphere, oceans, solid lithosphere, and fluid domains in the interior. These subsystems interact in various ways, exchanging energy and momentum. In addition, the earth and its subsystems are continually influenced by other parts of the solar system.

Every part of the mechanical system that constitutes the earth is a topic of vital interest to one or another scientific discipline. Thus, there are recognized topics such as dynamical meteorology, dynamical oceanography, solid-earth dynamics, and the dynamics of the earth's interior. Each of these disciplines has its challenging scientific problems of varying degrees of application to the concerns of society.

Some phenomena in earth mechanics are of peculiar concern to society because of their catastrophic character. Hurricanes, seismic ocean waves, earthquakes, and volcanic eruptions are all manifestations of the mechanical workings of the earth.

Some specific aspects of the earth system are of vital concern to NASA. One familiar example is the need for accurate positions for ground instruments observing spacecraft. Another is the need for parameter values involved in determining the orbits of spacecraft.

Also, NASA's interests are intertwined with earth mechanics in still more fundamental ways, through the capabilities that space techniques and instrumentation provide for studying the earth as a mechanical system. These techniques and instruments have been discussed in the previous chapter on instrumentation.

From a social point of view, it hardly needs emphasizing that the mechanics of the earth are integral to the problems of man's environment, which are achieving such prominence in today's world.

4.1.2 Short-Term Dynamics

The solid earth, including the fluid domains within it, exhibits a variety of motions with an extended temporal spectrum. At one extreme, portions of the crust move relative to each other by only a few centimeters per year. At the other extreme, in a few seconds a major earthquake may produce 10-m displacements of regions more than 100 km in extent.

For purposes of this report, "short-term dynamics" is defined as, roughly, that portion of the spectrum with frequencies higher than 1 cpc.

But before it is possible to study rigorously these motions and their causes, it is first necessary to define precisely the coordinate systems to which the motions will be referenced. A system specified by distant astronomical objects, approximating an inertial system, is obviously fundamental. A system with its origin at the center of mass of the earth and with axes in some sense fixed in the earth is another obvious choice. A system with its origin at the mass center of the solar system is another convenience. Section 4.2 examines the questions that arise in selecting reference coordinate systems. Among the problems is the realization that there are no points on the earth that can be considered fixed when all motions greater than 10-cm amplitude must be included.

The short-term dynamical phenomena now recognized as significant fall into three broad groupings: rotational motions of the earth (see Section 4.3), tides (4.4), and temporal variations of the geopotential (4.5).

The first of these categories can be further divided into a number of rotational motions that define the spatial orientation of the instantaneous spin with respect to an inertial reference frame (precession and nutation), the geographical orientation of the spin axis (pole motion), and the instantaneous rate about the spin axis (length of day). Each of these motions has several components, and the development of a theoretical earth model to account for each of the features in the spectrum of the earth's rotational motion has advanced unevenly. Further, we must exploit the geomagnetic data already accumulated from satellites, and we must make more accurate measurements in order to discriminate between present and future theoretical earth models and to expose previously undiscovered features.

The second grouping of short-term dynamical phenomena is concerned with earth tides. These tides are mainly caused by the action of the sun and the moon on the earth; however, ocean tidal loading significantly influences the earth tidal action. Unfortunately, ocean tides have the same periods as earth tides and are imperfectly known, except along coastal regions. It has therefore been difficult in the past to isolate the effect of ocean loading.

Analysis of earth satellite-tracking data has provided gross information on earth tidal deformations. The satellite altimeter promises to give great help in solving the problem of ocean tidal loading.

The temporal variations of the geopotential compose the last group of short-term dynamical phenomena discussed in this chapter. Recently, with the advent of precision satellite-tracking data, the detection and isolation of temporal variations of the geopotential have become practical. The benefits of a program that defines geopotential temporal changes include improved nutation constants, the ability to correct refined surface-gravity measurements, and, it is hoped, added insight into core-mantle coupling phenomena by finding whether there are correlations between temporal variations of the geopotential and other interesting phenomena such as temporal geomagnetic variations. However, such a program depends on developments in orbit-determination capability. These developments include an improved capability to represent the earth's motions in inertial space (for example, polar motion and variations in the rotation of the earth), more accurate tracking data, and a further reduction in the tracking-station location uncertainties.

4.2 REFERENCE COORDINATE SYSTEMS

4.2.1 Coordinate Systems Currently Used

The establishment of reference coordinate systems is a basic requirement for the study of the solid earth and the oceans. They provide the frame in which geophysical phenomena are expressed and to which the orbits of spacecraft will be referred.

Two distinct reference coordinate systems are currently in use. The first corresponds to an inertial system and defines directions through a star catalog. The FK-4 star catalog is internationally accepted as the fundamental reference. It lists less than 2000 stars and is considered to be internally consistent to better than $0\rlap{.}''05$. For many applications, other catalogs with a greater number of stars have to be used. These also refer to the FK-4 system, but they are of a lesser accuracy. The one most often used is the SAO catalog, which has an accuracy of $0\rlap{.}''3$ to $0\rlap{.}''5$, depending on the part of the sky.

The second system is a terrestrial one. The definition of this system, the "Geodetic Reference System 1967,"[1] which was adopted by the International Association of Geodesy in Lucerne in 1967, locates the origin at the center of mass of the earth, the orientation of the Z-axis in the direction that corresponds to the adopted astronomical latitudes of the International Latitude Service (ILS) stations, and the X-Z plane is oriented parallel to the astronomical meridian of the mean observatory as defined by the Bureau International de l'Heure (BIH).

The materialization of this terrestrial system is accomplished by assigning coordinates to a number of physical points on the earth's surface; such a system is sometimes referred to as "geographic."[2] The accuracy with which consistent coordinates can be determined today on a global scale is between 10 and 20 m. Standard ground-surveying techniques define local geodetic systems (datums) to a relative accuracy of about 10^{-5}, and in some few areas, to 2×10^{-6}. Local datums can be related to the terrestrial system.

The scale was previously defined by geodetic baselines, but now almost all distances are determined by measuring propagation times of electromagnetic radiation, and thus they use the light-second as a definition of length. The uncertainty in scale will depend on the accuracy of the refraction correction, which today is a few parts per million for horizontal lines. Scale is currently most accurately determined by the GM value found by the tracking of distant probes, with an internal error of the order of 10^{-6}.

4.2.2 Coordinate-System Refinements

A reference coordinate system should be selected so that the phenomena under study could be represented in a simple form and the necessary observations could be easily expressed in this system. Both inertial and terrestrial coordinate systems are needed. The inertial system is used primarily for orbit determinations, and the terrestrial for expressing the position of stations on the earth, the earth's gravity field, and other dynamical phenomena.

In addition to these, it will be useful to define a planetary coordinate system, since space probes will also be used to provide information on the rotational motions of the earth.

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[1] International Association of Geodesy, XIV General Assembly, Resolutions. Bull. Geod., 86, pp. 365-391, 1967.

[2] Munk, W. H. and G. J. F. MacDonald, "The Rotation of the Earth," Cambridge Univ. Press, 323 pp. 1960 (See p. 11).

It should also be mentioned that for some investigations (e. g., fault movements) there is no need to use a global terrestrial system; a local reference system will suffice. These local systems could be related to the terrestrial system by appropriate measurements.

A reference system is defined by its origin, the orientation of one axis, and the orientation of a plane containing this axis. However, when the origin is inaccessible, the system is defined in practice by assigning coordinates to points. It is apparent that any relative measurements between the points used to define the reference system imply conditions that must be satisfied by the assigned coordinates. If the accuracy of the measurements increases, so will the accuracy of the definition of the reference system.

To satisfy the requirements of higher accuracy in the dynamics of the earth, it is imperative that the reference system be defined to an accuracy comparable to that required to express and to analyze the different phenomena under investigation. It becomes apparent that the existing reference systems are not accurate enough for this purpose and that they will have to be improved by one or two orders of magnitude in accuracy and in time resolution.

The inertial reference system should continue to be defined by a star catalog. The requirements should be for $0\rlap{.}''01$ star positions and appropriate proper motions. It is questionable whether ground techniques could provide this accuracy in optical frequencies, mainly because of atmospheric refraction; probably the best solution for optical stars will be to prepare a catalog from an orbiting (manned or unmanned) astrographic telescope. A more precise inertial system could be established with a catalog of point radio sources by means of VLBI techniques. Since radio sources at great distances are expected to have, for all practical purposes, no proper motions, such a system will be superior to that of an optical star catalog, provided, of course, that it is easily accessible. An accuracy of $0\rlap{.}''001$ is expected with this method, but the density of sources in this catalog cannot be estimated as yet.

The terrestrial system will be defined by coordinates assigned to a number of stations and their time variations. This system should have as origin the earth's center of mass, and as Z-axis the principal axis of inertia, as determined from satellite dynamics considerations.

As a first step, since the principal axis of inertia will not be determined to the required accuracy before some time, an arbitrary geographic Z-axis can be used. The relative position of this geographic axis, the instantaneous spin axis, the axis of inertia, and the angular momentum axis should be given as functions of time.

It seems that satellite geodesy and other space techniques (radio interferometry, laser ranging to the moon, etc.) will be used to derive the coordinates of these axes in the terrestrial system. An accuracy of 1 m is expected to be achieved in the next few years, and of 10 cm in the next decade. Since points on the earth's crust may have relative displacements of up to 10 cm/yr, it will be imperative to select these stations with care. These stations must be tied to a local geodetic net. Measurements must be made at frequent intervals, so as to average the effects of local movements over a larger area and so that as many points as possible are selected for a statistically better definition of the terrestrial system. Furthermore, the stations should be placed in areas known to be tectonically stable.

Knowledge obtained for the displacements that result from crustal motions and from the tides will allow the reduction of the positions on the continuously deformed earth to equivalent positions in a rigid coordinate system.

An alternative that should be investigated is to define the terrestrial coordinate system through the intermediary of three geostationary satellites. These satellites should be equipped with cameras, laser retroreflectors, radio, and VLBI tracking capability so that their relative position and absolute orientation could be precisely determined. Tracking between ground stations and those satellites could provide coordinates on the earth and their time variations as well as the positions of low satellites used to study the solid earth and the oceans. Photographs of the earth (with several well-distributed laser-transmitter ground stations) with the star background taken from those satellites would also assist in transferring the reference system to the earth's surface.

It is also necessary to establish to the same accuracy the relation between the inertial and the terrestrial systems. This is done through the precession, the nutation, the polar motion, and UT1. The precession and nutation are known to better than $0\overset{''}{.}01$, the polar motion to about $0\overset{''}{.}003$, and UT1 to about 0.003 sec (or about $0\overset{''}{.}05$). This is the equivalent angular quantity. These values should be improved if an accuracy of a few decimeters is required (10 cm corresponds to $0\overset{''}{.}003$). The approach for such an improvement is explained elsewhere in this document.

4.3 ROTATIONAL MOTION OF THE EARTH

4.3.1 Current Knowledge

The earth rotates about an axis that continually changes. First, the direction of the angular momentum vector in space has a 25,800-yr cycle caused mainly by torques from lunar and solar gravitational interactions with the oblateness of the earth. This motion of the angular-momentum vector is called astronomical precession and nutation.

Second, since the axis about which the earth rotates at any instant is not quite the principal axis of inertia, the instantaneous spin axis should exhibit a precession or "wobble" about the angular momentum vector. However, the difference between the rotation axis and the angular momentum direction is so slight that they are essentially identical. The instantaneous axis, expressed relative to body-fixed coordinates, performs an irregular precession or wobble about the principal axis of inertia within the earth. This wobble has an amplitude of roughly $0.''15$. The wobbling motion includes two main periods, 12 and about 14 months. The latter period is longer than the theoretical force-free precession of a rigid body; the period is lengthened by the elastic and fluid (e.g., core and oceans) properties of the earth. This 14-month component is called the Chandler wobble.

Third, the position of the principal axis of inertia for the earth is not necessarily fixed relative to some set of axes attached to the earth. Besides the obvious possibilities of mass displacement in the fluid domains of the earth, it has recently been suggested that mass displacements associated with earthquakes may contribute significant changes.[3]

The rate of rotation of the earth about its instantaneous axis is not a constant when measured against atomic clocks; that is, the sidereal length of the day is not constant. The variations of UT2 versus atomic time are documented by tables produced by such agencies as the United States Naval Observatory and the BIH.

The various components of the rotational motions of the earth are tabulated in Table 4-1.

[3]Smylie, D. E. and L. Mansinha, Earthquakes and the observed motion of the rotation pole. J. Geophys. Res., 73, pp. 7661-7673, 1968.

TABLE 4-1. Rotational Motions of the Earth

A: Inertial Orientation of Instantaneous Spin Axis	B: Terrestrial Orientation of Instantaneous Spin Axis	C: Instantaneous Rate of Spin About the Axis
1. Steady precession (amplitude 23°.5; period 25,800 yr)	1. Secular motion of the pole (0".003/yr)	1. Secular accelerations (2 parts in 10^{10}/yr over centuries)
2. Steady decrease in obliquity (0".32/century)	2. Markowitz wobble (amplitude 0".02?; period 24 yr?)	2. Irregular accelerations (5 parts in 10^{10}/yr over decade to 3 parts in 10^{9}/yr over a year)
3. Principal nutation (amplitude 9".206 ± 0.007; period 18.6 yr)	3. Chandler wobble band (amplitude 0".15; period 425-440 days; damping time 15-70 yr?)	3. Seasonal fluctuations
4. Other periodic contributions to precession and nutation of smaller amplitudes than A.3	4. Seasonal wobble (amplitudes: annual 0".09, semiannual 0".01)	4. Irregular high-frequency ($\gtrsim$ 1 cpy) accelerations
	5. High-frequency contributions due to tides (amplitude 0".001)	5. Periodic contributions due to tides
	6. Diurnal wobble (amplitude 0".02?; period 24 (1-e) hr, where e is the ellipticity of the core-mantle boundary)	

4.3.2 Precession and Nutation

The relations between the inertial frame and spatial orientation of the instantaneous axis of spin are known as precession and nutation.

The principal term of nutation has a $9''.206 \pm 0.007$ amplitude and an 18.6-yr period. The amplitude is determined by astrometric methods. The precession constant $50''.2564$/yr is determined by the analysis of proper motions of many stars on the assumption that the proper motions are expressed as a gaussian distribution. However, it is difficult to separate the precession from the galactic motion of the stars.

The new instrumentation discussed in the previous chapter offers distinct opportunities to improve measurements of precession and nutation. The positions of distant radio sources, which can be considered fixed with respect to the inertial system, can be measured with respect to the spin axis by VLBI. Accurate values of the precession constant and the nutation constant can be derived by use of the radio sources since they should not have any proper motion. This will give us much more accurate relations between the reference frame and the spin axis.

If beacons for VLBI are established on planets, then interferometry as well as radar measurements of the planets will fix the position of the ecliptic with respect to the inertial frame. This should verify the nonorbital decrease of $0''.32$/century in the obliquity.[4, 5]

The present value of the precession constant is not so accurate as that of J_2 for the earth. If we can get the value of the precession constant as accurate as J_2, the value of C/M (C being the principal moment of inertia and M the mass of the earth) will be known to 100 times the present accuracy. This value, as well as a better nutation constant, is desired to discriminate better between models of the core.

Further, once we know the precession constant more accurately, the proper motions of stars in the Galaxy can be computed and the motion of the Galaxy with respect to the inertial frame will be known accurately.

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[4] Aoki, S., Friction between mantle and core of the earth as a cause of the secular change in obliquity. Astron. J., 74, pp. 284-291, 1969.

[5] Duncombe, R. L. and G. M. Clemence, Accuracy of the solar ephemeris. Astron. J., 63, pp. 456-458, 1958.

In addition to the forced precession and nutation caused by solar and lunar attraction, there exist free nutations with periods dependent on the earth's internal structure. One of these free periods differs slightly from a sidereal day. Of the principal tidal constituents, only the K_1 tide has a period close enough to that of the diurnal free nutation to have its amplitude greatly changed by a resonance effect. The effect on the K_1 tide is to reduce Love's numbers h (radial displacement) and k (potential about 15% relative to the semidiurnal tide M_2. The effect on Shida's number ℓ (lateral displacement) is only about 2 to 3%.

The tidal constituents of periods sufficiently longer than a sidereal day are not seriously affected by the diurnal free nutation. For example, the values of h, k, and ℓ for the 0_1 tide, of about 1^h56^m longer period, are essentially the same as those for the semidiurnal M_2 tide.[6,7,8]

4.3.3 Polar-Motion Observations and Theory

The motion of the pole is at present determined by observation of the variation of latitude at a number of observatories around the earth. This work has been carried out since the 1890s.

The original organization set up to make the measurements, the ILS, uses observatories on the 39° 08' North parallel. Location of observatories on a single parallel of latitude allows observation of the same stars by all stations, eliminating the dependence on the accuracy of star catalogs.

Since 1962 the ILS polar motion has been derived by the Central Bureau of the International Polar Motion Service (IPMS). This provides the fundamental pole path, at 0.05-yr intervals. The IPMS also publishes a pole path based on variations of latitude received from about 35 cooperating observatories that observe different stars.

Since late 1955, the BIH has reduced latitude data to produce a pole path used in correcting time measurements. BIH now issues unsmoothed 5-day means based on a reduction using latitude and time simultaneously, as measured at roughly 50 observatories.

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[6] Alterman, Z., H. Jarosch, and C. L. Pekeris, Oscillations of the earth. Proc. Roy. Soc., A252, pp. 80-95, 1959.

[7] Molodensky, M. S., The theory of nutation and diurnal earth tides. Marées Terr. Comm. Obs. Roy. Belg., No. 188, Ser. Géophys., No. 58, pp. 25-56, 1961.

[8] Melchior, P. J., "The Earth Tides," Pergamon Press, New York, 458 pp., 1966.

The existence of two pole paths has provided a unique opportunity for comparison. Both organizations quote standard errors of the order of 0.''01. On the other hand, differences of as much as 0.''1 are found between the two paths.[3] This probably indicates the presence of substantial systematic errors. If the errors were random in the BIH data, for instance, one would expect a scatter of only about 0.''01 in their unsmoothed 5-day means. The observed scatter of successive points is nearly 0.''05.

Analysis of the pole path to date has revealed several spectral components.

First, there appears to be a secular motion of the order of 0.''003/yr.[9] The reality of this motion was at first questioned, but over the last decade there has been general agreement that such secular motion exists. However, because of crustal motion, there is a possibility that the observatories may be moving with respect to each other. Thus, the apparent secular drift of the pole may not represent the true polar drift.

Moving up the frequency scale, there is some evidence that the pole may have a motion of 24-yr period with amplitude of 0.''02.[10] In addition to having an amplitude so small that it may be buried in the systematic error of the present observations, the long period of this motion makes it subject to the same difficulties of observation that afflict the secular motion. The motion is predicted theoretically as resulting from the presence of the solid inner core of the earth.[11]

The next spectral feature, centered at 1.2-yr period, is the strongest in the whole spectrum. It is the natural wobble of the earth. (If the earth is considered as a single deformable body, it has only one natural wobble. In fact, it has three degrees of freedom provided by the presence of the mantle, the liquid outer core, and the solid inner core, which result in two additional free periods: the 1-day free nutation plus, possibly, the one of 20- to 30-yr period referred to in the previous paragraph.) The motion is named after its discoverer, Chandler. The mean amplitude is about 0.''15 and broadening

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[9] Markowitz, W., Concurrent astronomical observations for studying continental drift, polar motion, and the rotation of the earth. In "Continental Drift, Secular Motion of the Pole, and Rotation of the Earth," Intern. Ass. Geodesy Symposium No., 32, ed. by W. Markowitz and B. Guinot, pp. 25-32, 1968.

[10] Markowitz, W., In "Methods and Techniques in Geophysics," ed. by S. K. Runcorn, Interscience Publishers, New York, p. 325, 1960.

[11] Busse, F. H., The dynamical coupling between the inner core and the mantle of the earth and the 24-year libration of the pole. Max-Planck Institut für Physik und Astrophysik, MPI-PAE/Astro., 17, 1969.

of the spectral peak indicates a Q of about 60. It has been suggested that the Chandler peak is split into two narrowly separated resonances and that this would explain the relatively low Q of the total peak compared with seismic values.[12,13] The existing 80-yr record would be barely capable of resolving these, even if there were no doubts about the level of systematic error.

The geophysical interest in the Chandler wobble is threefold: 1) what is the excitation mechanism? 2) what properties about the earth as a whole can be inferred from its frequencies of response? and 3) what is the damping mechanism?

In answer to question 3), the general consensus is that the damping occurs in the oceans, although the mechanism remains unknown. Electromagnetic core-mantle coupling cannot contribute.[14]

In answer to question 2), the extent to which decoupling of different parts of the earth's interior may contribute to splitting of the Chandler peak awaits better resolution, as previously stated:

In answer to question 1), the excitation mechanism is still much in debate. Changes in the mass distribution of the atmosphere fail by at least one order of magnetide.[15] Electromagnetic core-mantle coupling fails by three orders of magnitude on a linearized model,[14] but a much stronger, nonlinear interaction has recently been proposed.[16] Extensive mass shifts accompanying earthquakes have been shown to come within a factor of five in explaining the observed excitation.[17] The calculations were based on a mapped half-space displacement field. A full spherical theory for a vertically heterogeneous, self-gravitating earth with a liquid core will soon be available.

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[12] Yashkov, V. Ya., Spectrum of the motion of the earth's poles. Soviet Astron., 8, pp. 605-607, 1965.

[13] Colombo, G. and I. I. Shapiro, Theoretical model for the Chandler wobble. Nature, 217, pp. 156-157, 1968.

[14] Rochester, M. G. and D. E. Smylie, Geomagnetic core-mantle coupling and the Chandler wobble. Geophys. J. R. astr. Soc., 10, pp. 289-315, 1965.

[15] Munk, W. H. and E. S. M. Hassan, Atmospheric excitation of the earth's wobble. Geophys. J. R. astr. Soc., 4, pp. 339-358, 1961.

[16] Stacey, F. D., A re-examination of core-mantle coupling as the cause of the wobble. In "NATO Advanced Study Institute on Earthquake Displacement Fields and the Rotation of the Earth," 22-29 June, D. Reidel Publ. Co., 1969 (in press).

[17] Mansinha, L. and D. E. Smylie, Effect of earthquakes on the Chandler wobble and the secular polar shift. J. Geophys. Res., 72, pp. 4731-4743, 1967.

Some observational support for the earthquake excitation-hypothesis has been found in the form of a correlation between times of occurrence of major earthquakes and changes in the BIH pole path.[3] Assuming certain arbitrary definitions for the break in the pole path and the coincidence of events and assuming the earthquakes to be Poisson-distributed, confidence estimates for the significance of this relation range from about 95 to 99%. Unfortunately, one cannot rule out systematic error at the present time. The pole positions given by the ILS-IPMS are too infrequent independently to test the relation. In addition, weak evidence of premonition of great earthquakes is found in the BIH path.

At 1 cpy, there is a spectral line that has been shown to be due to seasonal variation in the mass distribution of the atmosphere. The amplitude is 0.''09. A closer check on the agreement between observation and theory could probably now be made using modern meteorological data.

No noticeable features appear in the spectrum derived from current measurements at frequencies higher than 1 cpy.

4.3.4 Prospects for Future Pole-Motion Measurements

Only marginal improvements can be expected in the existing optical astronomy techniques of measuring the pole path. Progress in resolving some questions will be slow, other questions will not be resolved without the adoption of new technqiues.

The question of the relation, if any, of earthquakes to the polar motion would appear to be of the most practical importance. This would require the measurement of pole positions to 0.''01 at 2-day intervals. It should be stressed that we need to be confident that the systematic, as well as the random, errors are below the 0.''01 level. Some systematic error at periods of 1 yr and greater could be tolerated for this application.

Should the evidence confirm that the mass displacements accompanying major earthquakes excite the Chandler wobble and that the pole path premonitors major earthquakes, some contributions to an earthquake-prediction system could be expected.

In combination with a near-fault monitoring system, changes in polar motion, reflecting the effect of strain integrated throughout the whole earth, might be a valuable indicator of the size of an impending quake. The preceding describes the maximum practical payoff that might be expected.

Detection and study of the diurnal wobble would be of prime scientific interest. It has an expected amplitude 0.″02. This would require a minimum of two observations per day to 0.″01. For full study, several observations per day to 0.″001 would be desirable. The theoretical period of the motion is 24(1-e) hr, where e is the ellipticity of the core-mantle boundary. This quantity is of importance in deciding the role of inertial-coupling in core-mantle interaction. The Q of the motion may directly reflect the strength of the electromagnetic coupling between the core and mantle.[18]

Further refinement in determination of the low-frequency part of the wobble spectrum by a system free of systematic error to 0.″01 for tens of years is desirable. Resolution of a peak in the region of 20- to 40-yr period would reflect the interaction of the solid inner core with the liquid outer core of the earth.

4.3.5 Axial Rate of Spin of the Earth

The spectrum of changes in the rate of spin of the terrestrial reference system about its instantaneous axis of rotation shows secular accelerations, irregular accelerations, seasonal fluctuations, and irregularities of frequency higher than 1 cpy.

Secular acclerations, $\sim 2 \times 10^{-10}$/yr, have been detected over geologic time by coral and similar molluscan "clocks," over historical time from ancient astronomical data, and recently by measurements of the orbital accelerations of the moon, sun, and planets relative to the terrestrial reference system. The previous difficulty in maintaining a uniform time scale by the sun's longitude is now compensated for by the accurate timekeeping of the earth's rotation provided by atomic clocks and PZT's. Theoretical interpretation of these accelerations involves: 1) insofar as they are decelerations due to tidal friction, a knowledge of the dissipation mechanisms acting in tidal friction such as ocean-bottom friction, bodily tidal dissipation, and core-mantle coupling (since ocean-bottom friction appears to be the most important and may be almost sufficient by itself, it would be most useful to know more about tidal currents and internal waves in the deep ocean); 2) atmospheric tidal acceleration; 3) nontidal effects (most likely changing ice load and exchange of angular momentum between the mantle and the core by electromagnetic coupling).[19,20]

[18] Rochester, M. G., Perturbations in the earth's rotation and geomagnetic core-mantle coupling. J. Geomag. Geoelec., 20, pp. 387-402, 1968.

[19] Miller, G. R., The flux of tidal energy out of the deep oceans. J. Geophys. Res., 71, pp. 2485-2489, 1966.

[20] Munk, W. H., Once again — tidal friction. Quart. J. Roy. Astr. Soc., 9, pp. 352-375, 1968.

Irregular accelerations exist that range from 5 parts in 10^{10}/yr over a decade or so to 3 parts in 10^{9}/yr over a few years.[21] Since 1955, sudden changes in acceleration (i.e., within 6 mo) every 4 yr or so have been detected by use of PZT data. There is no difficulty in measuring these with present astronomical techniques for frequencies lower than 1 cpy. However, to analyze other aspects of the earth's motion, it will be important to obtain a determination of the pole path to within 0.''01 and to measure time to within 2 msec or less every day. The slower accelerations probably depend upon angular momentum exchange between the core and the mantle, but the interpretation of the more rapid accelerations is hindered by our ignorance of the electrical-conductivity distribution in the lower mantle and of the possible role of other core-mantle interactions, for example, topographic coupling.[22,23]

Seasonal fluctuations of 0.5 msec occur in the length of the day at both annual and semiannual periods, and they are nearly the same each year. These fluctuations are thought to be due to winds and tides. A better understanding of the atmosphere and bodily tides will improve the agreement between theory and the observations. The same remark concerning accuracy of measurements of rotation speed as made in connection with irregular accelerations applies here.

Irregularities of frequency higher than 1 cpy in the rotation speed, including the so-called "sudden events," cannot be measured to the required accuracy by the PZT and atomic-clock combination; new techniques (laser lunar range, VBLI) promise to fill this gap. The irregularities may be due to air-sea and air-land interactions, but the possibility is open that once these are computed from the meteorological data provided by satellites, there will remain some observed discrepancies that could be attributed to high-frequency core-mantle interactions.[22,23]

4.3.6 Future Areas of Analysis

Development of theoretical earth models to account for each of the features in the spectrum of the earth's rotation has been uneven. The chief problem lies in modeling the earth's deep interior, especially the core. Problems in modeling the core concern its internal angular-momentum distribution and its interaction with the mantle.

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[21] Markowitz, W., Sudden changes in rotational acceleration of the earth and secular motion of the pole. In "NATO Advanced Study Institute on Earthquake Displacement Fields and the Rotation of the Earth, 22-29 June, D. Reidel Publ. Co., 1969 (in press).

[22] Hide, R., Interaction between the earth's liquid core and solid mantle. Nature, 222, pp. 1055-1056, 1969.

[23] Rochester, M. G., Core-mantle interactions: geophysical and astronomical consequences. In "NATO Advanced Study Institute on Earthquake Displacement Fields and the Rotation of the Earth," 22-29 June, D. Reidel Publ. Co., 1969 (in press).

Apart from more refined measurements of spectral features that may enable us to discriminate between competing theoretical models or to suggest new ones (even perhaps by uncovering hitherto-undiscovered spectral features), further progress requires the following:

1. analyses of the geomagnetic data already accumulated from satellites to infer more accurately the electrical-conductivity distribution in the lower mantle and the kinematic structure of the outer layers of the core;

2. continued study of the mathematical description of hydromagnetic dynamo action in the core, which is essential to understanding geomagnetism and to obtaining a satisfactory model for the angular momentum distribution in the core;

3. better experimental and theoretical values for the viscosity and electrical conductivity of the core, now estimated only to within several orders of magnitude;

4. improved seismic measurements and theory to infer to within better than ±5 to 10 km the topography of the core-mantle boundary.[2]

4.4 EARTH TIDES

4.4.1 Terrestrial Measurements

The solid body of the earth, responding to the tidal generating forces principally of the moon and the sun, deforms periodically in low-frequency, gravitationally driven oscillations, with a rise and fall of the elevation on the earth's surface on the order of 25 to 30 cm in the midlatitudes and of 50 cm near the equator. These motions are known as earth tides. Although the tidal-generating forces of the sun and the moon can be precisely determined astronomically, the tidal deformation of the earth, as well as the dynamics of oceans, is very complicated owing to the irregular distribution of water and land masses, the meteorological variations of the atmosphere, and the lateral and radial inhomogeneities in the earth's interior.

Tides are generally measured in terms of variations of tilt, strain, or gravity on the order of 0".02 (10^{-7} radians), 10^{-8}, and 2×10^{-4} cm/sec^2 (0.2 mgal), respectively. Because the earth is not perfectly elastic, it does not respond to the tidal-generating forces of the moon or the sun instantaneously. There would be a phase lag of about 0°.50 if the earth were free from oceans.

Recently, the combined effect of earth and ocean tides has been measured by analysis of perturbations in satellite orbits. With the use of satellite altimetry, it may become possible to measure the individual contributions of the earth and ocean tides through a study of the tidal displacements of the earth and ocean surfaces.

One of the classical problems arising in the study of earth tides is bringing the experimental results into a consistent system and then deriving conformable values of the characteristic numbers of the yielding earth that characterize its elastic behavior. The results of tidal gravity, tilt, strain, and astronomical observations for the largest amplitude tidal constituent M_2 give average observed values for the characteristic numbers h, k, and ℓ — 0.48, 0.29, and 0.05, respectively. The theoretical values for the earth models consistent with seismic evidence are about 0.6, 0.30, and 0.08, respectively.

Measurements of earth tides, whether in terms of tilt, strain, or gravity, even made far from the coast, are influenced by the indirect effects of ocean tides. Other effects of geological and tectonic origin and of meteorological changes, although frequently of large magnitude, may under favorable conditions be removed from earth tides by appropriate instrument design and analysis technique. Because the amplitudes of ocean tides are imperfectly known, the effects of ocean tides on earth tides are difficult to calculate. There are also some technical difficulties associated with elastic-loading calculations.

Tides can be measured by tiltmeters and extensometers. However, if a gravimeter is perfectly compensated for temperature and barometric-pressure variations, results of gravity observations are by far simpler to interpret and more reliable than those of either tiltmeters or strain measurements.

There are now enough reliable data from inland stations to indicate some unique features. The values of the gravimetric factor, $\delta = 1 + h - 3k/2$, for the M_2 constituent at stations in the Asian continent range from 1.17 to 1.21. Most important, the values of amplitude δ and phase lag χ decay logarithmically with the distance from the effective large body of water.

This apparent dependence of tidal constituents on the distance of the observation station from the coast prompted the Lamont-Doherty Geological Observatory to establish a transcontinental tidal gravity profile across the United States.[24,25]

The data obtained from the stations of the transcontinental profile for the principal tidal constituents M_2 and O_1 show that the observed values of the gravimetric factor

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[24] Kuo, J. T., K. Hunkins, and M. Ewing, Observations of spatial variations of tidal gravity in the eastern United States (abstract). Trans. Amer. Geophys. Union, 46, p. 47, 1965.

[25] Kuo, J. T. and M. Ewing, Spatial variations of tidal gravity. In "The Earth Beneath the Continents," Geophysical Monograph No. 10, Amer. Geophys. Union, pp. 595-610, 1966.

and the phase do indeed follow a definite pattern with regard to the distance from the Pacific and Atlantic oceans. Figures 4-1 and 4-2 show the relative differences of gravimetric factor $\Delta\delta$ in percent and the phase lag χ in degrees for the M_2 and O_1 constituents.

Ocean tides off the Atlantic and Pacific coasts are fairly well known, particularly the M_2 constituent. Calculated effects of ocean tidal loads (namely, the gravitational attraction of the displaced water, the deformation of the earth's crust and upper mantle by ocean tides, and the change in potential) are also plotted in Figures 4-1 and 4-2. The observed and calculated values of $\Delta\delta$ and χ for the M_2 constituent are in remarkably good agreement; for the O_1 constituent, fairly good. This excellent agreement between the observed and calculated deviations of the gravimetric factors and the phases substantiates that the effects of ocean tides on earth tides are indeed of primary importance and that the influence of geologic structure is negligible.[26,7]

4.4.2 Satellite Measurements of Earth Tides

In principle, at least two aspects of earth tides can be studied by methods arising from satellite observations.

The most obvious effect is the motion of a tracking instrument as its foundation rides with the tides in the solid earth. These motions should be detectable by the most precise tracking instruments, but a suitable observing campaign has yet to be mounted.

The second observable effect is caused by mass displacement in the earth due to tides. For a typical satellite, the magnitude of this perturbation is about one-tenth the direct gravitational perturbation by the sun and moon.

Newton[27] has used four satellites in polar orbits for which doppler tracking data from the TRANET system were available over intervals of 6 to 18 months. He obtained Love's numbers

k_S = 0.359 ± 0.042, for the solar tides,

k_M = 0.314 ± 0.036, for the lunar tides.

[26] Kuo, J. T., R. C. Jachens, G. White, and M. Ewing, A transcontinental tidal gravity profile across the United States (abstract). EOS, Trans. Amer. Geophys. Union, 50, p. 116, 1969.

[27] Newton, R. R., A satellite determination of tidal parameters and earth deceleration. Geophys. J. R. astr. Soc., 14, pp. 505-539, 1968.

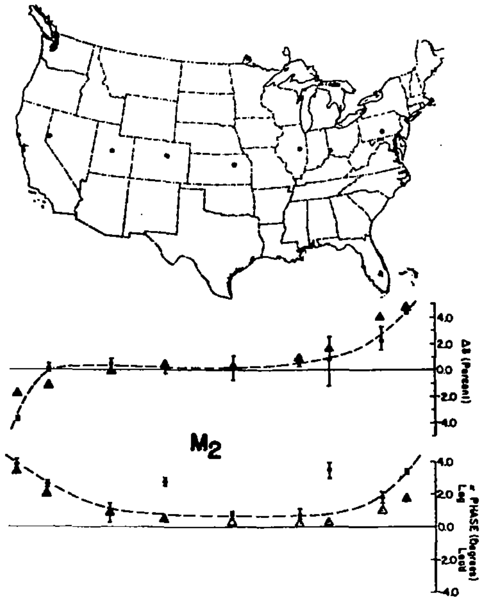

Figure 4-1. Observed (solid dots) and calculated (triangles) $\Delta\delta$ (M_2) and χ (M_2) for the transcontinental profile.

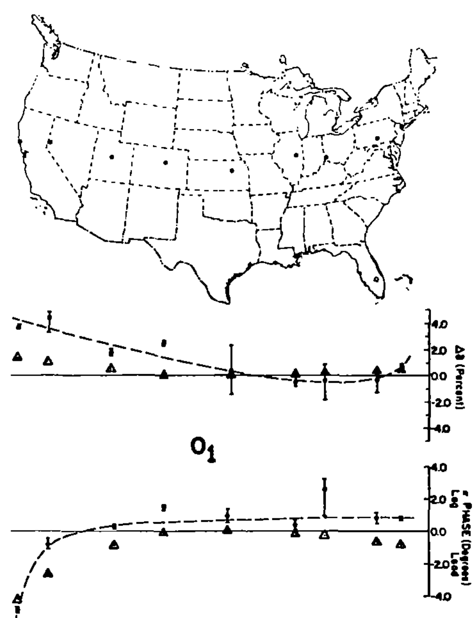

Figure 4-2. Observed (solid dots) and calculated (triangles) $\Delta\delta$ (O_1) and χ (O_1) for the transcontinental profile.

If the theoretical expectation is accepted that the two numbers should be about equal, the combined value obtained by Newton is

$$k = 0.336 \pm 0.028.$$

In his analyses, Kozai[28] used three satellites at inclinations 32°.8, 47°.2, and 50°.1. For these satellites he had Baker-Nunn photographic tracking data covering intervals from 2 to 5 years. His value for Love's number was derived from perturbations in the inclination of these satellites. He obtained

$$k = 0.29 \pm 0.03.$$

The same analyses by both authors also yield determinations of the phase of the earth tides relative to the longitude of the sun or moon. Frictional dissipation in the earth results in a maximum tidal displacement at a point on the earth somewhat after the meridian has passed the sun or moon. Kozai obtained a lag angle of 5°.0 ± 3°.0 for solar tides. Newton obtained 0°.8 ± 0°.3 for solar tides and 2°.1 ± 0°.2 for lunar tides.

4.4.3 Tidal Dissipation

Tidal dissipation is a subject of considerable interest. It is important to astronomers because it produces significant effects in the ephemerides of the earth and moon. It is important in cosmogony and geophysics because it has certainly influenced the evolution of the earth-moon system. It is also important to geophysicists because of the the amount of dissipation observed is difficult to explain and because the amount of dissipation may have observable effects upon the measured ocean tides.

The amount of tidal dissipation can be estimated from the observed deceleration of the moon,[29] which is about 22" per century per century, and from perturbations in satellite orbits.[27] The rate of dissipation obtained by either method is about 2.9×10^{12} W. This is also about the rate obtained by direct integration of the tide-raising forces over the shape of the oceans given by tidal charts.[2] Although the result from the integration is rather sensitive to errors in the tidal charts, we may tentatively conclude that most tidal dissipation occurs in the oceans.*

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[28] Kozai, Y., Love's number of the earth derived from satellite observations. Publ. Astron. Soc. Japan, 20, pp. 24-26, 1968.

[29] Spencer Jones, H., The rotation of the earth, and the secular accelerations of the sun, moon, and planets. Monthly Not. Roy. Astr. Soc., 99, pp. 541-558, 1939.

* Results obtained for earth tides across the United States suggest that a small amount of dissipation occurs in the earth tides. See the reference in footnote 27.

However, attempts to find the seat of the dissipation have so far been unsuccessful. The "shallow seas" hypothesis has been the most popular in recent years. It has so far not proved adequate, although the possibility that shallow seas may account for current dissipation cannot be categorically denied. Miller[30] has made a careful estimate of the dissipation in shallow seas. He estimates that shallow seas dissipate between 1.4×10^{12} and 1.7×10^{12} W and thinks that the correct value is unlikely to be as large as that demanded by the astronomical observations. No other source of dissipation that has been studied has proved to be significant.

Troubles in finding adequate mechanisms are multiplied when we consider the amounts of dissipation that apparently existed in the past.[31] Astronomical evidence indicates that the amount of dissipation as recently as 1000 years ago was nearly twice the amount given by recent observations. Paleontological data indicate that the average dissipation over the past 400 million yr has been about 50% greater than the estimated current value. There is trouble not only in finding sources of dissipation this large but also in finding a source that could have changed appreciably within historic times.

Pannella, MacClintock, and Thompson[32] have made the most extensive study of the number of solar days per synodic month within geological times. They find that the number of days per month has decreased between about 70 million yr ago and the present and that it also decreased between about 500 million and 300 million yr ago. However, it was almost constant between 300 million and 70 million yr ago.

Tidal dissipation produces secular changes in the orbital elements of the moon. Simplified calculations of the lunar orbit indicate that the earth-moon system originated about 2 billion yr ago, and it has been assumed sometimes that this result is hard to reconcile with the estimated age of the earth (4 billion yr or more). However, this calculated age for the moon is based upon severe simplifications of the behavior of tidal friction; for instance, it is usually assumed that friction has varied simply as some power of the earth-moon distance, starting backward from the current estimate of 2.9×10^{12} W. As Alfven and Arrhenius[33] have emphasized, we cannot extrapolate backward confidently and the age estimates formed from extrapolation are highly uncertain.

[30] Miller, G. R., Op. cit.

[31] Newton, R. R., Secular accelerations of the earth and moon. Science, 1969 (in press).

[32] Pannella, G., C. MacClintock, and M. N. Thompson, Paleontological evidence of variations in length of synodic month since late Cambrian. Science, 162, pp. 792-796, 1968.

[33] Alfven, H. and G. Arrhenius, Two alternatives for the history of the moon. Science, 165, pp. 11-17, 1969.

In sum, an understanding of tidal dissipation is important for many areas of science. At present, our understanding is woefully inadequate. Some, but not all, of the measurements needed for an improved understanding can be obtained with the aid of artificial satellites.

4.4.4 Prospects and Major Problems

The earth models deduced from seismic body waves, for instance the Gutenberg-Bullen model and the Jeffreys-Bullen model, have long been regarded as a close approximation to the actual earth. They have been further supported by excellent agreement between the theoretical and experimental values of the periods of the free oscillations of the earth. At present, we have a far better knowledge about the earth itself, from which the characteristic numbers for earth tides are derived, than about the tides on the open ocean.

It is evident now that it is fruitless to verify the theory of earth tides by use of the inferred or theoretically calculated ocean cotidal and corange charts to make corrections for the effects of ocean tides on tidal gravity or on tidal tilt and strain, as has often been done in the past. If earth-tide measurements are made to an accuracy of 1% or better, it is most appropriate to consider the inverse problem of indirect mapping of ocean tides on the open oceans by means of extended earth tidal gravity measurements on the adjacent lands, supplemented by a few ocean-bottom stations to observe tidal gravity and ocean tides.

Ocean tides on the open oceans are largely unknown and have to be either inferred from coastal stations or theoretically calculated. Such basic information is of vital importance to the fundamental understanding of the tidal deformation of the earth and the dynamics of the earth-moon system. Direct satellite measurements of ocean tides on the open oceans are highly desirable.

It has come to be fully appreciated that the tidal gravity variations across the US continent are principally influenced by ocean tidal loading. It has been further realized that a great number of independent determinations of tidal gravity over a long period and with an accuracy of better than 1% is required to evaluate the indirect or secondary effects of geological structures on the tidal gravity. Several base profiles of trans-continental nature should be established in the US and other continents. These base profiles should serve as the references for the eventual satellite mapping of both solid-earth and ocean tides on a global basis.

4.5 TEMPORAL VARIATIONS OF THE GEOPOTENTIAL

For the past decade, coefficients appearing in the expressions of the geopotential have been derived by many investigators by analyzing satellite observations under the assumption that the geopotential is time-independent. Only combinations of observations made for different periods for different satellites provided sufficient information to determine the geopotential. There were too many unknowns to be determined, and there were not enough observations with sufficient accuracy well distributed, both in time and space, to allow a search for time dependence in the geopotential.

However, the geopotential does vary because of tides, atmospheric motion, earthquakes, and other mass motions inside and on the earth — whenever mass displacements occur on or inside the earth, the geopotential changes. Evidences of such mass shifts are the variations in rotation discussed in Section 4. 3.

Since satellite-tracking data provide the most powerful technique for measuring the geopotential, the next objective should be to detect temporal variations of the geopotential. For this purpose, satellite analyses have particular advantage over time-consuming gravity measurements of classical geodesy.

In reality, it has already been possible for satellite observations to identify tidal effects, which are the perturbations in the orbits due to the tidal deformations of the earth, and to identify an annual variation of J_2, the coefficient of the most dominant term in the geopotential.

Of course, more accurate orbit determination resulting from better tracking data, better coordinates of observing stations, and related improvements are needed to further refine and identify temporal variations.

At present, the initial solutions from satellite observations for the annual change of J_2 indicate that about half of the seasonal variations in the length of the day are due to a change in the principal moment of inertia, and the other half, to transfer of angular momentum.[34]

Whether terms depending on longitude in the geopotential are time dependent and correlated with the known westward drift of the geomagnetic field is important as a possible clue to mechanisms of core-mantle coupling.

[34] Kozai, Y., Seasonal variations of the geopotential inferred from satellite observations. SAO Special Report, 1969 (in press).

Not only periodic variations, but also secular and irregular variations of J_2 and other coefficients, as well as of G (the gravitation constant), can be detected if accurate satellite tracking is continued for many years.

There also exists an apparent temporal variation of the geopotential that is not due to the variation of the mass distribution but is due to the motion of the equator and the axis of the figure in inertial space. Newton's equations of motion of the satellite must be referred to an inertial coordinate system, not to the equator of the earth. Therefore, the satellite position must be measured with respect to the fundamental reference coordinate system. If appropriate satellites were tracked over 19 years, the amplitude of the principal nutation term would provide a better nutation constant.[35]

4.6 PROGRAM OBJECTIVES FOR SHORT-TERM EARTH DYNAMICS

A program of activities to advance the understanding of short-term earth dynamics follows the patterns outlined in the four preceding sections. In fact, investigations of these topics are already benefiting from space instruments and techniques. Hence, the future possibilities are in part natural extensions of ongoing activities.

The first objective, discussed in Section 4.2, calls for refined inertial and terrestrial coordinate systems and for precise relations between them. The inertial or celestial system would be defined most easily by reference to an improved catalog of optical or radio stars. Perhaps a telescope system carried above the atmosphere in a spacecraft could support the improvement of an optical catalog. Probably, VLBI will provide a catalog of radio sources with small apparent diameter. Directions to the stars in either refined catalog should have about $\pm 0\overset{''}{.}001$ accuracy.

The terrestrial coordinate system should be capable of expressing coordinates of points on our earth's surface to ±10-cm accuracy without introducing uncertainties from the determination of the coordinate system itself. This is difficult because at the 10-cm scale, a set of points on the land that can be considered fixed with respect to each other over, say, a decade, typically cover somewhat less than a continent.

The instrumentation discussed in Chapter 2 offers techniques for locating the essential elements of a terrestrial coordinate system. In particular, the center of mass of the earth is the most natural choice for the origin of the system. This point is accessible indirectly through the motion of satellites and accurate ground station tracking. In

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[35] Kozai, Y., Effect of precession and nutation on the orbital elements of a close earth satellite. Astron. J., 65, pp. 621-623, 1960.

fact, at the present 10-m uncertainty level, the determination of a geocentric system has been one of the prime products of satellite geodesy. Improved observation techniques and satellite orbits should allow the necessary refinements of the system.

The mathematical transformations relating the inertial and terrestrial systems have two principal roles. First, they complete the requirement for well-defined coordinate systems in which to formulate and study the mechanical problems of the earth. Second, they incorporate a kinematical representation of the rotational motions of the earth; that is, they must specify the time-dependent position of the earth as it rotates about its axis.

The determination of the rotational motions of the earth and the generation of theoretical models and interpretations of these motions embrace the second principal objective of this chapter (see Section 4.3). Again, the emerging instrumentation and techniques promise that the motion can be measured with significantly more accuracy than present methods provide. A reasonable accuracy goal seems to be absolute angular uncertainties around $\pm 0\overset{\prime\prime}{.}01$ on a daily basis and relative accuracies over shorter periods to $\pm 0\overset{\prime\prime}{.}002$.

These accuracies will permit valuable investigations of the mechanics of the earth. For example, the spatial and temporal resolution for the position of the spin axis in the earth will allow a definitive examination of its relations to earthquakes and other detailed processes in the mechanics of the earth.

The third major objective, discussed in Section 4.4, is a more penetrating understanding of the tidal processes in the earth. Here, the most valuable step forward may come indirectly through the measurements of ocean tides. The ocean tidal loading on the solid earth is a technically difficult aspect of current treatments of earth tides. Satellite altimeter measurements of the oceans promise to alleviate this problem.

The actual tidal motion of the earth beneath instruments observing spacecraft and stars will implant its signature in the data generated by the instruments. The tide displacements extracted from the data from a global network of instruments will provide information previously unavailable. Finally, the tidal mass displacements themselves are detectable through the time-dependent changes they impose in the geopotential and the resultant orbital perturbations on satellites. This possibility has already been demonstrated at current satellite-tracking accuracies and will improve in precision as tracking instruments and orbit determinations attain new standards.

Tides are not the only phenomena[1] that move mass within the earth system. As discussed in Section 4. 5, one of the unique contributions of space activities is the possibility of measuring significant mass displacements through the perturbations they generate on satellite orbits. This, in turn, can answer such questions as whether the changes in the rotation rate of the earth are due to exchange of angular momentum between different parts of the earth system or whether they are due to mass displacements and corresponding changes in the moment of inertia. A seasonal variation of the J_2 geopotential parameter has already been detected. Thus, the fourth major objective of the short-term earth-dynamics effort should be the monitoring and interpreting of temporal variations of the geopotential.

The four major objectives are summarized as follows:

1. develop instrumentation and procedures that provide and relate reference inertial and terrestrial coordinate systems to an accuracy consistent with expressing the spectrum of motions of points on the surface of the earth to 10-cm accuracy;

2. establish a program to monitor and interpret the rotational motions of the earth to $\pm$ 0."01 accuracy with respect to the inertial coordinate system over decades and to $\pm$0."002 relative accuracy over a few days;

3. establish a program to monitor and interpret the earth tidal motions including the effects of ocean loading (surface displacements should be determined to a $\pm$10-cm accuracy with respect to a terrestrial coordinate system);

4. establish a program based on analysis of satellite dynamics to measure mass displacements in the earth that produce changes of one part in 10^8 in the position of a satellite.

CHAPTER 5
LONG-TERM DYNAMICS OF THE SOLID EARTH

5.1 INTRODUCTION

Topics of considerable interest to solid-earth geophysicists that may be classed as relatively long-term effects include five broad areas: 1) earth movements of various types, 2) the earth's gravity field, 3) physical processes acting within the earth's mantle (particularly convection currents and other possible driving mechanisms for global tectonics), 4) geological data pertinent to the physics of the earth such as satellite photography, and 5) glaciology. Transmission of geophysical data by satellite is an additional area that appears to offer a large potential for the solution of geophysical problems. Earth movements as considered here include displacements along major faults both preceding and at the time of major earthquakes, motions of the earth's surface on an intercontinental scale, strains and stresses associated with major fault zones, and vertical motions such as those related to glacial rebound and earthquakes.

Several important contributions to a fundamental understanding of the physics of the earth, to earthquake prediction, and to the rapid identification (and hence warning) of earthquakes that have generated seismic sea waves (tsunamis) appear to be possible in the next 10 yr. A new class of problems can be attacked if a precision of 1 to 20 cm becomes available in the measurement of long distances. This precision is needed for studies of continental drift, earth strain, and earthquake prediction.

Each of the above topics will be discussed at greater length in the following sections. An attempt is made to identify several of the more important problems from the viewpoints of both scientific and social value. Several new applications, however, are possible now with current technology. These include satellite transmission of geophysical data and the measurements of displacements associated with major earthquakes. The latter displacements are of the order of meters to tens of meters and are well within the limits of current detectability with satellites. Use of satellites has already yielded fundamental information about the earth's gravity field and, hence, about the internal constitution and physical processes within the earth. Further contributions in these areas can be expected from satellite gravity and geodesy.

5.2 LARGE-SCALE MOTIONS OF THE EARTH'S SURFACE

5.2.1 Status

During the past 5 yr there has been a rapid accumulation of evidence that the earth's surface is extremely mobile. Large blocks or plates constituting the outer 50 to 100 km of the earth with horizontal dimensions of thousands of kilometers appear to be moving with respect to one another at average long-term rates from 1 cm/yr to as high as 15 cm/yr. The diagram in Figure 5-1 depicts the configuration of plates of lithosphere and their relative motion for a broad region of the South Pacific extending from South America on the right to the Western Pacific on the left.

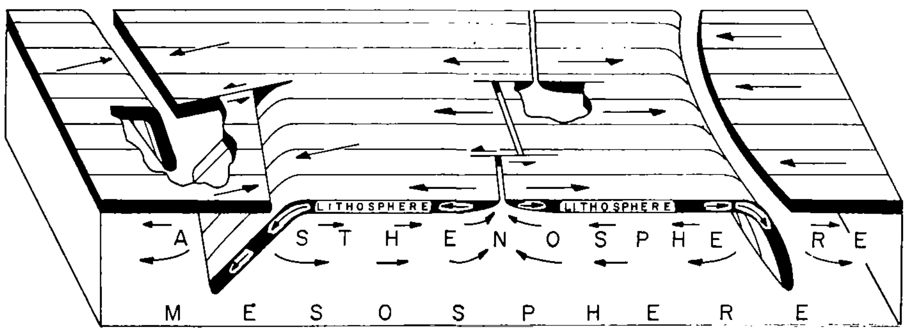

Figure 5-1. Block diagram illustrating schematically the configurations and roles of the lithosphere, asthenosphere, and mesosphere in a version of the new global tectonics in which the lithosphere, a layer of strength, plays a key role. Arrows on lithosphere indicate relative movements of adjoining blocks. Arrows in asthenosphere represent possible compensating flow in response to downward movement of segments of lithosphere. One arc-to-arc transform fault appears at left between oppositely facing zones of convergence (island arcs), two ridge-to-ridge transform faults along ocean ridge at center, simple arc structure at right.[1]

The interactions of these plates appear to be responsible for a wide variety of effects, including the frequency of occurrence of large earthquakes, mountain building, generation of tsunamis, and the confining of nearly all active volcanoes to only a few narrow belts. In fact, nearly all large-scale geological and geophysical phenomena occurring on the surface of the earth or in the outer 600 km of the earth appear to be intimately related to this global pattern of motions.

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[1] From Isacks, B., J. Oliver, and L. R. Sykes, Seismology and the new global tectonics. J. Geophys. Res., 73, pp. 5855-5899, 1969.

5.2.2 Prospects and Major Problems

The present simple model of earth deformations (or global tectonics) has already had a large impact on basic research in the earth sciences and has been called a "revolution in earth science" by J. Tuzo Wilson.[2] These ideas promise to play a dominant role not only in future research related to the solid earth, but also in foreseeable applications such as earthquake prediction, economic geology, and improved tsunami warning. Despite the successes to date with this simple model of global tectonics, a number of opportunities and major problems are now evident. For example, continental drift and other large-scale earth deformations have not yet been detected by astronomical or geodetic methods. If the lunar laser or VLBI methods can measure variations in intercontinental distances to within 10 to 20 cm, then the discrepancy might be resolved by 1980. While geodetic measurements do indicate average motions of about 8 cm/yr along the San Andreas fault of California, similar measurements are not available for nearly all the other major earthquake zones of the world. In particular, there are no successful geodetic determinations of the growth (or spreading) of sea floor and of the return of surface materials back into the mantle along island arcs. Attempts of this type are now in progress for rift zones in Iceland and the Gulf of California.

Measurements across island arcs such as Japan, the Aleutians, and Southern Alaska are particularly needed since some of the world's highest rates of deformation appear to be associated with those regions, most of the world's greatest earthquakes occur in island arcs, most destructive tsunamis are generated in these regions, and the required baselines are at least several hundred kilometers long (and hence are often not well suited to ground-based measurements). While magnetic data and seismic data now yield a consistent pattern of movements for the oceanic ridges, the only quantitative evidence for directions and rates of movements in island arcs comes from seismology. Although the seismic data furnish strong arguments for motions in the arcs, the rates are uncertain to within a factor of 2. Thus, achieving a precision of 5 to 10 cm in the measurements of long baselines spanning arcs should provide a more accurate description of these motions. At this and at higher accuracies, earth strains could be obtained for most of the major seismic zones of the world. Such measurements are almost certainly required before a fundamental attack can be made in the field of earthquake prediction.

Also, much of the evidence for global movements represents averages over thousands to millions of years. How global motions occur over periods of a few years or less is not well known and requires thorough investigation because of its great relevance

[2] Wilson, J. T., A revolution in earth science. Geotimes, pp. 10-16, Dec. 1968.

to earthquake prediction. The present concept of plate tectonics assumes that the plates may be regarded as rigid. Attempts should be made to check the validity of this assumption by use of two points on the same plate. The assumption of perfect rigidity may break down at the 1-cm/yr level or smaller.

At the present time, determinations of earth movements represent merely relative movements of two blocks. Efforts should be made to relate these motions both to the axis of rotation and to a precise reference system. Such measurements should provide important clues to the problem of polar wandering, the interpretation of past global motions from paleomagnetic results, the dynamics of the upper mantle, and possible changes in the earth's obliquity.[1,3,4]

5.2.3 Recommendations

1. A precision of about 10 cm in the relative locations (both horizontally and vertically) of points on the earth's surface should be regarded as a major goal to be attained in the next 5 to 10 yr.

2. To achieve this precision, we strongly urge the development and testing of the VLBI and laser ranging to the moon or satellites as well as the continued improvement in other methods of positioning and in star catalogs.

3. These methods should be tested against results from geodetic networks across the San Andreas fault zone.

4. A study should be conducted of where to place stations and baselines relative to surface plates so as to maximize the knowledge that could be attained by precise measurements of intercontinental distances. Island arcs should be regarded as prime candidates for investigation. A suggested series of VLBI lines is shown in Figure 5-2.

5. Measurements of intercontinental distances should be repeated as often as the precision of the method and logistics will allow. For example, long baselines across the Japan Trench where the rate of movement is about 10 to 15 cm/yr, should be repeated twice a year when a 10-cm resolution is attained and about 20 times a year when 1 cm is achieved. The latter should permit a precise estimate of strain buildup, of the detection of possible changes in the strain rate, and of a possible earthquake prediction.

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[3] Le Pichon, X., Sea-floor spreading and continental drift. J. Geophys. Res., 73, pp. 3661-3697, 1968.

[4] Morgan, W. J., Rises, trenches, great faults, and crustal blocks. J. Geophys. Res., 73, pp. 1959-1983, 1968.

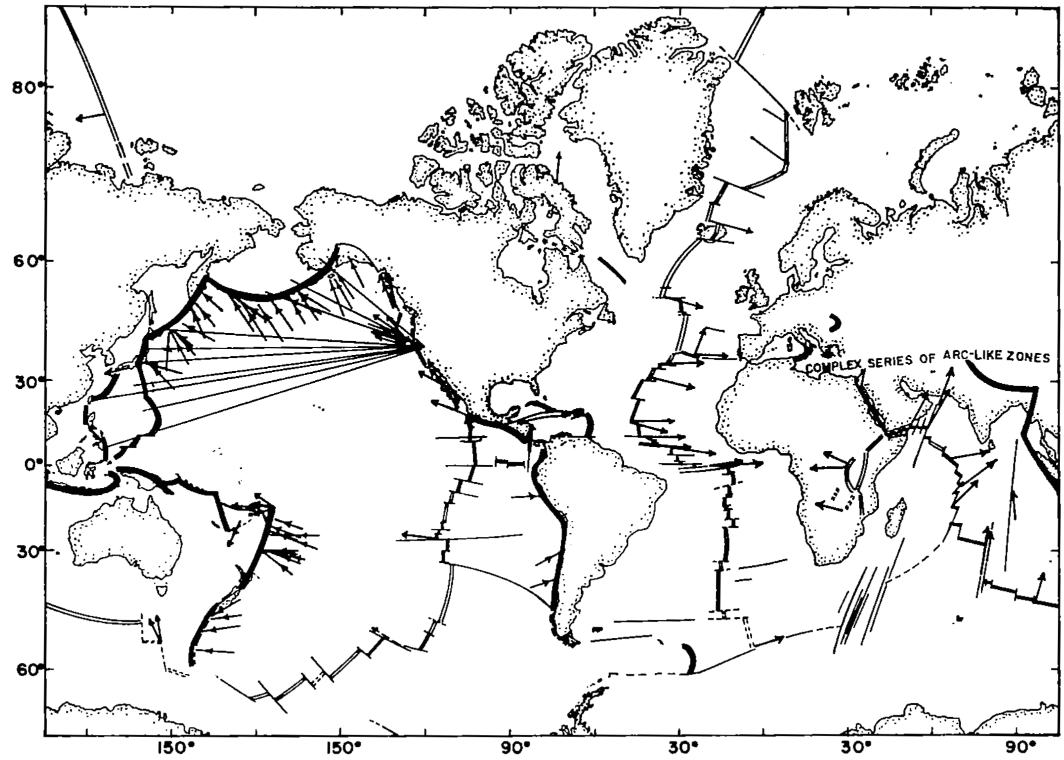

Figure 5-2. Slip vectors derived from earthquake-mechanism studies. Short arrows indicate horizontal components of direction of relative motion of block on which arrow is drawn to adjoining block. Compare with the directions in Figure 5-3 inferred from magnetic anomaly patterns. Long arrows indicate suggested radio-interferometer baselines using the Goldstone facility. [1]

6. The North American part of the Americas plate (Figure 5-3), exclusive of seismically active regions of California and Nevada, is recommended as a fundamental reference system because the region appears on seismological evidence (the near lack of earthquakes in this area is seen in Figure 5-4) to be undergoing relatively little deformation. The assumption of lack of deformation should be tested for long baselines in this area when a 10-cm or better resolution in location is obtained.

7. Research on the problem of global tectonics should be continued and strengthened to develop earth models that will be of sufficient reliability and detail to explain a wide variety of earth processes and to make predictions of environmental hazards such as earthquakes, volcanic eruptions, and tsunamis.

8. Attempts should be made to detect the motions of large plates of the earth's surface relative to the mean rotational pole. Since it is doubtful if the data of the ILS or BIH will be adequate for this purpose, measurements with VLBI or laser-ranging methods should be used.

9. Attempts to detect continental drift over distances of a few hundred kilometers (such as across the rift zones of Iceland, East Africa, or the Gulf of California) should be encouraged.

5.3 DEFORMATION AND RUPTURE IN MAJOR FAULT ZONES

One of the important features of sea-floor spreading and plate tectonics is that nearly all crustal deformation can be shown to be located at the narrow boundaries between moving plates of lithosphere. Thus, almost all the seismic activity of the earth can be explained with a single simple model. Not yet well understood, however, is the precise manner in which strain accumulates in major fault zones and how it is correlated with periodic great earthquakes. This is a problem of crucial importance since a knowledge of strain accumulation and release in areas such as California and Alaska promises attainment of the understanding necessary to evaluate and predict earthquake risks.

As a result of very recent work, we now have sufficient knowledge of strain accumulation and release to pose the problem in a well-defined way.

5.3.1 Strain Accumulation

By analysis of geodetic data in tectonic regions such as California, it is possible to deduce the deformations due to the interactions of moving plates of lithosphere at their boundaries. Data from the Imperial Valley, California, during the period 1941-1954 show that the two plates on either side of the Imperial fault are moving relative to one

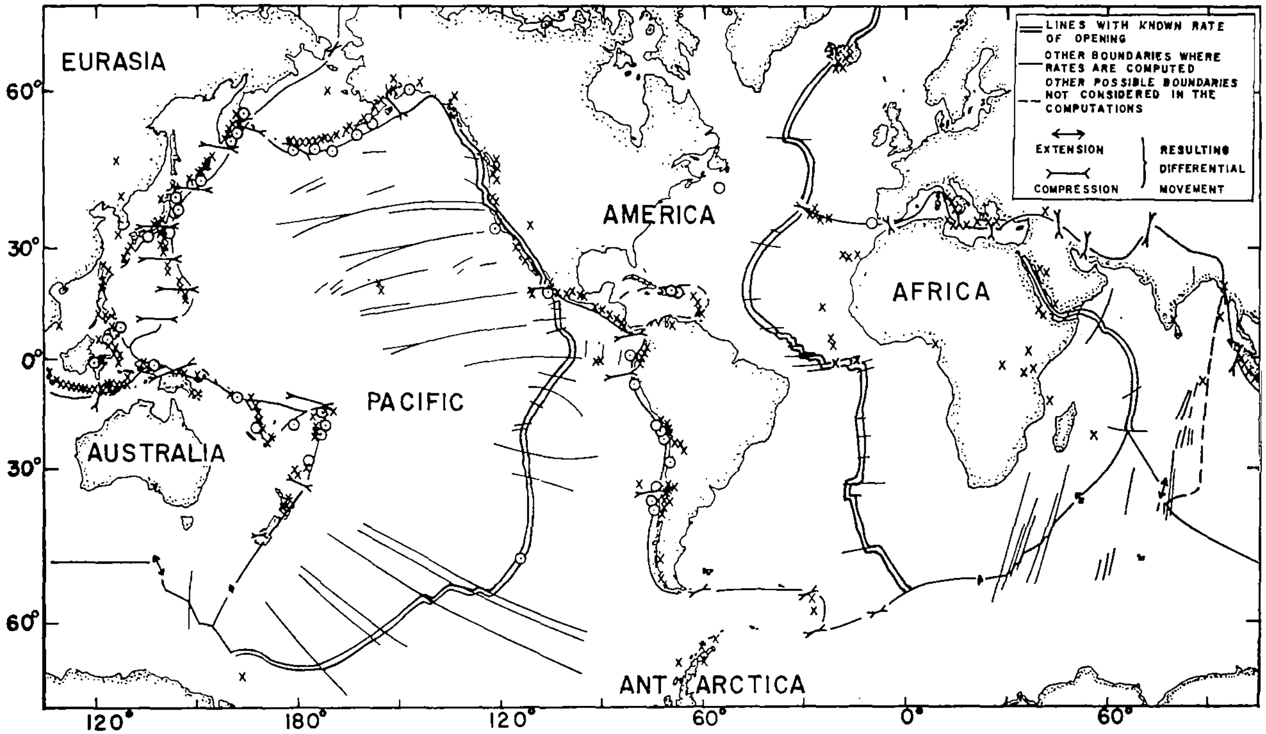

Figure 5-3. Computed rates of compression and extension along boundaries of six lithospheric blocks (after Le Pichon[3]). Computed movements were derived from rates of spreading determined from magnetic data and from orientations of fracture zones along features indicated by double lines. The extensional and compressional symbols in the legend represent rates of 10 cm/yr; other similar symbols are scaled proportionally. Symbols appearing as diamonds represent small computed rates of extension for which the arrowheads coalesced. Historically active volcanoes (see Gutenberg and Richter[5]) are denoted by crosses. Open circles represent earthquakes that generated tsunamis (seismic sea waves) detected at distances of 1000 km or more from the source.[1]

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[5] Gutenberg, B. and C. F. Richter, "Seismicity of the Earth and Related Phenomena," 2nd ed., Princeton Univ. Press, 310 pp., 1954.

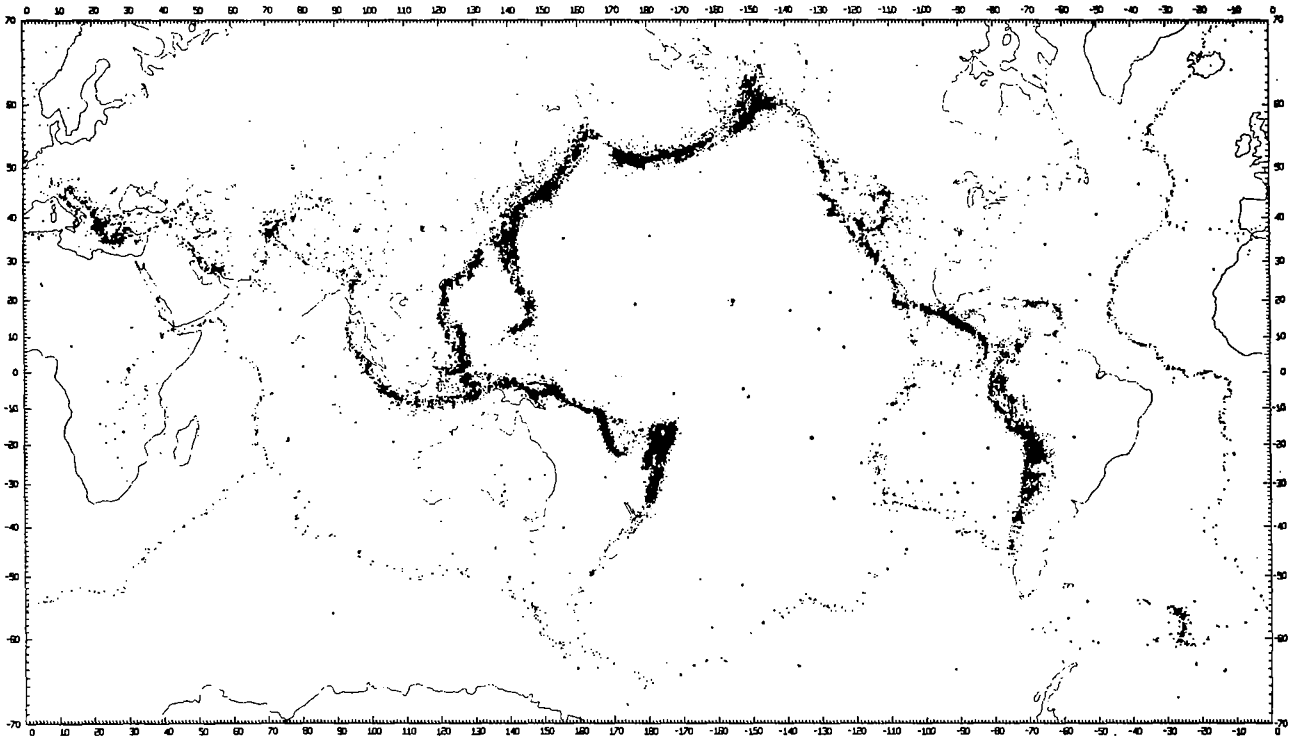

Figure 5-4. Worldwide distribution of all earthquake epicenters for the period 1961 through 1967 as reported by US Coast and Geodetic Survey (after Barazangi and Dorman[6]). Note continuous narrow major seismic belts that outline aseismic blocks; very narrow, sometimes steplike pattern of belts of only moderate activity along zones of spreading; broader very active belts along zones of convergence; diffuse pattern of moderate activity in certain continental zones.[1]

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[6] Barazangi, M. and J. Dorman, World seismicity map of ESSA Coast and Geodetic Survey epicenter data for 1961-1967. Bull. Seismol. Soc. Amer., 59, pp. 369-380, 1969.

another at a rate of 8.5 cm/yr and that the fault is 25 to 40 km deep there. Strain is almost all concentrated within a band approximately 150 km wide centered on the fault, and the highest strains, near the fault, accumulate at about 1.0×10^{-6}/yr.

The above results demonstrate the manner in which strain accumulates in tectonic areas like California, Alaska, and Japan. With a complete knowledge of the accumulating strain field, it is possible to make a precise quantitative statement regarding the elastic energy available for an earthquake at any time. This energy is, in turn, the basis for the estimation of earthquake risk, the first step to prediction. Unfortunately, it is not now possible to make these calculations in any area of California or Alaska other than the Imperial Valley. This is a result of insufficient geodetic coverage. In California, geodetic measurements made to study crustal movement have not been made far enough from the fault to yield the desired results. Analysis of those data, however, shows that near the fault, strains are accumulating at a steady rate of about 1.0×10^{-6}/yr nearly everywhere along the San Andreas fault. Furthermore, only a small portion of these strains is being released by creep and small earthquakes. It appears that strain in California is released only in substantial quantities by infrequent large earthquakes that produce meters to tens of meters of slip on the fault.

5.3.2 Seismic Strain Release

In order to use strain-accumulation data to deduce seismic risk, we must know the amount and patterns of strain released by earthquakes of various sizes and in different areas. Radiation patterns of earthquakes have been studied in great abundance, and all results support the idea of a double couple earthquake source. In this case, the earthquake can be visualized as shear failure of rock across a fault plane. The total shear strain, or shear stress, causing the rupture is one of the most fundamental parameters in an earthquake. At the present, it is not possible to measure this value, but it is possible to estimate a lower bound for it. This lower bound is called the apparent stress because it is the product of the seismic efficiency and the average shear stress in the source region. The apparent stress is obtained from seismograms by comparing the amplitude spectral density of short-period waves with that of long-period waves. The ratio of short-period to long-period waves is equivalent to the ratio of seismically radiated energy to seismic moment. Hence, since the seismic energy is a lower bound for the total energy, the computed ratio is equal to a lower bound of the energy density, i.e., the shear strain, in the source region. These methods have been applied to earthquakes associated with oceanic trenches. The apparent stresses appear to be a strong function of focal depth. Near the surface, a mean value for the apparent average stress is 18 bars, whereas at depths between 45 km and 150 km, it is 270 bars. At 600-km depth, the mean value is again small, averaging 20 bars. Differences in apparent average stress likely reflect differences in strength of the material in the source region. Comparison of the apparent stress with estimates of stress drop indicates an upper bound of about 0.1 for the seismic efficiency of large, deep, and intermediate-depth earthquakes. That means a better estimate of the total shear stresses is obtained by multiplying the above quoted numbers by at least a factor of 10.

The apparent stresses of earthquakes on oceanic ridges and fracture zones are smaller than 10 bars. This indicates very low strength of the material on oceanic ridges and fracture zones.

The apparent stresses obtained for small earthquakes in the western US vary considerably. Along the San Andreas, they vary between less than 10 bars near Parkfield to 125 bars at St. Gorgonio Pass. Earthquakes with epicenters in the Owen's Valley and the Laguna Salada regions indicate values of 300 bars. Parts of these variations could be due to differences in focal depth, to which the apparent stresses seem to be very sensitive even between 0- and 10-km depth.[7]

When geodetic data are available where large earthquakes have occurred, the displacement field due to the earthquake can be deduced. These results have shown that large earthquakes may produce tens of meters of displacement across the fault zone, and direct estimates of the depth and dip of the fault can be deduced.

5.3.3 Seismic Slip Rate Between Tectonic Plates

The rate of slip across fault zones can be estimated by summing the seismic moments of all earthquakes that occurred in a particular major fault zone during a certain period of time. This method provides an independent check on the slip rates determined from magnetic lineation evidence. In regions where results of both methods are available, the agreement is good. In island arc regions, where the faulting due to large earthquakes is largely submarine, this method is at present the only way to infer slip rates.

5.3.4 Aseismic Strain Release

Aseismic strain release, characterized by a slow slippage of a fault, termed creep, was first reported in 1959 at Hollister on the San Andreas fault. The creep displacements there were of a periodic nature in the order of a few millimeters and have

[7] Wyss, M. and J. N. Brune, Seismic moment, stress, source dimensions for earthquakes in the California-Nevada region. J. Geophys. Res., 73, pp. 4681-4694, 1968.

produced 1-cm/yr slip on the fault for the past 10 yr. More recently, rather large creep rates — up to 1 cm/day and totaling 30 cm — were found to follow the 1966 earthquake (magnitude 5.8) at Parkfield, California. The creep phenomenon is not limited to the San Andreas fault. Aseismic displacement of 18 cm accumulated on the Anatolian fault between March 1967 and May 1969. Creep measurements along the San Andreas fault indicate that aseismic displacement is occurring more or less continuously over large parts of the fault, while other parts of the fault do not move.[8,9]

Creep measurements are important for the detailed understanding of strain release on faults. Aseismic and seismic strain release must be intimately related, and one may serve as a gauge for the other.

The creep displacements measured along the fault include only points within a few kilometers of the fault trace. This indicates that this type of creep extends only to very shallow depth, about 4 km. Below that depth, seismic strain release seems to be predominant to depths of 10 to 15 km. Below 15 km, strain may be released by some kind of fault creep or plastic flow.

Monitoring of surface creep is important and may lead to earthquake warning. Such monitoring should be almost continuous, at least weekly, and it should be done with an accuracy of 1 mm.

5.3.5 Problem Areas and Recommendations

The understanding of crustal loading and release depends crucially on observations of the relative positions of a great number of points in fault zones. The geodetic monitoring of even the most intensely studied fault zone in the US, the San Andreas, is at the present time inadequate in coverage. With the currently available data, a complete picture of strain accumulation can be determined along only about 10% of the entire length of the San Andreas. Additional geodetic control in all major fault zones of the world, except Japan, is greatly needed. Since the rates of strain accumulation in the earth's crust are small, of the order of a few centimeters per year, at least 10 yr are required to monitor strain buildups with present techniques. Development of more

[8] Tocher, D., Creep on the San Andreas fault: creep rate and related measurements at Vineyard, California. Bull. Seismol. Soc. Amer., 50, pp. 396-404, 1960.

[9] Smith, S. W. and M. Wyss, Displacement on the San Andreas fault subsequent to the 1966 Parkfield earthquake. Bull. Seismol. Soc. Amer., 58, pp. 1955-1973, 1968.

accurate geodetic instrumentation is needed to allow more frequent observation of the changing state of strain.

The accuracies desired for displacement measurements vary considerably for different problems. Table 5-1 specifies for several important problems the range over which a desired accuracy needs to be maintained and the recommended techniques. There are basically two types of problem: 1) the measuring of strain or displacement fields, which requires positioning of a dense network of points, and 2) the measuring of a single displacement or line-length change. Presumably any projects of the first type would be in cooperation with other agencies, particularly ESSA, that have competence in this field.

The following are our recommendations:

1. The problem of highest priority, both scientifically and socially, is that of monitoring strain accumulation in areas like California and Alaska.

In order to develop a complete knowledge of the seismic process in California, for example, a geodetic network with station spacing of not more than 10 km should be installed along the entire length of the San Andreas fault system and extend 100 km on either side of the fault. Present accuracies of 10^{-6} available with geodimeters will allow usable data to be extracted every few years. Advanced instruments, such as a three-wavelength laser-ranging device, that promise higher accuracy on longer lines should be developed.

Aerial and satellite photogrammetry techniques that may supplant expensive field observations should be vigorously pursued. Development of inexpensive beacons that could be positioned with aircraft or satellites should also be supported. On a local scale, strain accumulation could be monitored in a particular region by use of such a network over an extent 50 km $\times$ 200 km, with the long dimension perpendicular to the fault. Such networks would also serve to determine patterns of strain release due to earthquakes and to determine the rates of slip between lithospheric plates.

2. For the purpose of establishing ground truth for VLBI and lunar-reflector measurements of continental drift, limited networks of the type described above should be installed across active plate boundaries such as the Gulf of California, the Red Sea, or the African rift system. In connection with the Chandler wobble, it has been suggested that creep surges in the mantle could precede earthquakes. This question could also be answered by the above approach. Single line measurements, such as with a three-wavelength laser device, could be used to measure slip rates, but valuable information on deformation within the zone would be lost.

TABLE 5-1. Problem Requirements in Fault Zone Deformation

No.	Problem	Estimated Quantity to be Measured	Range	Accuracy	Techniques
1	Determining strain-accumulation field in major fault zones	Total displacement across zone, 5-10 cm/yr; maximum strain rates 10^{-6}/yr	2-dimensional network, minimum spacing 10 km, minimum extent 50 km × 200 km. Long dimension perpendicular to fault	1 cm	Geodimeter trilateration, triangulation. For larger grids, 3λ laser recommended for long baselines. Photogrammetric techniques.
2	Measurement of slip or spreading rate across major fault zones, rifts, and oceanic ridges	2-15 cm/yr	100-5000 km	1 cm for short lines, 10 cm for long lines	3λ laser for short lines, VLBI and lunar reflector for long lines.
3	Measurements of fault creep	1-10 mm/yr	0.1 km	0.01-0.1 cm	Invar-wire creepmeters, triangulation.
4	Slip from major earthquakes	5-20 m horizontal 0-5 m vertical	5000-10,000 km	1 m	Horizontal displacement from VLBI or satellite ranging. Vertical from radar altimetry. Photogrammetric techniques.
5	Earthquake strain-release field	Displacements 0.1-20 m; maximum strains 10^{-4}	Same as Problem No. 1	1 cm	Same as Problem No. 1

3. Slip during major earthquakes of Richter magnitude 8 or more is of the order of tens of meters and contributes most of the displacement along fault zones. Since most such earthquakes occur in island arc regions and hence are submarine, it is not possible with ordinary geodetic techniques to measure directly the slip produced by them. It would be possible to do this with very long-line measuring techniques.

In Figure 5-2 we show the major fault zones of the world, where the arrows indicate the direction of slip deduced from earthquake focal mechanisms. The lines indicate very long-baseline interferometer lines from Goldstone to points behind the seismic zone that circles the North Pacific. Such lines should be installed and, in the event of a local large earthquake, which on this scale occurs every few years, the stations closest to the epicenter could be relocated; an accuracy of 1 m is required. Other techniques such as satellite tracking of ground points may be equally feasible. Since such earthquakes have fault lengths around 500 km, a station spacing of approximately 200 km would be required. Judicious study of patterns of past seismicity could conceivably widen the required spacing to twice that distance.

5.4 THE DRIVING MECHANISMS FOR PLATE MOTIONS

5.4.1 Status and Problem Areas

The existence of large-scale horizontal motions of continents and ocean basins has now been established by several independent techniques, and all observations appear to be compatible with the theory of plate tectonics. This theory postulates that the outer 50 to 100 km of the earth consists of a number of segments of rigid spherical shells in relative motion and that their boundaries are the earth's seismic belts. Sea floor is created along the oceanic ridges, which form raised linear features across most of the world's oceans, and the total amount of surface area is conserved by large-scale underthrusting in trenches. The continents drift about the earth on the moving plates but are neither created nor destroyed in the manner of the oceanic crust. This theory has been strikingly successful in accounting for tectonic observations, but since plate tectonics consists of little more than the theorems of rigid spherical geometry, its success has done nothing to solve the problem of the origin of the forces that maintain the motions. Indeed, the situation has in some ways become worse than it was a few years ago, when many geophysicists believed that ridges and trenches occurred exactly on top of the upwelling and sinking limbs, respectively, of mantle convection cells. Since the success of plate tectonics, many observations on the shape and evolution of ridges and trenches are difficult to understand if they are the direct expression of deep movements within the mantle. An example of such an observation is the high rate of heat flow on oceanic ridges. It is possible to explain the high heat flow associated with ridges by means of hot mantle upwelling between separating plates, rather than the surface expression of the rising limb. It is therefore important to examine all observations in the light of plate tectonics and to decide which, if any, are relevant to the problem of driving forces. When this is done, rather few observations remain: clearly the plate motions themselves are related to the driving forces, although in a complicated way because they can transmit forces over distances of thousands of kilometers. Another relevant observation is gravity field determined from the orbits of satellites, which cannot be supported by the strength of the plates themselves. Less obvious, but probably important, are the regional variations in the depth of the ocean basins where they are not crossed by ridges. For instance, the regional depth of the Western Pacific is about 2 km deeper than that of the Eastern.

This does not amount to a very long list, nor does it impose very severe restraints on theories of the origin of the forces. At present, only one theory exists that shows any promise, that of thermal convection.[10,11] The principal objection to all other mechanisms is that they are unable to generate the energy of 10^{25} erg/yr released by earthquakes. Since earthquakes are produced by plate motions, this value is a lower bound on the annual energy requirements. The annual rate of heat loss from the earth is about 10^{28} erg/yr, and therefore the mantle can be a rather inefficient heat engine and yet move the plates. Up to this point there is general agreement, but on further details there is rather little agreement. In particular, are the convective motions cellular and steady, or do large blobs of hot matter move unsteadily upward? What are the rheological properties of mantle rocks at high temperatures and pressures; how do they vary with depth within the earth, and how do they affect the motions? How are the motions themselves related to the surface deformation, the external gravity field, and the plate motions and their boundaries? At present, none of these questions can be answered with any confidence, yet if they could be, they would probably help greatly in understanding the evolution of the earth's interior.

There seem at present to be two directions in which progress is possible. The first is experimental and consists of improving our knowledge of the external gravity field. Present published determinations are limited to harmonics with $\ell \lesssim 15$, yet simple calculations show that the gravity field will not be dominated by the strength of the lithosphere until $\ell = 50$. It therefore appears that there is much more information

[10] McKenzie, D. P., The influence of the boundary conditions and rotation on convection in the earth's mantle. Geophys. J. R. astr. Soc., 15, pp. 457-500, 1968.

[11] Turcotte, D. L. and E. R. Oxburgh, Finite amplitude convective cells and continental drift. J. Fluid Mech., 28, pp. 29-42, 1967.

about the mechanism in the gravity field than has been determined. If it were possible to put a relay transmitter on a distant satellite, terrestrial gravity anomalies could presumably be detected by the same methods by which mascons were discovered on the moon.

The other promising approach is a theoretical study of the behavior of convection in fluids. Surprisingly little is known about finite convection, even in liquids with constant Newtonian viscosity, because the equations are complicated and intractable analytically. They can, however, be solved by finite-difference techniques on large computers, though the results should be interpreted with caution and checked against analysis and experiments whenever possible. It is also important to calculate the external gravity field produced by any such flow, since this alone is observable. Studies of this type are of general interest in fluid dynamics and may well permit us to understand the major features of mantle convection.

Further progress on the problem of convection in the mantle requires the following:

1. More experimental information about stress-strain relation for mantle material. If diffusion creep is the governing mechanism, it should be possible to provide such a theoretical relationship. If other deformation mechanisms are important or if partial melting plays an important role, it may be necessary to use a strictly empirical relationship.

2. A reasonable estimate for the concentration of radioactive elements and hence the rate of heat generation.

3. An understanding of finite amplitude convection in fluids whose rheological properties vary widely with temperature and pressure. Such studies will involve finite-difference calculations on large computers, as well as analytical work and laboratory experiments.

4. More detailed maps of the external gravity field of the earth. Why should NASA support work in these fields, and what applications will the results have? Measurement of the external gravity fields of the earth and moon has been one of the major scientific achievements of the space program and depends mainly on the use of satellites. It can be anticipated that with the application of new techniques, satellites will continue to be the prime source of data. Hence, NASA support is appropriate for the exploitation of the data.

If these results are to be interpreted correctly and usefully, the processes that maintain the nonhydrostatic gravity field of the earth and other planets must be understood. Our present understanding of the rheology and convective motions within the earth is almost nonexistent. If the arguments above are correct, an understanding of the forces in the earth's mantle that move terrestrial plates will depend almost entirely on a careful analysis of the gravity field; it cannot come from surface measurements. Unless we have knowledge of the flow field, however, the mass distribution derived from the gravity is not very useful. Therefore, support for studies of convection and rheology is required to make a full analysis of the satellite-generated data. The time required for such analyses will be several years. It is one of the important problems concerned with the evolution of the earth and other planets that at present depend almost entirely on the data supplied by NASA. Although some minor support for studies of mantle convection and rheology is at present coming from other agencies, this is not sufficient to produce any significant progress in either rheological experiments or the theory of finite-amplitude convection.

The main expense in any theoretical investigation of the finite-amplitude convection problem will be in computer time, and not in salaries or equipment. Since NASA possesses a large number of fast, modern computers, time could perhaps be provided for such work. Such an arrangement would be particularly useful after the necessary programs are developed on smaller university computers, since the production runs could easily be controlled by data links.

Should NASA employ resident experts or encourage universities to carry out research in convection? Since any useful work must take into account what is known about the earth, it is very important that the people involved should be working closely with other geophysicists interested in tectonics. This argument suggests that the work should be done within the universities. Yet if NASA is to support good people and benefit from the results, some geophysicists interested in the tectonics of the mantle should be employed to provide contact between the planning of new space projects and the theoretical work carried on outside the agency. Perhaps some arrangement that permits investigators and their students to visit the NASA laboratories and to use the computers there could provide the necessary contact, which, up till now, has been absent in the field of solid-earth geophysics.

5.4.2 Recommendations

1. Measure the gravity field of the earth in particular and of other planets when possible, to determine the finer details of the field down to wavelengths of a few hundred km (degree numbers of about 80). Such studies will improve our understanding of the forces in the mantle that move the continents and sea floor.

2. Support experimental work in rheology to determine the creep behavior of silicates at high temperatures and small stresses. Such studies are essential if our knowledge of the rheology of the earth is to be improved.

3. Support research in finite-amplitude convection, aimed at understanding the physical processes involved, especially in liquids whose viscosity varies widely with temperature. Little is known at present about the behavior of such systems. Such research would lead to an improvement in our knowledge of the evolution of the earth, and also perhaps of that of other planets.

4. Employ a few scientists within NASA who are interested in solid-earth geophysics and convection to provide contact between the universities, where most of this work should be carried out, and the teams planning new orbiting spacecraft.

5.5 RHEOLOGY OF THE MANTLE

5.5.1 Laboratory Experiments

Before any progress can be made in understanding mantle convection, the long-term mechanical behavior of the mantle must be known much better than it is today.

Any treatment of convection or similar processes will require knowledge of the functional form as well as the temperature and pressure dependence of the stress-strain-rate relation. At present, our knowledge of these is very limited: even the identification of the mechanims responsible for creep is not at all certain. It is quite likely that different mechanisms will dominate at different depths and that there may be major changes in the constitutive relation with depth.

Progress in determining the rheology of the mantle could be achieved in two ways: through laboratory and theoretical investigations of the rheological properties of likely mantle materials under conditions of high temperature and pressure, and by direct estimates of the response of the earth to long-term stresses by measurement of long-term motions of the earth.

Because of the extremely slow strain rates, high temperatures and pressures, and long-time scales associated with flow within the earth, it is not possible to use directly the knowledge of creep that has been obtained by investigation of creep at much higher strain rates in order to predict the behavior of the material in the earth. It may be reasonably expected, however, that the creep will be controlled by thermally activated processes and thus will be highly dependent on temperature. Hence, the first object of investigation should be the determination of the functional form of the stress-strain relation and its dependence on temperature. Once this is known, the pressure dependence may be ascertainable from considerations of the changes of the atomic structure of the minerals with pressure. This should be done by experimental investigations of creep at high temperatures.[12]

In this respect, the importance of investigating the specific behavior of silicates should be stressed. The elastic properties of silicates have been found to depend primarily on the mutual interaction of oxygen atoms and only secondarily on cation-anion interactions. This is because the silicon atoms are relatively small and are usually isolated in the center of a tetrahedron, formed by four oxygen atoms, which tends to behave as an isostructural unit. The size of this unit is controlled by the interactions of the oxygen atoms, as is the interaction between tetrahedral units.

It is therefore difficult to predict the behavior of silicates from knowledge of either metals or ionic compounds. For these classes of materials, the properties are governed primarily by the interactions between adjacent anions and cations. This has been demonstrated by the investigations of the elastic properties of silicates.

One might expect similar differences between the nonelastic properties of silicates and other materials. Thus, silicates should be investigated both experimentally and theoretically as a class separate from the more extensively studied metals and ionic compounds.

Studies of covalent oxides have been undertaken in the development of high-temperature ceramics for use in nuclear reactors and rocket engines. Some of this work has been supported by NASA or carried out in NASA facilities. Thus, it would seem proper for NASA to support those experiments that can be done in laboratories funded by NASA or else to facilitate the efforts of other groups doing the experiments by making available the expertise achieved from currently active experimental programs.

Possible, indeed likely, side benefits of such research are readily apparent. The minerals found in the earth's mantle constitute a large class of refractory compounds, most of which are abundantly available and for many of which uses may be found in

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[12] McKenzie, D. P., The geophysical importance of high-temperature creep. In "The History of the Earth's Crust," ed. by R. A. Phinney, Princeton Univ. Press, pp. 28-44, 1968.

various engineering applications where high temperatures and stresses exist. Knowledge of the nonelastic properties of these materials will permit the assessment of their possible applications and will be essential to the fabrication of specific items from these materials.

In addition, the understanding of the behavior of ordinary materials at high temperature and pressure has been shown to be of considerable use in obtaining a general understanding of the behavior of materials under more ordinary conditions. Thus, knowledge of the high-temperature and high-pressure properties of silicates and oxides would be of general interest in the field of solid-state physics.

5.5.2 Direct Estimates

The direct determination of the nonelastic response of the mantle to stress is also essential for two reasons. First, the behavior of mantle material will be highly dependent on the state of the material in the mantle. Since the temperature, composition, mineralogical state and phase of the material in the mantle are not at present known, it may not be possible to apply directly the results of laboratory or theoretical investigations to the earth. For example, the existence of partial melting in the mantle might be expected to have a drastic effect on the rheology of the mantle; in particular, the functional relation between stress and strain could be quite different from that for completely solid material

Second, even a rough determination of the variation of rheology with depth is necessary in order to provide a starting point for the discussion and investigation of the long-term dynamics of the mantle. The concept of relatively thin crustal plates sliding over the mantle is heavily dependent on the concept of a low "viscosity" zone in the upper mantle, the existence of which was suggested before the formulation of a theory of plate tectonics. Similarly, investigations of the driving mechanisms for plate motions require knowledge of the viscosity structure of the mantle.

Studies of post-glacial uplift can determine the viscosity of the upper mantle. Indeed, our present knowledge is based almost exclusively on the uplift of Fennoscandia. The depth to which the viscosity can be determined depends on the spatial extent of the deformation of the surface. For this reason, studies of larger areas would be desirable. An improved knowledge of long-wavelength gravity anomalies over the area covered by the North American ice sheet, Antarctica, and the oceans (the level of which rose as the ice sheets melted) would reveal to what extent the earth has reequilibrated to the change in surface load. This would permit both a better knowledge of the viscosity structure and an indication of such a structure over a much greater portion of the earth than is now available. Improved geodetic control over large distances could also permit more accurate measurements of present rates of post-glacial uplift, particularly over Canada. Similarly, improved knowledge of long-term variations of sea level would be of help, since evidences of uplift have come from long-term changes in tide gauge records.[13]

Estimates of the viscosity of the lower mantle have come from considerations of the extremely long-wavelength components of the geopotential, the secular variation in the length of day, and polar wandering. These estimates vary from $\sim 5 \times 10^{21}$ poise (g/cm/sec) to $\sim 5 \times 10^{26}$ poise. Since thermal convection would be inhibited by a viscosity greater than $\sim 10^{24}$ in the lower mantle (for one simple convection model), a better determination of this viscosity is crucial in order to understand mantle convection. This could come from 1) better knowledge of the geopotential: for example, if an association between some features of the geopotential and certain features of the earth were well established, the contributions of these features could be subtracted from the geopotential and the resulting field then investigated to see to what extent the earth had reequilibrated to the change in surface load following deglaciation; 2) more precise measurement of secular changes in length of day and of the frictional component thereof. This could come from better measurement of solid-earth tides (to determine their contributions to tidal friction), of oceanic tides, and of the effect of tidal torques on satellites.

We finally note that measurement of the nonelastic properties of the earth for short-term motions may indirectly help in determining those for long-term motions by revealing mechanisms of deformation and the state of the material in the mantle. Appropriate measurements would be the damping of seismic waves and free oscillations, the damping of the Chandler wobble, and the phase lag of solid-earth tides.

The measurements that would most aid direct determination of the rheology of the earth are the following:

1. improved gravity measurements, both at very long wavelengths ($\ell \lesssim 20$) and at shorter wavelengths, to assess the contribution of specific features to the geopotential;

2. measurements of relative plate motions and the secular motion of the rotational pole; and

3. improved geodetic measurements to detect post-glacial uplift at a rate of 1 cm/yr over regions possibly up to 2000 km in extent, primarily in Canada.

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[13] O'Connell, R. J., Pleistocene glaciation and the viscosity of the lower mantle. J. Geophys. Res., 74, 1969 (in press).

5.5.3 Recommendations

1. In order to determine the rheology of mantle material, laboratory experiments of creep at high temperatures and slow strain rate should be performed on silicates and oxides likely to be important constitutents of the the earth's mantle.

2. The long-wavelength ($\ell \leq 20$) components of the geopotential should be determined to considerable accuracy (several percent at least) in order to ascertain if any long-wavelength anomalies resulting from deglaciation and the rise in sea level are still present. This will permit direct estimates of the rheology of the lower mantle.

3. The geopotential should also be accurately determined for wavelengths up to ~1000 km over formerly glaciated regions and the continental shelves. This will permit direct determinations of the rheology of the upper mantle.

4. Geodetic control should be improved to detect post-glacial uplift at a rate of 1 cm/yr over areas up to 1000 km in extent.

5.6 THE GRAVITY FIELD

Variations of the gravitational field are a powerful tool in the study of lateral density changes in the earth's crust and mantle. Their use so far has been mainly restricted to local studies limited to the crust and upper mantle. Their importance in that respect still pertains and the study of trenches, ridges, continental margins, seamounts, etc. is in this category. Global interpretation of gravity anomalies has been difficult so far because of the inadequate extent of coverage of gravity data.

5.6.1 Status

1. Terrestrial Gravimetry. Gravity measurements on the earth's surface can be classified in three categories: 1) the reference system, which comprises absolute measurements and a network of very accurately measured relative measurements; 2) relative measurements in detail on the land; and 3) relative measurements at sea.

The absolute measurements in recent years have mostly been made by timing the free fall of objects; they have an accuracy of the order of $\pm 10^{-4}$ cm/sec^2 at about four laboratories. The reference network between these laboratories comprises east-west connections by gravimeter (spring balances sensitive to small changes in g) and north-south connections by pendulums (which are not subject to systematic calibration error). The accuracy of this network after a forthcoming adjustment is anticipated to be a few times 10^{-4} cm/sec^2.

Measurements on land differ significantly from those at sea both technically and as regards the gravitational environment. On land, relative measurements are made within 10^{-3} cm/sec^2, and the main problems are of transportation and elevation measurement. At sea, gyrostabilizing devices are necessary to counteract wave motion, and observations are averaged over minutes to remove the vertical component of wave motion. The main limitation, however, is navigation to obtain both location and east-west velocity, and the accuracy of most sea gravimetry is not much better than $\pm 5 \times 10^{-3}$ cm/sec^2.

On land, variations in gravity anomaly are not readily extrapolated from topography and geology more than a few tens of a kilometer in many areas. At sea, the gravity field can be extrapolated from bathymetry with fair accuracy up to 200 km in many areas.

This difficulty of extrapolation is the principal inadequacy of the terrestrial gravimetry, the error of representation, which is the nonrepresentativeness of a point measurement for the area around it. The distribution and quality of available terrestrial gravimetry data expressed in terms of $5° \times 5°$ mean anomaly, are shown in Figure 5-5. With this coverage, the intermediate wavelengths of the order of 200 to 2000 km, the gravity field is still poorly determined in many areas. These wavelengths are most important because they pertain to inhomogeneities in the upper mantle, the main origin of geologic change.

2. Satellite Determinations. Current work in the determination of the gravity field depends on the tracking of close satellite orbits by networks of a dozen or so ground stations distributed around the world, principally those of the Smithsonian Astrophysical Observatory with telescopic cameras and of the Johns Hopkins Applied Physics Laboratory with radio doppler systems. The best solutions publicly available, primarily those of E. M. Gaposchkin of the Smithsonian,[14] are reliable for all spherical harmonic coefficients up through about the 8th degree, plus several more of higher degree, totaling about 100 coefficients; i. e., features of the gravity field are resolved to about 2500 km in the east-west direction and 1500 km in the north-south direction. Of the total variability of about $33^2 M^2$ in the geoid, about $28^2 M^2$ is measured by the satellites, leaving about $18^2 M^2$.

[14] Gaposchkin, E. M., Tesseral harmonic coefficients and station coordinates from the dynamic method. In "Geodetic Parameters for a 1966 Smithsonian Institution Standard Earth," SAO Spec. Report No. 200, vol. 2, pp. 105-258, 1966.

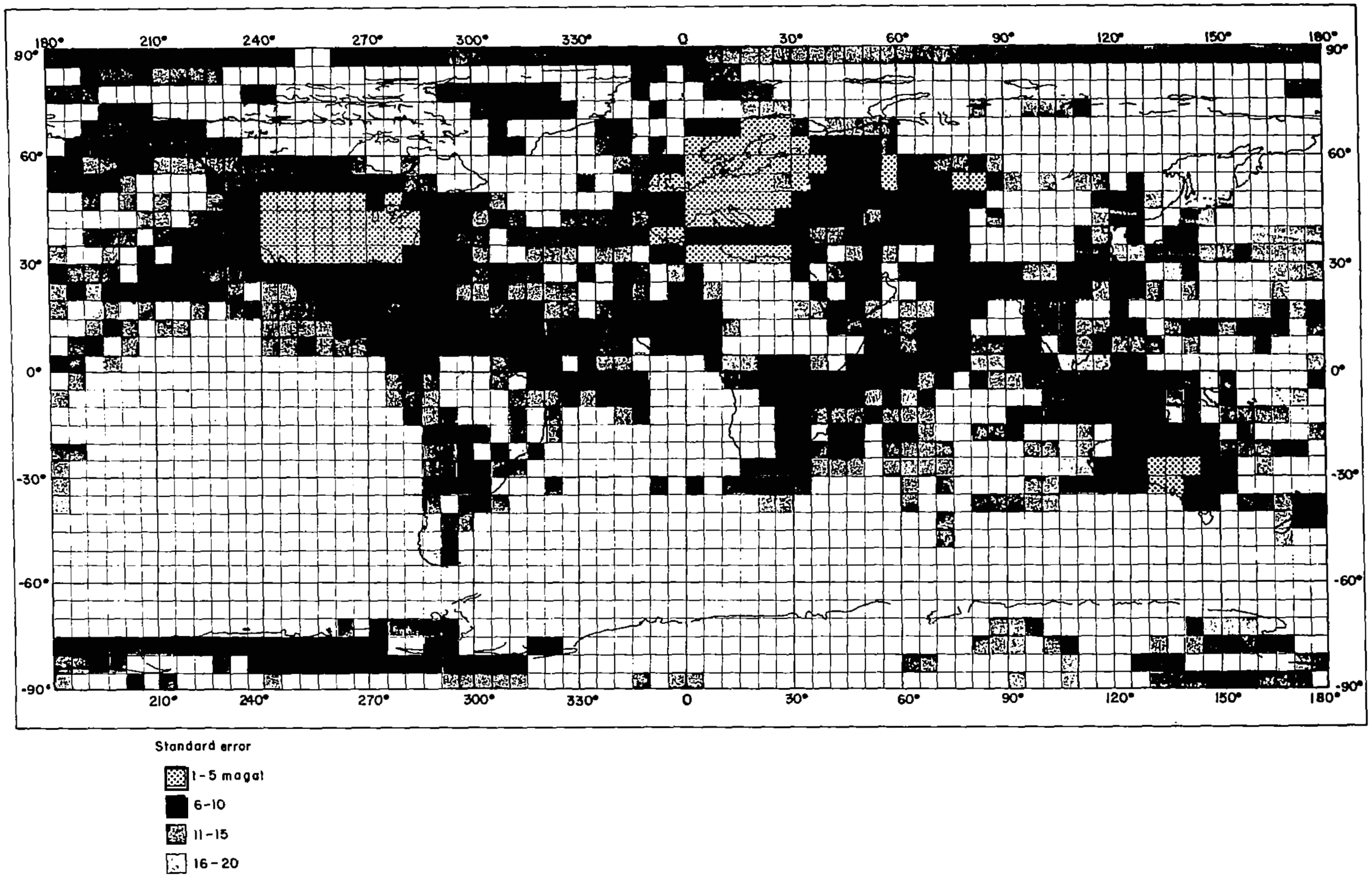

Figure 5-5. Distribution and quality of terrestrial gravity data.[15]

[15] Rapp, R. H. Gravitational potential of the earth determined from a combination of satellite, observed, and model anomalies. J. Geophys. Res., 73, pp. 6555-6562, 1968.

3. Comparison and Combination of Satellite and Terrestrial Data. Systematic statistical tests comparing the gravity field as determined by satellites with that determined terrestrially indicate a high degree of reliability: there is absolutely no doubt that the same field is being measured. For about 30% or 40% of the earth's surface, the terrestrial data are sufficiently dense to give a superior representation, but the satellite data are needed to show the rest of the field. Hence, the best solutions for the gravity field utilize a combination of the two types of data. These solutions show some geophysically interesting features, even in areas where entire reliance is based on satellite data. Figure 5-6 is the result of such a combination.[16]

5.6.2 Prospects

1. Terrestrial Gravimetry. Various institutions are involved in the collection of gravity data at sea. This is not done in any systematic fashion and is usually part of integrated geophysical surveys. Considering that the present coverage has been obtained in the last 10 yr and that the number of ships participating is constantly increasing, it is realistic to say that the present coverage will be doubled in the next 5 yr. Such a coverage should be sufficient to provide $5° \times 5°$ mean gravity maps over the main oceans with an accuracy of the order of ± 5 to 10×10^{-3} cm/sec^2. Some areas, especially in the high latitudes, will remain uncovered because of their inaccessibility.

In order to obtain a satisfactory global map, additional data are still needed in certain areas. We recommend first that additional oceanographic ships carry a gravimeter as part of their program.

Second, it is highly desirable that the accuracy of the radar altimeter be tested by comparison with geoid-height determinations obtained from surface measurements and that a test area for the radar-altimeter experiment should be chosen. Site-selection criteria would involve such questions as: 1) Which areas have extremely small geoid undulations so that variation of sea level caused by dynamic phenomena (currents, etc.) can be studied? 2) Which areas would yield maximum information for solid-earth geophysics regarding properties of the upper mantle? 3) Which areas have the greatest amount of available data, both gravimetric and astrogeodetic?

[16] Kaula, W. M., Tests and combination of satellite determinations of the gravity field with gravimetry. J. Geophys. Res., 71, pp. 5303-5314, 1966.

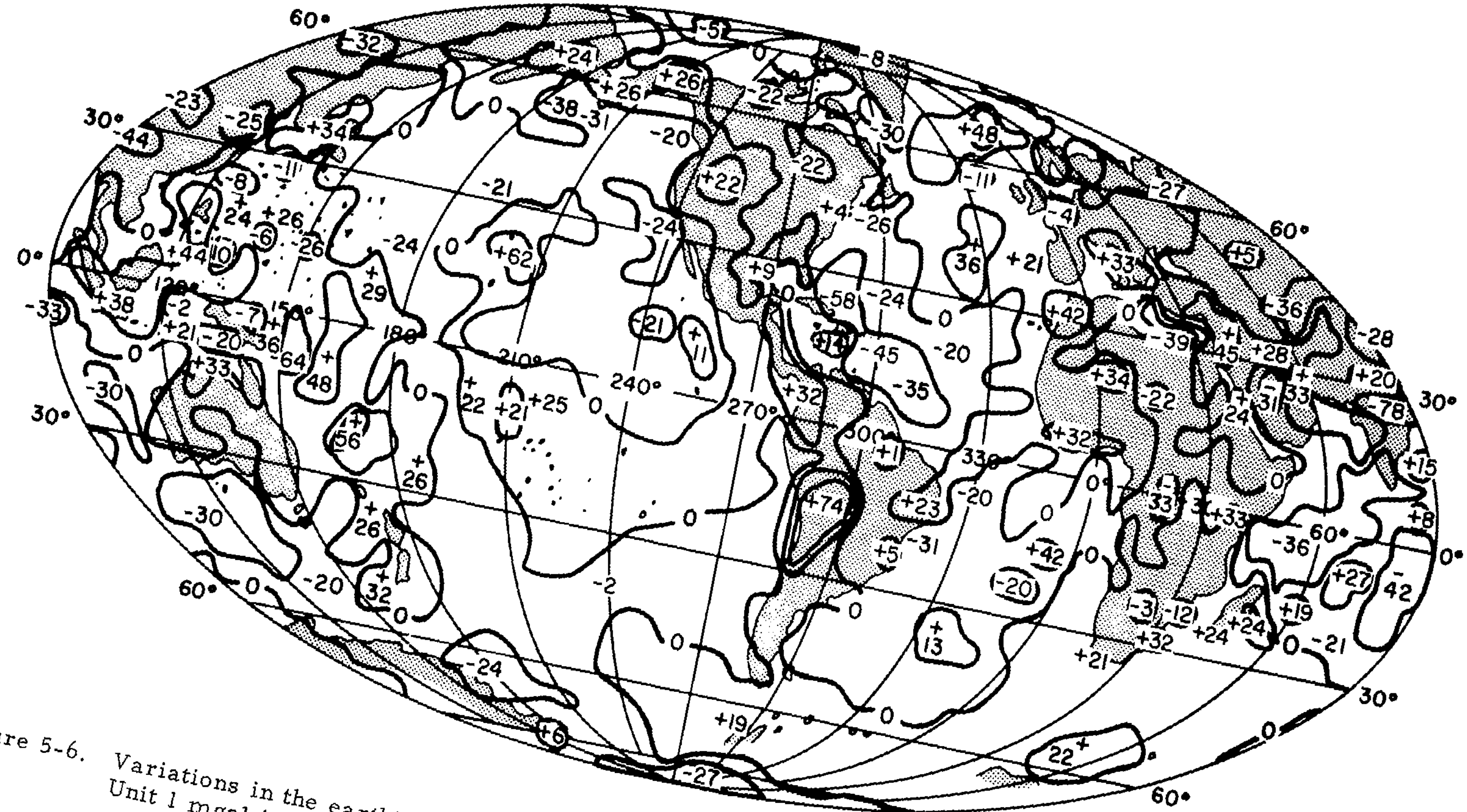

Figure 5-6. Variations in the earth's gravity field in the form of mean gravity anomalies for 5° × 5° squares. Unit 1 mgal (0.001 cm/sec^2).

Once a site is selected, a gravity contour map should be compiled from available data. The geoid should be evaluated from detailed data close to the points of computation. The effect of the distant zones should be incorporated from $5° \times 5°$ mean gravity-anomaly compilations and from satellite-derived geopotential information. Techniques should be developed to compare the marine gravity-based geoid with the geoid derived from a satellite radar altimeter.

2. Satellite Determinations. The present technique of determining the variations of the gravity field from satellite orbits depends mainly on the perturbations of the orbit that build up because they are not averaged out in a single resolution. The method has remained relatively unchanged for about 9 yr and is becoming more and more complex and expensive as the amount of data required to achieve improvement increases. Significant improvement would require a better variety of satellite orbit inclinations, necessary to resolve ambiguities in the perturbations, and a more widespread net of tracking stations, necessary to obtain more uniform coverage of various cycles of perturbation.

The current National Geodetic Satellite Program has one further satellite, GEOS-C, planned for a 15° inclination in order to obtain the aforementioned greater variety of orbital specifications. The field as determined after the GEOS-C experiment will probably be reliable for nearly all coefficients up through the 10th degree, plus several additional through the 15th.

GEOS-C will also carry the first new device that promises an order-of-magnitude increase in detail of the gravity field: the radar altimeter. Any accuracy better than about ±5 m will immediately obtain significant improvement, first because it permits much more accurate orbit determination, and second because the variations of the general level surface will stand out clearly as residuals with respect to this orbit since, as indicated by Figure 5-7, they are of significantly shorter wavelengths than any anticipated error in the orbit. Since it is unlikely that more than 0.5% of the total variance of altimeter error will be in any particular wavenumber band, the anticipated error of ±1 m should be able to determine the field to at least degree 35, or half-wavelength 600 km.

It is therefore recommended that first priority be given to a radar altimeter and that consideration by given to putting GEOS-C into a new polar orbit. Furthermore, a study contract should be granted to determine the best location for a test area in which the geoid can be calculated from surface data. The Caribbean Sea, which has ample gravimetry and is entirely surrounded by an astrogeodetic net, seems a likely choice. However, it may also be desirable to find an area geophysically "quieter" in both its solid-earth and its oceanographic properties.

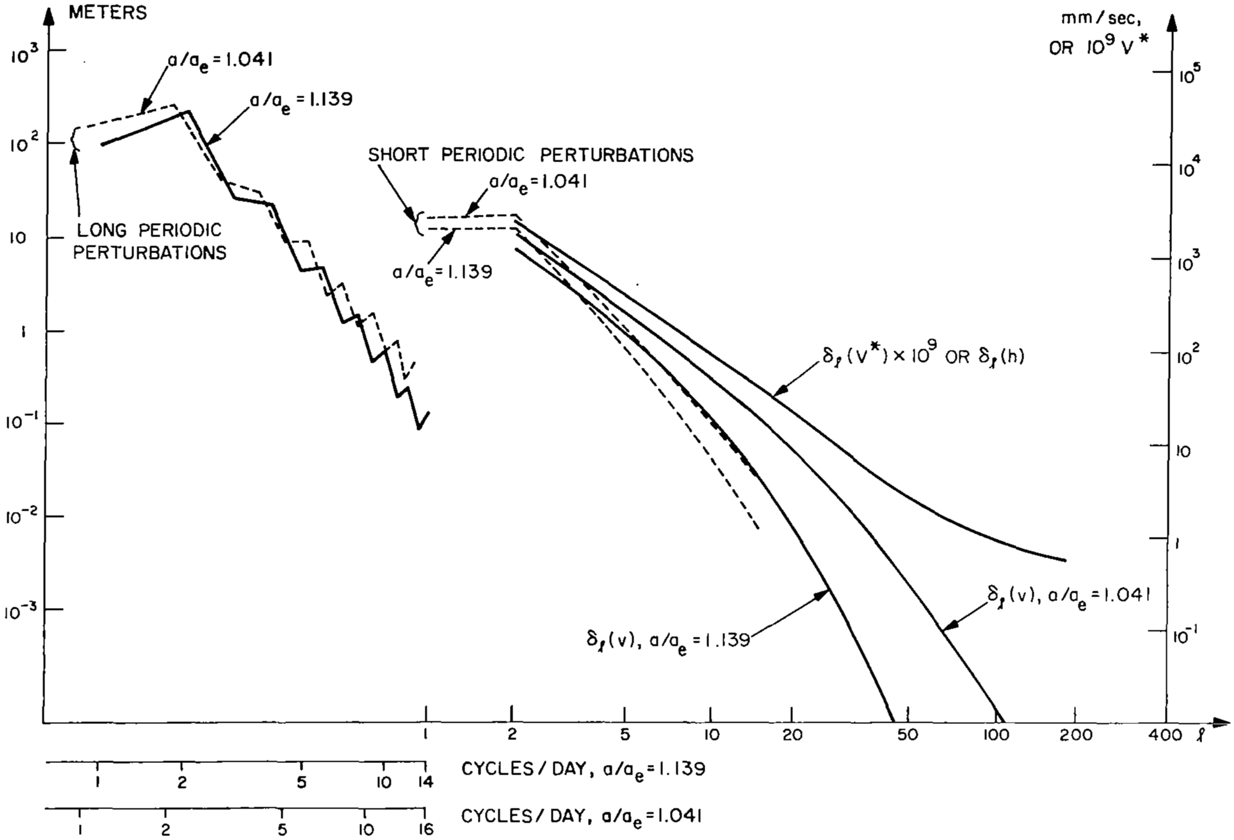

Figure 5-7. Spectra related to the earth's gravity field in terms of the root-mean-square amplitude of a single normalized spherical harmonic coefficient of degree ℓ, δ_ℓ, for 1), the dimensionless potential V^* (right ordinate), and geoid height h (left ordinate); 2) velocity v (right ordinate) for orbits of altitude 260 km (a/a_e = 1.041) and 890 km (a/a_e = 1.139); and 3) long and short periodic perturbations (left ordinate) for orbits of these same altitudes.[17]

The prospect of an eventual accuracy of 10 cm in satellite altimetry, which would be of great benefit to oceanography as well as to geodesy, indicates a need for research in techniques to distinguish the geometrical mean sea level from the geopotential (the geoid) both in observational techniques of obtaining the gravity acceleration to reduce the potential from satellite to sea-level height and in theory to determine the tradeoffs between observational accuracy and averaging over areas, etc. The possible observational techniques appear to be very accurate satellite-to-satellite tracking, satellite-borne gravity gradiometry, and surface gravimetry or gradiometry.

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[17] From Kaula, W. M., The appropriate representation of the gravity field for satellite geodesy. Bull. Geod., 1969 (in press).

The great success of Muller and Sjogren[18] in obtaining the gravity field of the moon from residuals in DSIF range-rates, illustrated on the front cover of Science for August 16, 1968, indicates that the determination of gravity variations from satellite perturbations can be done much more simply if the tracking coverage is complete. The most obvious technique to obtain a comparable coverage of an earth satellite is to track it from a distant satellite. With the same assumptions for the error spectrum as for the radar altimeter, a 1-mm/sec range-rate accuracy would determine the field to about the 80th degree from a satellite of altitude 260 km. It is therefore recommended that this development be carried out.

The satellite-to-satellite tracking system would require three geosynchronous satellites to give nearly full coverage of a close polar satellite. It would obtain the gravity field over land areas as well as oceans, of course.

Further study should be made to determine the optimum orbits for the distant satellites, taking into account 1) maximizing coverage of the close satellite, 2) variety of directions of observation of the close satellite, 3) geometry for intercontinental locations, 4) accuracy of determination of the distant satellite orbits, and 5) minimizing aliasing of the rotation and wobble spectra by errors in the distant satellite orbits.

For the satellite-to-satellite tracking to measure the velocity accurately enough to provide the potential at the satellite for reduction to sea level, the accuracy would have to be better than ±0.1 mm/sec for an averaging time of 10 sec.

To reduce drag perturbations, it would be desirable to have the satellite instrumented to be drag free. However, at 260-km altitude, the drag-free state could be maintained by a cold gas system for only a few weeks. However, ion engines using a cesium source have already been developed to exert a 1900-dyne force with a lifetime of 1 yr. Such a force should be adequate to maintain a satellite at an altitude of 250 km. Hence, further development should be directed toward attaining lower altitudes and longer lifetimes.

5.6.3 Rationale

Modern geophysical theories imply that the upper few hundred kilometers of the earth's mantle plays a key role in global tectonics. Increased knowledge of variations in the physical properties of the upper mantle and the relationship of these variations

[18] Muller, P. M. and W. J. Sjogren, Mascons: Lunar mass concentrations. Science, 161, pp. 680-684, 1968.

to phenomena observed at the earth's surface is therefore essential to improved understanding of the mechanisms that have formed the earth as it exists today and are continually in the process of altering it.

Although gravity data taken alone cannot be interpreted unambiguously, they provide important indications of the sum of the processes operating in the upper mantle in terms of the existing anomalous mass and stress. In order to obtain information on the upper few hundred kilometers in vertical extent, it is necessary to have information on that part of the gravity spectrum encompassing variations with horizontal dimensions ranging between 200 and 2000 km.

Gravity variations with horizontal wavelengths of 100 to 200 km would also be of interest but are less critical since they are usually correlated with observable topographic and crustal geologic variations.

If the gravity field could be defined on a worldwide basis down to the 100- to 200-km level of detail, it would serve the following important functions:

1. Taken with other data already available on an almost universal basis such as topography, it could be used to classify types of geologic provinces using as large a population as possible.

2. Analogous to its use in exploration geophysics, gravity could serve as a reconnaissance tool on a global scale to indicate areas of interest for more detailed investigation by other methods.

3. Through its correlations with other parameters such as seismic travel-time delay, conductivity, and heat flow, gravity can be used to extrapolate and interpolate our knowledge of these parameters.

4. More detail in the gravity field would aid in resolving such questions as the roles of fractionation and of erosion and sedimentation in tectonic processes and would aid in the interpretation of petrological information in terms of its structural significance.

5. Gravity information would aid in the interpretation of the narrow compressive zones at the junction of plates that appear to exert a strong influence on the entire pattern of plate tectonics.

In addition to providing information on the present status of stress in the upper mantle, analyses of gravity information in conjunction with knowledge of the age of stress-producing forces (as, for example, the loading of the upper mantle by the ice sheets) should provide information on the rheological character of the upper mantle as a function of time.

A better definition of the shorter wavelength variations of the gravity field will also serve to remove any distortions now present in the longer wavelength data. This would remove any doubts concerning the validity of these data and would allow their more effective use both in terms of their implications as to the constitution of the interior of the earth and in orbital analysis.

5.7 GEOLOGICAL ASPECTS OF SATELLITE MONITORING

5.7.1 Status and Problems

The facilitation of continental geological studies using satellites is most immediately evident in the production and refinement of surface geotectonic maps. Though not in itself a solution to earth-dynamics problems, the availability of such maps is obviously a first step toward knowing where and in what manner tectonic processes are currently active and have been acting in the past. In this respect, the geologist is much less well served than the selenologist, who has an excellent and comprehensive set of photographs taken by the Lunar Orbiters. For example, although the African rift system was ordered to be photographed on one of the Gemini missions, this program was for various reasons carried out so that less than 10% of this system was covered; and of this small fraction, much of the photography is rendered useless to the geologist by cloud cover.

Of the many dynamic geological processes, the one of greatest current interest is that of crustal deformation: specifically, the steady accumulation of strain across tectonic lineaments and its sudden release as earthquakes. Ground monitoring of horizontal strain accumulation is already being made in active tectonic zones such as the Icelandic rift, the African rifts, and the San Andreas fault system by use of geodimeters and, most recently, multiwavelength laser rangers. These instruments are monitoring movements of the order of a few centimeters per year, although faster movements can be expected in island arc regions such as Indonesia. It will be many years before ground monitoring of all active continental tectonic zones is operational, yet the implications of the global tectonic hypothesis of interacting crustal plates urgently invite a complete global study of these zones. This is important when it is seen that if there is a global interaction of crustal plates, and therefore of crustal strain accumulation, there should be a tendency to a global pattern of strain release in time and space, thus leading to a possible prediction scheme. Satellite monitoring, if capable of the desired accuracy, offers the best hope of global monitoring of all continental tectonic zones on the earth.

Furthermore, the boundaries (and thus the number) of crustal plates on the earth are uncertain in parts of Asia and Africa. This uncertainty is due partly to lack of geological knowledge and partly to the complexity of not altogether minor tectonics within particular crustal plates. Satellite monitoring of deformation rates within crustal plates would therefore also be most useful, although the rates are expected to be of an order less than between plates.

The vertical dimension of crustal deformation is equally of interest to the geologist: in the uplift of orogenic mountain ranges, the uplift of continental plateaus, the isostatic uplift consequent on glacial retreat, and the subsidence of basins and rift valleys. Vertical crustal movements are currently being ground monitoried in, for example, Israel and the Icelandic rift. However, the magnitude of such movements is at least an order less than horizontal crustal movements, which would seem to place it outside the scope of satellite monitoring in the foreseeable future.

Other dynamic geological phenomena include external ones like rock and soil weathering and concomitant sedimentation. Normally, these processes are so slow (1 cm in ±100 yr) as to rule out satellite monitoring. One peculiar process, acting externally on the earth's crust, that could be measured is the rate of flow of glaciers and the vertical component of motions of ice caps. This study relates also to oceanography and meteorology.

Finally, the *monitoring of active volcanoes is a field where satellites could prove* very useful: not in measurements of strain accumulation, which is so small that ground monitoring is much more suitable, but, pending the establishment of observatories on every active and dormant volcano, in infrared sensing. Sensing techniques have already been proved, for example in detecting the Surtsey volcano in Iceland, and it would be valuable to know the times, duration, and intensity of heat buildup and decline in volcanoes. Initially this would be intended to establish the periodicity (if any) of activity and an attempt to correlate activity with local seismicity, and ultimately to relate volcanism to the movement of crustal plates and seismicity on a global scale. Submarine volcanic eruptions that disturbed surface waters might also be detected by satellites; at present, their occurrence passes largely unnoticed.

A close coordination between ground and satellite monitoring of geological dynamics would be essential to the success, initially, of the latter approach.

5.7.2 Recommendations

1. Systematic coverage of earth's land areas by cloud-free satellite photography, for producing a uniform series of geotectonic maps in detail comparable with the lunar orbital coverage of the moon, would be of great value to structural geology and geophysics. Resolution should be sufficient for 1:500,000 maps. A library of these photographs should be available to all interested scientists, perhaps through the UN Committee for the Geological Map of the World. Such photographs might also be of use to those exploiting the mineral resources of the developing countries. Any resolution better than 500 m would be useful.

2. A global program of infrared sensing to monitor active and dormant volcanoes, will determine when, for how long, and with what intensity both minor and major eruptions occur. Volcanic activity should then be relatable to large-scale horizontal crustal motions (discussed in another part of this report).

3. Monitoring of ice cap and glacier motions from satellites capable of resolving horizontal movements of 10 m and vertical movements of 1 m.

5.8 ICE MOTION

This panel recognizes the importance of better determinations of the motions of the large grounded ice masses of Antarctica and Greenland as well as the floating Arctic ice pack. Improved knowledge of ice motions can contribute significantly in such theoretical and practical areas as the relation of ice masses to climate, ice mechanics, and the determination of the feasibility of shipping in the Arctic Ocean. Moreover, because of the inherent difficulty of surface operations in polar areas and the lack of nearly fixed reference points to which ice motion may be referred, satellite positioning methods would appear to have a considerable potential for application to polar ice-motion measurements.

However, no member of the panel felt sufficiently qualified to review adequately the status and to define specific requirements in this field. Therefore, the panel limits itself to the statement that there appear to be important potential applications of satellite positioning to problems of ice motion. It is recommended that NASA obtain the views of suitable experts in ice-motion analysis as a supplement to this panel report in order to identify the specific manner in which satellite capabilities might be applied.

5.9 SATELLITE TRANSMISSION OF GEOPHYSICAL DATA

5.9.1 Prospects

Although most of this report discusses the active monitoring of geophysical phenomena, the panel felt strongly that the transmission of data by satellite could now offer great potential for two classes of problems. In the first, nearly real-time transmission of data is essential. A tsunami warning system or a warning of a volcanic eruption are two examples of situations in which real-time transmission is required.

In the second group, satellite transmission could be justified either economically or by the remoteness of recording sites.

Instruments for the detection of earthquakes and volcanic activity are now largely confined either to accessible areas of continents or to some islands. Seismograph stations on remote islands, in ice-covered regions such as the Arctic Ocean, or on the sea floor would constitute a most important contribution to geophysical studies. For example, only one permanent seismograph station operates continuously in the Aleutian Islands. Yet, this area has the highest frequency of seismic and volcanic activity in the United States, and many of the most destructive tsunamis in the Pacific originate there. Retrieval of data from many stations in the Aleutian Islands (or other island arcs) would be possible by use of satellites for data transmission. Obviously, the economics of the best method of data transmission and techniques for data selection and compression should be examined case by case. It seems reasonable, however, that satellites become most valuable for transmission when data from a great number of remote stations are assembled in one place.

5.9.2 Tsunami Warning

Tsunamis are sea waves generated by large earthquakes near seacoasts. These waves have propagated across oceans and have caused widespread damage thousands of miles from their source area. Two factors appear to be necessary for the generation of a large tsunami: 1) a large earthquake, and 2) appreciable <u>vertical</u> motion of the earth in a water-covered area. The presence of vertical motion can be detected by the examining of the first motions of seismic waves from the earthquakes or by the monitoring of tide gauges near the earthquake. Seismic waves can give a useful warning because they travel to distant stations within about 10 <u>min</u>, while the sea waves propagate to similar distances in a matter of <u>hours</u>. Since only a few of the world's large earthquakes generate large tsunamis, methods of identifying those that do are essential in order to prevent issuance of false warnings.

The following data would greatly increase the reliability of the present system for tsunami warning and would be required only at the times of major earthquakes:

1. Transmission of the P waves from about 50 seismograph stations. Each P wave should be sampled about once a second for the 1-min interval of the P wave. From this information, a focal mechanism solution could be obtained at a critical receiving point and the presence or absence of vertical motion could be ascertained in a matter of minutes.

2. Transmission of the seismogram from the same 50 stations for a 1-hr period sampled once every 10 sec. This would provide a measure of the magnitude of the seismic mantle waves in the period range 50 to 300 sec. The presence of appreciable seismic energy in this period range would be a good indicator that an appreciable sea wave was generated.

3. Transmission of appropriate readings from tide gauges once per 30 sec for a few hours. This would confirm the generation of an appreciable sea wave.

It should be remembered that this data stream would be required only a few times per year at most. The data rates proposed are well within the data-handling capabilities of present satellites.

5.9.3 Recommendations

1. The transmission of geophysical data by satellite offers a great potential to a number of scientific and social problems. The usefulness, economics, and applicability of data transmission in earth physics should be studied and appropriate experiments started.

2. Nearly real-time transmission of selected seismic data and tide-gauge readings would significantly increase the accuracy of warnings of destructive seismic sea waves.

CHAPTER 6

INTERACTION WITH OTHER DISCIPLINES AND PROGRAMS

6.1 TERRESTRIAL GEODESY AND CARTOGRAPHY

The fundamental objective of a geodetic control system is to serve as a frame of reference for orbit determinations, monitoring movements and deformations in the earth crust, determination of polar motion and the variations in the rate of rotation of the earth, cartography, and navigation.

Such a reference frame is established conventionally through the coordinates of selected control points that, based on the above requirements, are located at satellite-tracking stations (one at each), on independent tectonic plates (three on each) and around fault zones (at 1000-km distance), on independent geodetic datums (three on each), on islands and other isolated points of interest, at selected "super-control" points within existing triangulation systems (at 1000-km distance; the usefulness of such a "densification" net is currently being investigated by ESSA/USC and GS), and at navigational beacons (one at each).

At present, such a reference frame could be established, with some additional effort to what already has been accomplished, with an accuracy between 10 to 20 m with respect to the center of gravity of the earth (with a much better relative accuracy). With the currently available technology, this accuracy can be improved by a factor of 2 in the next few years and by a factor of 10 or 20 in the next decade as more precise instruments become available.

It is recognized that a geodetic reference frame established through the coordinates of control points is not an ideal one, since it is likely that these points move relative to each other. Other sections of this report deal with the establishment of the reference frame by means of methods other than the system of control points. These methods, however, will not likely be available in the immediate future. Therefore, at least for the time being, the more conventional geodetic control point system will have to be used; it will also serve as a backup system in case the proposed methods fail.

For the above reasons, NASA should plan (possibly through a special committee) to unify the various satellite-geodetic networks, specifically the ones in Table 6-1. The unification may require new observations in reasonable number to establish or to

TABLE 6-1. Existing Satellite-Tracking Systems of Geodetic Significance

Network	Instrument	No. of Stations	No. of Stations Useful for Reference Frame	Remarks
Apollo	USB (S-band radar)	12	12	2 GHz
Apollo	FPQ-6 (C-band radar)	6	6	6 GHz
Stadan	Minitrack	12	12	
Stadan	MOTS camera	15	3	12 collocated with minitrack
DSN	USB (S-band radar)	3	3	2 GHz
USC&GS-DoD	BC-4 camera	44	44	3/5 complete
TRANET	Doppler	100	56	44 collocated with BC-4
SECOR		50	15	15 collocated with BC-4
AF	PC-1000 camera	35	5	10 to be observed in S. America
SAO	Baker-Nunn camera	18	15	
W. European	camera	20		
Euro-African	and/or	10	8	Uncertain number
E. European	laser	10	5	
TOTAL		333	184	

improve the ties between the networks (or between certain individual stations). The result should provide a global reference frame of 10- to 20-m accuracy and could be interpreted as the fulfillment of the geometric objective of the NGSP. In this connection, because of the limited lifetime of the existing geodetic satellites, attention is called to the urgency of the planning and the implementation.

NASA should also plan a network of scientific reference stations based on this seminar's recommendations and start implementing this plan as soon as possible. Stations in this new network should be selected from those in Table 6-1 whenever possible to ensure continuity. The accuracy of this network should be 1 to 5 m with respect to the geocenter (and less than 1 m relatively). In this connection, the study of and possible cooperation with the French GEOLE project are strongly recommended. Project GEOLE is a proposed modification of the EOLE system, a meteorological project designed to study the global winds by tracking 100 balloons. The GEOLE system is proposed by CNES to include a satellite in polar orbit with 100 ground transponders. Range and range-rate measured from the satellite to ground transponders will be controlled by an atomic clock in the satellite and recorded on a memory in the satellite for subsequent transmittal to a telemetry station.

It is proposed that the ranging accuracy be ±2 m and the range-rate ±1 cm/sec. The critical feature is that such accuracies can be attained at an estimated cost of about $15,000 per ground transponder unit. Such economical accurate ground transponders would be of great value, of course, for many surveying purposes.

6.2 METEOROLOGY

6.2.1 Relationship with Programs in Meteorology

Included in NASA's Earth Observation Program is the meteorology program. This consists of continuation and improvement of the infrared thermal and visual cloud-mapping capabilities of Tiros operational satellites, and continued development and testing of advanced meteorological sensors and techniques for sounding the atmosphere by use of polar-orbiting Nimbus satellites. Cloud-mapping sensors and techniques that will give both day and night coverage, as well as sensors for observing the structure and dynamics of the atmosphere from synchronous altitude, are to be developed and tested. These programs are expected to develop into a program that will have the capability of providing accurate, long-range, worldwide weather maps, which could be used by the Earth Physics Program (EPP) to locate windstressed ocean surfaces, to correct for atmospheric propagation delays, to evaluate sea-state effects, and to locate ocean currents.

From Tiros and Nimbus thermal-mapping sensors and data-reduction hindcasting techniques, surface temperature maps of high quality might be generated, which could be used to locate ocean currents and ocean sources and sinks.

From Application Technology Satellites (ATS) and Earth Resources Technology Satellites (ERTS), multispectral color photography of high quality could be used to map ocean features.

The Nimbus program has partially demonstrated that satellites may be used to collect data from remote sensors and to determine the position of mobile remote sensors.

6.2.2 Location of Windstressed Oceans from Windfield Maps

The windfield history can be used to form an estimate of the location and amount of windpiled ocean surface independent of the estimate of these same features from satellite altimetry measurements.

6.2.3 Correction of Atmospheric Propagation Delays

Atmospheric soundings can generate vertical pressure, temperature, and humidity profiles from which the index of refraction can be derived to correct both the altimeter and the ground-to-satellite laser and radar tracking measurements. The accuracy of such atmospheric index-of-refraction estimates will need to be better than 3×10^{-6} for a ±3-cm residual error in the altimetry, laser, and radar tracking data.

6.2.4 Sea-State Evaluation

Use of pressure-, temperature-, and humidity-profile histories and windfield histories over ocean regions will provide information about the air-sea energy-transfer mechanisms in operation. This information supplemented with sea-surface altimeter measurements provides a second useful form of sea-state information, which can be used to generate accurate sea-state evaluations. These mechanisms can also be used to estimate the position and strength of ocean currents, sources, and sinks that supply energy to or take energy from the atmosphere.

6.2.5 Sea-Surface Temperature Maps

To be useful to oceanographers, meteorological satellite observations of surface temperatures should yield maps of sea-surface temperatures showing temperature changes of about ±0.5° C with position and resolution accuracies of ±10 km. These maps would then provide another estimate of the position and strength of ocean currents and areas of upwelling. An accurate independent estimate of these same features is to be obtained from reduction of the satellite altitude data, which will also provide estimates of the flow rates and depths of currents.

6.2.6 Ocean-Feature Mapping

Multispectral and color photographic observations from both the meteorological and earth-resources satellite programs can provide several varieties of color maps, which would be useful to the satellite ocean-physics program. In coastal waters, multispectral color maps are able to show details of depth, turbid surface currents, fresh-water influx, sediment content, and biological content. There is encouraging evidence that multispectral color photography will be able to show biological content in detail in the open ocean with the development of the proper sensors and data-reduction techniques.

6.2.7 Atmospheric Mass Distribution

Calculations of mass distribution from meteorological data could be used to estimate the wobbles in the earth's axis of rotation, variations in the rate of the earth's rotation, and perturbations of close satellite orbits arising from these mass shifts.

6.3 EARTH-RESOURCES SURVEY

There will be an interaction between NASA's Earth Resources Survey Program (ERSP) and a NASA Earth Physics Program (EPP) even though these two programs will have different objectives and make use of different measurement techniques. ERSP is concerned with the application of earth-oriented satellites and remote-sensor techniques to surveys of resources on continents, islands, and the ocean surface. An EPP will involve the application of space technology and ground-based and satellite-borne precision measurement techniques to investigations of the dynamics of the solid earth and the oceans. It is anticipated that there will be major interactions between the two programs in the fields of oceanography and geology.

Current plans for the ERSP call for a series of ERTS to be flown at 1-yr intervals starting in 1972. The first two satellites, ERTS-A&B, will be carrying remote-sensor payloads designed primarily for agriculture, forestry, geology, and hydrology surveys of land masses. These payloads will consist of three high-resolution television cameras with wide-band filters to provide color imagery in addition to a multichannel narrow-band spectral imager. Ocean-survey missions are planned for later satellites.

If the ERTS-A&B cameras are operated over the ocean, they would provide color imagery from which it may be possible to derive information about the features of ocean currents. Since the color of ocean-current water differs from that of the surrounding water, it should be possible to study the spatial and temporal variations of current meanders. The significance of this information is that it can contribute to a further understanding of the circulation of the ocean, which would be a major objective of an EPP.

The ERSP will provide high-resolution photography of coastal regions that will contain information on near-shore tidal actions. This information will supplement measurements of tides in the open ocean, which will be obtained by EPP satellite altimeters, and thus enable physical oceanographers better to understand ocean-tide dynamics on a global basis and geophysicists to determine the interaction of ocean tides with crustal tides.

The ERSP will provide photographic coverage of regions of the oceans containing sun glints, which are indicative of smooth ocean-surface conditions. Since oil slicks of natural origin arising from oil seepage through the ocean floor, or oil slicks of fish origin, act to moderate sea waves, pictures of sun glint off the ocean surface will permit the determination of the location, extent, and perhaps, through repetitive coverage, the persistence of slicks. It is anticipated that EPP satellite altimeters will be able to sense differences between calm and rough sea conditions and serve as a means of indicating the presence of oil slicks. If on repeated overflights of the same regions the altimeter senses a persistence in calm sea conditions, it will be indicative of natural oil slicks and thus of the possible presence of oil beneath the sea floor.

The ERSP may also benefit from an EPP, which may provide basic information about the circulation of the oceans. Through the determination of geoidal undulations over the broad extent of the oceans, it may be possible to develop models for ocean circulation that could lead to predictions of regions of upwelling and convergence. These predictions could be checked by a satellite having an ocean-survey mission, by employing remote sensors to measure temperature gradients and variations in water color that may be indicative of upwellings and convergences.

Oceans are a long-term indicator of climatic anomalies, and, in turn, once the oceans have established an oceanographic anomaly, the feedback to the atmosphere produces persistent climatic anomalies. Thus, if the geoid is determined by these satellite-altimeter procedures to sufficient precision, the year-to-year departures of the sea surface from the geoid will have important implications in long-term weather prediction. For example, if the Gulf Stream currents were found to be 20% stronger than average, this would imply anomalous weather conditions in the Iceland, Great Britain, and Scandinavian regions that would persist for several months. In addition, shifts in current strength could also affect zones of upwelling where fish are normally found. It is, therefore, through an interaction of ERSP and an EPP that oceanographers and meteorologists could better obtain the types of information required to understand the mechanisms responsible for oceanic processes that influence weather and the availability of fisheries.

The ERSP should have a direct interaction with an EPP in designating ocean ground-truth test sites for the calibration and verification of ocean-survey remote sensors and satellite altimeters.

ERSP high-resolution photography could be used to record areas of high strain buildup. In the event of a large-scale surface displacement due to a major earthquake, these photographs may be used to make a direct comparison of the extent of the displacement and to gain further understanding of crustal motion.

6.4 ORBIT DETERMINATION

Orbit determination is one aspect of space science common to all space missions; hence, consideration must be given to the influence of spacecraft orbit on the scientific output of experiments, and vice versa. It is therefore logical and necessary to pay attention to both the systematic and the noise error characteristics inherent in all orbit-determination processes.

These orbital errors originate from errors of the theory and the computation processes used and from lack of knowledge of the environment.

At present, orbital errors for geodetic-type satellites are 10 to 30 m in position and 0.5 to 1.5 cm/sec in velocity. Height errors, being only a fraction of the total position error, are, say, 5 to 15 m.

An increase in the knowledge of the environmental conditions will result in an increase of our capability to determine satellite orbits. This then will contribute to our ability to measure and observe variation in the magnetic field, which in turn gives information about the core dynamics of the earth.

More accurate geocentric locations of the tracking stations for deep-space probes will also lead to significant economies in the correction of deep-space trajectories.

In summary, it can be stated that a strong mutual benefit will result between the ability to determine spacecraft orbit and earth-survey observations.

6.5 NAVIGATION

6.5.1 Positioning at Sea

Even though NASA has launched some experimental systems, the US Navy TRANSIT Navigation Satellite System is the sole operational navigation system. The term "operational" has a strict legal meaning. For example, the safety of life may depend upon its reliable operation. Therefore, changes in the system, including changes in the geodetic models used in the tracking and prediction operations, are made only after careful testing in which reliability is considered more important than an improvement in accuracy. For this reason, the ephemeris accuracy available on an operational basis will always be some years behind the state of knowledge.

On the assumption that data from the full tracking system are available and that the station coordinates have been determined to an accuracy consistent with the accuracy of the best current gravity models, it is safe to say that a fixed point can be located to within, perhaps, a 20-m accuracy. In any event, the accuracy is limited by geodetic knowledge and not by measuring techniques. On ship, the figure is about 30 m plus the error in the ship's velocity during the pass of the satellite (approximately 15 min). In speaking of the measurement accuracy, the instrument should be of GEOCEIVER quality or better; SRN-9 measurement accuracy is distinctly worse.

If the best geodetic models and the data from the full tracking net are used, there is little difference between "interpolated" positions and positions extrapolated for 24 hr. The difference in position errors may be ±20%.

6.5.2 Velocity at Sea

Suppose that the velocity of a ship is known exactly. The error in one fix would be 30 m. The error in the vector displacement between two consecutive fixes at 2-hr intervals would be $30\sqrt{2}$, say, 45 m. The error in the mean velocity would be

22.5 m/hr. The contribution of this velocity error to each fix error would be about 3 m, which is negligible. Therefore, to the extent that the error in the on-board velocity sensor is constant over 2 hrs, the velocity can be determined to about 0.7 cm/sec. Continuous velocity determinations are about a factor of 10 worse.

From these figures, it is evident that present navigational capabilities do not meet the requirements of the proposed program.

The more accurate determination of the gravitational field recommended by this report would also, of course, contribute to the improvement of navigation systems, but that does not appear to be a critical problem.

6.6 OTHER INTERACTIONS

6.6.1 Communications

In considering both the programs proposed here and some ongoing programs, it is clear that satellites can provide considerable support to solid-earth and ocean physics by acting as data-relay devices. Data-relay requirements are of two types: for transmission of data in near real-time at random intervals and for transmission on preprogramed schedules.

One ongoing program that could profit by rapid data relay is the tsunami warning program. This requires transmission of approximately 2500 bits of data per station from some 50 seismic stations around the world to a central station within a matter of minutes after a potentially tsunami-producing earthquake.

Some programs proposed in Chapters 3 to 5 require or would be greatly facilitated by satellite communications capabilities. By use of satellite communications capability, automatic seismic stations could be placed at remote areas to monitor earthquakes as well as to interrogate and transmit data following earthquakes. In oceanography, data relay is essential to the operation of free-floating buoys. The number of stations of the above types requiring data-relay capabilities is not clear at present, but the capacity required would appear to be of the order of 10^5 bits per transmission with transmissions several hours or days apart.

These requirements should be included among the inputs to the planning of satellite communications systems.

6.6.2 Computing Capability

Computing capability interfaces with the program proposed here in two ways. First, the capacity and speed of present-day computers make feasible the numerical computation of orbits, which appears essential for the spacecraft positioning accuracy required to support the proposed programs. The second interface lies in the exploitation of the data generated by the programs. It seems clear that the successful execution of the programs makes it essential that the software necessary to handle the large amounts of data to be generated be available in a timely manner.

Also in the area of computing capability, it is recognized that to make maximum use of the data concerning both the oceans and the earth's interior, theoretical numerical studies of flow systems must be carried out, which generate requirements for large segments of computer time on some of the largest computers available today. Active steps should be taken to ensure that such computer time is made available.

6.6.3 NASA Ship and Aircraft Capability

In the development of the satellite altimeter, considerable ground-truth and surface support for in-flight calibration must be provided. In addition, before the altimeter on a spacecraft is mounted, it may be desirable to test it on an aircraft. NASA possesses the required ship and aircraft capability to support these requirements. The NASA Apollo tracking ships with their multiplicity of navigation systems and on-board satellite-tracking capability using both range (C-band radar) and range-rate (doppler) systems are ideal for supporting in-flight calibration while at the same time providing ground truth related to sea state. The NASA Earth Resources aircraft is available for any aircraft testing that may be required.

6.6.4 Manned Space Flight

In view of NASA plans for a manned orbiting space station, consideration was given to the possible contributions of man in space to the programs proposed here. The primary space systems proposed to meet the scientific objectives of the group involve low, drag-free satellites and high-altitude satellites employing electronic and laser range and range-rate devices and satellite-borne altimeters. Although any of these systems might be mounted on a manned vehicle for system-evaluation purposes, the group was unable to identify any other way in which man could contribute to the successful operation of systems. In the case of the drag-free satellite system at approximately 200-km altitude, the possibility of man would appear to be precluded since the satellite lifetime requirements and the amount of propellant required to sustain this lifetime appear to make a small satellite mandatory.

The areas in which man and manned space stations might contribute are the photographic ones. These include high-resolution photography of the earth as well as star photography for the development of a definitive star catalog. Here, the ability of man to make nonprogramed camera-pointing decisions and the greater resolution to be obtained by return of film might make man and manned operations valuable.

Manned satellites might also be used to eject subsatellites.

6.6.5 Other Agency Participation

This panel recognizes that the programs proposed here must involve, in addition to NASA, other agencies of the Federal Government that are concerned with research and operations in earth and ocean physics such as ESSA, the US Geological Survey, the Office of Naval Research, the Naval Oceanographic Office, and the Smithsonian Institution, among others. These agencies should be involved both in terms of support of the NASA efforts by providing ground truth for the satellite measurements, as well as in the exploitation and operational utilization of the data and techniques that are developed. It is assumed that, in any implementation of the recommendations of the group, NASA will take the lead in coordinating its activities with those of other US agencies involved in related problems to ensure maximum utilization of US capabilities in support of the program and maximum interaction with ongoing efforts of other governmental agencies in ground-based earth and ocean-physics programs.

6.6.6 International Cooperation

For any program that is global in scope, international cooperation is essential. Since the inception of the NGSP, from which the Solid-Earth and Ocean Physics Program would evolve, NASA has strongly stressed international cooperation. This has contributed significantly to the fact that in satellite geodesy, international cooperation has become the rule rather than the exception. In turn, this sense of cooperation has contributed strongly to the success of the NGSP. The Solid-Earth and Ocean Physics Program proposed here is also a global program. Therefore, NASA should continue to inform the international scientific community about plans related to the Solid-Earth and Ocean Physics Program and actively seek cooperation and participation within the framework of the program.

Specifically, in planning its proposed GEOS-C mission, NASA should consider carefully the possibility of satisfying requirements for a low-inclination satellite through cooperation in proposed French and Italian low-inclination geodetic satellite projects.

In this way, it might be possible to launch GEOS-C in a higher inclination orbit and thus increase significantly the amount of scientific data, both oceanographic and geodetic, that is obtained.

CHAPTER 7
DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

7.1 CRITERIA

Any choice, or expression of priority, is a balance between feasibility and importance. Chapter 2 of this report is essentially devoted to feasibility: the immediate and eventual accuracies attainable by various space and astronomic measurements of geometric or gravitational quantities. Chapters 3 through 5 are devoted to importance, defined mainly by the scientific interest of applying the feasible measurements to problems of oceanography and the short- and long-term dynamics of the solid earth. Chapter 6 discusses various supplemental considerations that might either affect the feasibility or add to the importance of measurements proposed in the earlier chapters.

In this chapter, we wish to discuss briefly the criteria of social benefit.[1] The areas of potential social benefit from a Solid-Earth and Ocean Physics Program include the following:

1. Material resources. This area has a particularly significant application to the ocean. Within a few decades, parts of the ocean will have been taxed to the limit as an ultimate disposal area. If mankind must pass from the hunting to the husbandry of life in the sea, the quality of the marine environment must be preserved through intelligent management. It is easily foreseeable that proper management of the oceanic "range" will in the next century become an industry of several $10 billion/yr.

An appreciable shift from exploitation to recycling must also take place in the use of materials extracted from the earth's crust. However, it is difficult to imagine the attainment of complete waste recovery of such materials. Hence, there will be for the foreseeable future a continued exploitation of the crust. This exploitation will eventually be greatly facilitated by the improved understanding of the processes of crustal formation that will emerge from the research recommended in Chapter 5.

2. Environmental quality. This area comprises the entire effect of the atmospheric and oceanic environment, including protection against hazard and pollution.

The use of the radar altimeter to delineate storm surges and to track tsunamis and the use of satellite communications to transmit seismic and tidal data pertaining to tsunamis will contribute to protection against storm hazards. The recommendations

[1] See, e.g., Stratton, J. A. et al., "Our Nation and the Sea." Report of the Commission on Marine Science, Engineering and Resources, US Gov't. Printing Office, Washington, D. C., 305 pp., 1969.

related to plate tectonics and Chandler wobble also contribute somewhat to earthquake protection insofar as they pertain to the understanding of earthquake mechanisms and statistics. The improved understanding of ocean circulation may have a minor effect on the use of the ocean as a place for mining, etc.

The contribution the radar altimeter will make to the oceanic pollution problem may be very great. The circulation of the ocean, as revealed by precise radar altimetry and satellite measurements of diffusion rates, can serve as a guide to the management of waste disposal in relation to protein husbandry. The circulation also gives better knowledge of the role of the ocean in maintaining the global heat balance, and this in turn leads to improved weather prediction by numerical methods.

3. Technological capability. A significant by-product of space research efforts such as those proposed in this report is, of course, the increased ability to solve practical problems through technical advances and knowledge of the environment. For example, the improvements in electronic techniques required to attain the measurement accuracies necessary for this program could have many applications in the laboratory.

4. Intellectual capability. Perhaps more important than technological by-products is the fact that undertakings of purely scientific interest are of social benefit not only because they offer direct payoffs, such as those mentioned in the three preceding sections, but also because working on challenging scientific problems is a mind-stretching exercise that improves philosophical understanding, adds to the cultural quality of life, and increases the capability to cope with other problems. It is a significant application of Justice Brandeis' principle: "The final end of the state is to enable men to develop their faculties."

The best indicator that an area of endeavor is of a beneficially mind-stretching character is that it attracts bright young people to work in it. This attraction certainly exists in the aspects of geophysics related to this report — for example, the ferment in fluid dynamics — and is evidenced by the youth of several contributors to this report. More conventional indicators are the subject areas of invited reviews at scientific meetings and the recommendations of advisory committees. Recent meetings of the most relevant scientific society, the American Geophysical Union, have been largely dominated by discussions of plate tectonics and related matters. Of the various National Academy of Sciences studies pertinent to this report, those on planetary exploration are most motivated by scientific interest rather than by application. These studies persistently state that understanding the earth is one of the three major goals of planetary exploration.[2] The members of these study groups also manifest their belief that the earth is more interesting by the fact that the great majority of their papers are on earth-related topics.

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[2] See, e.g., National Academy of Sciences, "Planetary Exploration 1968-1975," Space Science Board Report, Washington, D.C., 1968.

It is therefore somewhat ironic that we now have much letter geologic photography and determination of the gravity field for half the moon than we have for most of the earth.

Most of the social benefits stated here are somewhat distant. They are difficult to state in terms of economic value or to schedule, because they depend mainly on increased understanding of the environment. But there is no doubt that they are important, and the fact that they depend on the unschedulable achievement of understanding makes it more, rather than less, urgent to attack the pertinent problems.

7.2 GOALS

In accord with these criteria, we can briefly state certain improvements in understanding or capability as scientific goals toward which recommended programs should be directed. These goals we place in a rough order of priority:

1. The long-term dynamics of the solid earth: to identify the driving forces and response mechanisms that account for the plate motions, earthquakes, the variations of the gravitational field, and the tectonics observed by the geologist.

2. The general circulation of the oceans: to account for the observed currents, temperature, salinity, etc.; to infer the necessary return flows; and to furnish inputs to numerical weather prediction.

3. Earthquake mechanism: to improve understanding of how earthquakes occur and hence to improve the protection against damaging earthquakes and tsunamis.

4. Currents and heat transport: to improve knowledge and understanding of the global heat balance and hence, to some extent, of air-sea interaction.

5. The geomagnetic dynamo: to identify the energy source and mechanisms of interaction in the core and hence to account for the patterns of the internal magnetic field and the variations in core-mantle coupling.

6. Energy dissipation in the oceans: to define the locations and mechanisms of energy dissipation and thus to help explain such phenomena as the damping of the Chandler wobble, the ocean-tide pattern, and the evolution of the earth-moon system.

7. The rotational dynamics of the earth: to explain the entire complex of excitation mechanisms, rheology, resonances, damping, etc. associated with the spectrum of variations in the rotation rate and wobble of the rotation axis.

Of these goals, the first four can clearly be related to the material-resource and environmental-quality aspects of the social benefits. But all the goals, by being challenging scientific problems, contribute to man's ability to cope with practical problems.

7.3 RECOMMENDATIONS

The recommendations are arranged in two categories: "immediate" and "eventual." The immediate recommendations are proposals for which fabrication of the necessary instrumentation could be undertaken now, provided funds were available. Possibly some could be applied on the planned GEOS-C. The eventual recommendations are proposals that appear technically feasible but require appreciable development to attain the desired accuracies, resolutions, or lifetimes. The placement of a recommendation in the eventual catagory must not be construed as lower priority than immediate.

Within each category, the recommendations are arranged in priority of decision elements, i.e., major funding entities. Following each decision element, supplemental recommendations are given for actions that should be undertaken for optimum use of the major project.

7.3.1 Immediate Recommendations

I.1. Satellite-borne radar altimeter: ±1-m accuracy, 10-sec intervals, 1-yr lifetime; circular orbit, not sun- or moon-commensurate, preferably high inclination.

The radar altimeter at the accuracy estimated by the instrumentation panel as immediately attainable would provide a wealth of new information about the fixed gravitational field, tidal variations, storm surges, etc., as well as a start toward the ±10-cm system desired for the ocean-circulation problem.

The inclination should be given further study: germane are the desirability of having a low inclination for conventional orbit-perturbation analysis, the possibility that France or Italy will launch a low-inclination satellite, and the availability of the TRANET doppler tracking network to give adequate coverage of a high-inclination orbit.

Supplemental research supporting the radar-altimeter prime system should be the establishment of test areas of two types, one gravitationally and oceanographically "noisy," such as the Caribbean, and one "quiet," such as the Saragossa Sea. Both types should have an abundance of surface gravimetry.

I.2 Close-satellite-to-distant-satellite range-rate tracking: ±1-mm/sec accuracy, 10-sec smoothing time; circular orbit, 350-km or lower altitude, high inclination for the close satellite.

The tracking of a very close earth satellite from a point distant enough to obtain continuous coverage would yield a wealth of additional detail of the earth's gravitational field even at the ±1-mm/sec level, in a manner analogous to the determination of the moon's gravitational field from lunar-orbiter tracking. The ±1-mm/sec accuracy would push the resolution of variations in the gravitational field to about 250-km half-wavelength.

It is desirable, of course, that this very close satellite also be the satellite that carries the radar altimeter. Whether it can be depends on consideration of satellite lifetime, accuracy of orbit determination, etc. as discussed in Section 2. 3.

The obvious choice for the high satellite orbit is geosynchronous; however, a single such satellite would yield only one-direction coverage of half the world. Supplementary study should be given to the use of other altitudes so as to obtain a variety of directions and to avoid distortion of forms in the rotation and wobble spectra by satellite-orbit errors. The optimum system might entail three distant satellites at 120°-longitude intervals, occasionally shifted about 30° or 60°.

Supplemental supporting research should be the development of orbit-determination techniques for both the close and the distant satellites. This work will entail considerable computer requirements. In addition, there should be research on the generalization of Stokes' theorem: the inference of a potential field from accelerations in a variety of directions.

I. 1-2. Supplemental research exploiting the data generated by both the radar-altimeter and the satellite-to-satellite tracking systems should range from the descriptive extreme of the systematic relation of the resulting gravity data to the available geology, seismic velocities, etc. to the analytic extreme of convective models of the mantle. The latter area of investigation has now reached the stage where large-scale numerical integrations of convective models, similar to those for the ocean and atmosphere, are worthwhile. The scale of the work could easily exceed $1 million/yr. Another area of research pertinent to the problem is creep experiments with silicates at high temperature and pressure.

I. 3. Improved navigation at sea.

1. For ship-borne gravimetry, current, and internal wave measurement, velocity accuracies on the order of 5 cm/sec with averaging times of several minutes would be desirable. Means of attaining these accuracies, as well as position to 100 m or better, by economical tracking systems, increased fixing frequency, and improved transit orbit definitive ephemerides should be investigated.

2. For large numbers of inexpensive floats, position accuracies of ±2 km at intervals of about 5 days need to be developed to obtain better knowledge of current patterns and diffusion rates.

I. 4. Laser ranging to the moon or a distant artificial satellite: ±15-cm accuracy.

The laser ranging system is one of two techniques that show promise of measuring changes in the earth to a centimeter-per-year resolution to verify the inferences of the plate-tectonic theory and to monitor more accurately the polar wobble and rotation. The initial system should include stations in the stable portions of at least three of the major plates: for example, the Canadian Shield, Hawaii, and Australia. The number of additional stations that could be effectively employed at the stated accuracy level is related to the likely number of tectonic plates, which is now estimated to be 20 or more.

Supplemental supporting research required for the laser ranging system is the selection of the optimum satellite. The moon may introduce too many irregularities of its own; a geosynchronous satellite may have errors that would alias the longer periodic motion of the pole. The ongoing program of laser tracking of close satellites by the SAO and other agencies should be carried out for the purposes of developing techniques and organizational capability toward the above-stated system.

I. 5. Very Long-Baseline Interferometry: ±15-cm accuracy.

About the same considerations apply to the siting of VLBI antennas as to the laser ranging. Ideally, the two systems are complementary since they use different parts of the electromagnetic spectrum and observe different components of position. The laser ranging has the advantage of less susceptibility to tropospheric refraction, and the VLBI, of observing capability in cloudy weather and reference to an inertial coordinate system. The increased confidence in results obtained by the combined systems would be well worth the extra expense.

I. 4 & 5. Supplemental research exploiting the data generated by both laser ranging and VLBI should include:

1. observations to determine deformation and rupture along fault zones, as well as around the ranging and VLBI sites;

2. theory and data analysis of earthquake mechanism, including its effect on the Chandler wobble;

3. investigation of core-mantle coupling and of the geomagnetic dynamo;

4. definition of, and relations between, fundamental reference systems;

5. connection of the laser/VLBI to conventional geodetic control, satellite as well as terrestrial.

NASA's support of research in these areas should take into account the considerable work already being carried out by other government agencies, particularly ESSA and USGS, and by universities, with NSF or DoD support.

I. 6. Drag-free satellite: circular orbit, 250-km altitude, 2-yr lifetime.

With a close satellite tracked by a higher satellite, the drag-free instrumentation will be effective in 1) perpetuating the lifetime for the determination of the higher degree variations in the gravitational field, and 2) enabling the detection of the long-periodic perturbations arising from tidal effects. The latter will be a valuable independent check on tidal inferences from the radar altimeter. For both detection of tidal perturbations and verification of radar altimetry, it would also be of value to have a subsequent satellite at an intermediate inclination, say 45°. To maintain the orbit over 2 yr at 250-km altitudes, an ion engine exerting a force on the order of 3000 dynes is required.

Supporting research to exploit the drag-free satellite in tidal theory and tidal perturbations of orbits is appropriate.

Other proposals in the immediate category are as follows.

I. Satellite communication of geophysical data. The use of satellites to transmit data generated by geophysical instruments on the surface falls into two distinct classes:

a. seismic and tidal stations of the tsunami warning net, which may utilize override capability to transmit data rapidly. There are about 50 such stations; the override would need to operate only a few times per year with a maximum load of about 2500 bits per station.

b. remote stations (manned or unmanned), the most prominent of which are the floats and buoys for oceanographic purposes, such as have been recommended for study of current systems. However, there is also the prospect that seismological networks and other land stations could be used more effectively if data were transmitted with allowable delays on the order of a few days or weeks. Whether satellite facilities would be appropriate should be the subject of a systems analysis based mainly on economic considerations.

I. High-resolution photography for geologic purposes. A global coverage of photography with better than 500-m resolution would be a boon to analyses of tectonic patterns (this would be complementary to the measurement of motions recommended in this report) as well as to other geologic research. Because of the dependence on judgment regarding cloud conditions and the desirability of returning film, this type of photography is an obvious application of the manned satellite.

I. Satellite-borne magnetometry: ±0.1 gamma, 350-km or lower altitude, polar orbit. Systematic global coverage with accuracy of ±0.1 gamma would be useful to resolve the higher harmonics of the geomagnetic field more accurately and hence to obtain a more accurate representation of the flow pattern in the core for dynamo theories. Analysis of temporal variations would yield better determinations of the electrical conductivity of the mantle, desirable for both core-mantle coupling and thermal regime studies. The need for extreme accuracy in altitude (±10 m) to exploit ±0.1 gamma makes it desirable to incorporate such a magnetometer on the same close satellite as the radar altimeter and satellite-to-satellite tracking.

I. Satellite photogrammetry. The recommendations of the National Academy of Sciences for cartographic satellites centered on the 12-in. photogrammetric camera[3] are endorsed for the scientific value of global topographic mapping and monitoring of fault zones, as well as for the economic justification.

I. Satellite-borne infrared detection of small intense sources. Consideration should be given to the use of such a system for monitoring volcanoes.

7.3.2 Eventual Recommendations

E.1. Satellite-borne radar altimeter: ±10-cm accuracy, 1- to 5-sec intervals, 2-yr lifetime; circular orbit, not sun- or moon-commensurate, predominantly polar inclination, occasional intermediate inclination.

The development of altimeters to an accuracy such that they can be applied to the problem of the general circulation of the oceans requires a great amount of supplementary supporting research, which should be started as soon as practicable:

1. the mathematical theory of the determination of the geopotential from satellite range-rates in a variety of directions;

2. gravity sensors necessary to determine the gravity field accurately enough to attain the ±10-cm resolution; satellite-borne gradiometers or ship-borne gravimetry;

3. statistical analyses of the gains in accuracy attainable by use of area means; the effects of interruption of the altimetry record by land, etc.;

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[3] National Academy of Sciences, "Useful Applications of Earth-Oriented Satellites," 13: Geodesy-Cartography, Washington, D. C., 1969.

4. theoretical and experimental efforts in precise return analysis, taking into account the nature of the wave surface, with emphasis on its effect on mean-sea-level definition;

5. research and development in atmospheric refraction effects on the radar signal, including use of the infrared soundings by meteorological satellites.

E.2. Close-satellite-to-distant-satellite range and range-rate tracking: ±10-cm and ±0.05-mm/sec accuracy, 5-sec smoothing time; circular orbit, preferably about 200-km altitude, predominantly polar inclination for the close satellite, occasional intermediate inclination.

Pushing to the limit of technological capability in range-rate would permit determination of the variations of the gravitational field down to a half-wavelength of about 100 km and would provide the potential at the satellite with ample accuracy for downward continuation to the sea surface.

E.3. Laser ranging and VLBI: ±2-cm accuracy.

The attainment of ±2-cm accuracy of position would permit the generation of a time history of tectonic plate motion, i.e., the extent to which the plates move continuously or intermittently. It would also enable measurements of the amount of differential movement that occurs within a plate.

Supplementary research required to attain these accuracies includes improvements in timing stability and transfer and in the determination of atmospheric refraction through multiple-wavelength or radiometric techniques.

Other proposals in the eventual category are as follows.

E. Economical ground beacons or transponders: accuracy ±1 m. Unmanned transmitters or transponders that could be left untended and to which range could be measured upon interrogation by a satellite within ±1 m (or ±1-mm/sec range-rate) would be very valuable for a wide variety of uses such as geophysical surveys and mapping, if a cost per unit of about $10,000 could be attained.

E. Satellite star telescope: ±0."01 catalog positions. The attainment of the accurate determination of an inertial reference system appears feasible by means of optical satellite-astronomy techniques.

Supplementary research required would be the relation of this optical reference system to the radio sources used by the VLBI system.

E. Apollo ship ulitization for marine geodesy. The adaptation of the Apollo tracking ships to obtain accurate recoverable positions at sea should be studied.

E. VLBI navigation. Consideration should be given to using very long-baseline radio-interferometry for ship navigation. It is estimated that 2- to 4-ft shipboard antennas would be required.

The decision elements that appear in the recommendations obviously contain groupings that could utilize the same satellites and ground-station complexes. Some consideration of such a combination is undertaken in the chapter on instrumentation. However, it was felt that for the purpose of priority-ordered recommendations, it was better to make the basic unit the decision element: the minimum block of research, development, and fabrication that should be undertaken in connection with the realization of a particular measurement capability.

A question on which it is difficult to give advice is the relative priority of funding between immediate and eventual decision elements. The answer depends heavily on the program level, discussed in the next section. The optimum scale is one in which the increase in accuracy and detail of data keeps step with the improvement in theoretical understanding. At such an optimum level, a fair percentage of the effort — say 10 to 30% — would be devoted to the instrumentation development needed to attain the eventual next stage.

7.4 ALTERNATIVE PROGRAM LEVELS

As noted in Chapter 1, a program addressed to problems of the earth might be implemented at various levels of activity. To examine the implications of this option on the recommended program for solid-earth and ocean physics, three program levels can be considered.

Program A assumes that the main thrust of the national space effort will now be turned toward the earth. In bringing Apollo to its spectacular fulfillment, NASA has developed organizational structures suitable for attacking the problems of the earth's environment and resources. Within this effort, there should be a program dedicated to solid-earth and ocean physics. The philosophy of Program A would match that applied to Apollo in the sense that sufficient effort would be marshalled and committed to ensure a safe and pleasant environment and adequate development of resources well into the next century. A necessary complement to such a program would be a major increase in the efforts of other Federal oceanographic, meteorological, and earth-science agencies. The scope of this effort would be truly global and would require a greatly increased level of international collaboration.

Program B assumes that earth observations and applications will now be one of the four or five major goals of the space effort. Hence, there would be an appreciable increase in the program level, reflecting the rising informed concern in society about the terrestrial environment and resources. Such a program would also be commensurate with the increase of interest in the earth as an object of scientific study. While the program would include some global aspects (similar to GARP*), the scope of the effort would necessarily entail concentration on certain problems of national interest or scientific fruitfulness, such as the Gulf Stream ocean system or the Americas-Pacific tectonic-plate interaction.

Program C assumes continuation of the current level of effort. Some new techniques and ideas of application to solid-earth and ocean physics would eventually evolve.

Implementation at the level of Program A clearly requires the accomplishment of both immediate and eventual recommendations in Section 7. 3 within the next few years. There would necessarily be undertaken an ongoing observational program to improve our understanding of the earth's behavior in order to utilize most effectively the more accurate eventual systems, which would concurrently be under development. The aim within a 5- to 8-yr time frame would be an integrated system comprising a large number of instrumentation sites on the land; close satellites in both polar and intermediate orbits; distant satellites in orbits optimized for both spectral resolution and coverage; oceanographic ships; and instrumented buoys, both free and fixed.

The density of ground instrumentation sites (radio interferometers, lasers, etc.) for Program A should provide for three to five sites per lithospheric plate, depending on the size of the plate. The exact locations of these sites would depend on considerable study involving collaboration with seismologists, structural geologists, etc. in order to use to the best advantage the data in conjunction with those obtained by seismometers and other ground sensors. Each site would be equipped with auxiliary instrumentation to monitor both solid-earth oscillations (e.g., tidal gravity meters) and atmospheric effects on propagation (e.g., radiosonde). Each site would be connected to regional geodetic and geophysical ground surveys, whose extent and frequency of resurvey would depend on the tectonic character of the area.

*Global Atmospheric Research Program.

The close satellites should be in circular orbits at as low an altitude as possible for the ion-engine technology to achieve drag-free behavior. All would carry altimeters and satellite-to-satellite tracking, of course, plus possibly temperature sensors. Most of the close satellites should be in polar orbits, but at least one should be at an intermediate inclination. The exact periods and distribution in inclination should optimize determination of the spectrum of temporal variations in the earth's mass distribution and ocean heights.

The distant satellites would serve the dual purpose of transponders for the precise ground instrumentation and trackers of the close satellites. They could also serve as communication links and may, in an ultimate phase, furnish a reference coordinate system by interobservation. The numbers and orbits of the distant satellites should be such as to furnish sufficiently frequent targets at adequate elevation for the ground instrumentation and to maintain almost continuous coverage of the close satellites. Whether or not the distant satellites could be in commensurate orbits (primarily with the earth's rotation, but also with the solar and lunar motions) depends on how terms in the spectrum of the earth's rotation and wobble might be aliased.

The oceanographic ships would use the satellite systems for the position and velocity they require. They would also contribute to the integrated system by making the surface measurements necessary to utilize the satellite altimetry effectively. The full extent of interaction between ships and satellites would require considerable collaboration between NASA and the expanded oceanographic agency that would be a necessary concomitant of a Program A.

The number of instrumented buoys in a Program A effort would be such as to constitute a considerable communication and tracking burden on the satellites. In deciding on orbit specifications, the requirements to obtain positions of free buoys should also be taken into account, of course.

As mentioned in Section 7.3, the undertaking of any of the recommended improvements in measuring capability logically entails appreciable supporting research of a theoretical as well as an experimental sort. Furthermore, attention should be paid to the most effective utilization of existing programs directed to the same purposes, such as the photozenith-tube monitoring of the earth's rotation.

Implementation at the level of Program B would entail a stretch-out in the time of attainment of the recommended technical capabilities, a reduction in the geographic extent of surface facilities, and possibly a reduction in the number of satellites in the eventual system. However, as mentioned in Chapter 1, the attainment of all the leading recommendations except the first and third by 1975 seems quite reasonable. The use of this capability with the addition of the precise ground instrumentation at some already existing NASA tracking sites, two or three high-inclination close satellites, and geosynchronous satellites already planned for other purposes would result in a significant increase of information for solid-earth studies. A part of such a program could also be the capability of obtaining the low-accuracy positions required for free buoys. The more accurate ship navigation probably would be best obtained by better use of the TRANSIT system.

Attainment of the eventual recommendations at the Program B level would probably require increases in the budget to the level of several $10 million/yr by the late 1970s in order to obtain the more accurate instrumentation, the optimized distant satellites, and the more extensive deployment of surface instrumentation necessary to accomplish the suggested studies in the north Pacific-America-Atlantic area.

Important to the maximum benefit attainable at the Program B level would be the fostering of international participation.

For the foreseeable future, implementation at the level of Program C would have to be limited to the immediate recommendations in Section 7.3. These immediate systems would even enable some economy in closing down overseas tracking stations. However, the frequency of satellite flights would be too low to encourage participation by good young scientists, and the utilization of the space and astronomic space capabilities would lag behind the rate of evolution of other aspects of solid-earth and ocean physics.

7.5 FINAL REMARKS

The planning exercise that produced this report was stimulating; it is impressive how many new ideas about apparently obvious matters occur during a few days' intensive discussion. However, a less intensive and more continuous participation in planning probably would be more effective in the long run. There is also needed a greater interaction with the other earth-oriented scientific uses of satellites, the meteorology and earth-resources survey programs. In order to preserve the momentum of this program initiated by the dialogue among scientists, engineers, and management at the Summer Seminar, it is recommended that NASA consider the establishment of a permanent, formal working committee. An Earth Missions Board, patterned after the Lunar & Planetary and Astronomy Mission Boards, could serve this purpose by setting long-range objectives and assessing priorities within the discipline as well as relative to others. Its scope should encompass all the earth-oriented scientific uses of satellites: the meteorology, earth-resources survey, and solid-earth and ocean physics programs.

At the exponentially increasing rate at which we are plundering the earth of its resources and befouling the environment in which we live, it is extremely difficult to predict what life will be like in the 21st century. However, there are a few things of which we can be absolutely sure:

1. The planet earth is the only home for the human race for at least several centuries to come.

2. If the quality of life is not to decline drastically within 100 yr, then we must either limit the population or attain a much more thorough understanding of this earth on which we must live. It is imperative for us to understand the circulation system of the oceans, on which we will depend much more for our food, and the processes in the formation of the earth crust, from which we tear the materials to build our evermore complex technology.

3. The attainment of this improved understanding will be a long and difficult task, with some trends we can now predict, but also with many twists and turns we cannot foresee. But we do know that we now have at hand several tools to help mightily in this task: an increasingly accurate and elaborate technology, a ferment of exciting ideas in several related areas of geophysical research that are attracting brilliant young people, and a management capability in NASA that could well be turned to matters of social benefit.

It is difficult to see why anyone who cares two cents about his own great-grandchildren (let alone the rest of the world) does not agree we should get on with the job now.

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Panel on Oceanography

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Panel on Short-Term Dynamics of the Earth

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Panel on Long-Term Dynamics of the Earth

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