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44. This research was supported by NASA grant NGL05-002-069. I thank E. Stolper, A. E. Ringwood, P. Wyllie, A. Boettcher, G. J. Wasserburg, C. Allègre, S. Jacobson, L. Silver, H. Taylor, and D. Green for helpful conversations. R. Oxburgh, J. G. Schilling, P. Wyllie, and G. Ernst reviewed earlier versions of the manuscript. A. Boettcher kindly provided a most useful preprint coauthored with J. O'Neil and made some important suggestions. I thank an anonymous reviewer for his editorial comments. Contribution No. 3432, Division of Geological and Planetary Sciences, California Institute of Technology.

Application of Space Technology to Geodynamics

Edward A. Flinn

Despite the rapid progress achieved within the last decade, there are many important questions in geodynamics that we cannot yet answer. For example, How are the plates moving at the present time? Is the movement smooth or jerky? How do the local movements caused by earthquakes at active plate boundaries contribute to the gross movement of the plates? How do the plates deform in response to the driving forces? How is strain distributed near active plate margins, and how does the strain change with time? What relationship, if any, is there between variations in polar motion and other geodynamical phenomena such as great earthquakes? What is the rheology of the lithosphere and the asthenosphere? Are large-scale vertical movements taking place at the present time?

What these questions have in common is that progress in finding their answers depends, at least to some extent, on measuring the relative position and movement of points on the earth's surface, over distances ranging from a few kilometers to many thousands of kilometers. An accuracy of at least 2 to 3 centimeters is required because of our desire to measure average plate movements (a few centimeters per year) within a reasonable time and because of the necessity to detect episodic changes in motion.

There are several reasons why classical ground-based geodetic surveying methods—leveling and trilateration—are impractical for making frequent measurements of station position over distances greater than about 100 km (these methods, of course, cannot be used at all over the oceans). The major reason is that ground surveys must be made in a sequence of line-of-sight measurements between points up to a few tens of kilometers apart, and the resulting accumulation of random (and possibly systematic) errors soon brings the uncertainty in position above the required level of a few centimeters. The best trilateration measurement is good to about three parts in 10^7, an error that exceeds 3 cm beyond about 100 km; the best leveling measurement accumulates random error at the rate of about 1 millimeter multiplied by the square root of the length of traverse

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0036-8075/81/0703-0089$01.50/0

in kilometers, that is, about 3 cm in 100 km, although systematic errors can be larger (*1*). Another problem of ground surveys is that they are time-consuming, particularly for leveling, and can be compromised in active areas by motion actually taking place during the survey. A third problem is that the cost of monitoring vertical movements by leveling two to three times per year, in even a few tectonically active areas, is prohibitive (*2*).

Summary. Measurements of the movement and deformation of tectonic plates are needed for many research areas in geodynamics, but observations with adequate accuracy and frequency of measurement are not feasible if classical geodetic methods are used. Long-baseline microwave interferometry and laser ranging to Earth satellites are among the new techniques that have been developed within the past decade to make the required measurements. Fixed and mobile stations using both these methods have been constructed in several countries and are now being used in an internationally coordinated research program. Baseline length accuracy better than 2 to 3 centimeters (1 standard deviation) is expected within the next 5 years.

A possible observable effect of large-scale tectonic activity is in the motion of the polar axis of the earth. The classical astronomical methods of measuring polar motion and rotation of the earth appear to have an accuracy of about 0.5 to 1 meter in pole position and a few milliseconds in time. Theoretical estimates of the change in polar motion due to a large earthquake suggest that this accuracy must be improved by over an order of magnitude (that is, to a few centimeters) if we are to be able to study possible relationships between these global parameters and other geodynamical phenomena (*3*). It is also necessary to have measurements at intervals of 1 or 2 days, rather than the 5-day averages of pole position reported at present by the Bureau International de l'Heure.

Space technology has been used in geodesy and geophysics in various ways for many years, for example, in satellite geodesy. Only in the past decade has it become possible to develop methods of meeting the geodynamical needs described above. This development has taken place at various rates in many countries, for example, in the Netherlands, West Germany, Japan, the United States, and the U.S.S.R. In the United States the major part of this developmental work has been sponsored by the National Aeronautics and Space Administration (NASA) in its Geodynamics Program.

There are two principal space techniques: laser ranging to satellites and microwave interferometry. The rest of this article is devoted to a description of these methods and plans for using them for geodynamical research and geodetic operations. In these space-related systems, the concepts are simple but practical realization is very difficult. To measure position to an accuracy of 2 or 3 cm over distances of hundreds of kilometers or more requires a high level of technical sophistication both in the hardware to make the measurements and in computer modeling to interpret the results. The hardware required includes accurate sources of time and frequency, short-pulse lasers, and wide-band recording systems. The effects that must be modeled with extreme care include the earth's gravity field, tides, ocean loading, and the effects of the earth's precession, nutation, and diurnal rotation, as well as both special and general relativity. The cost of the required technology development is justified on the grounds of the practical and scientific importance of the information obtainable by space methods and because we are unable to make these measurements by other methods. In contrast to the development costs, the operational costs of the new equipment are moderate and, particularly in the case of frequently repeated precise vertical position measurements of traverse lengths greater than a few kilometers, considerably less than would be required if conventional methods were used.

In addition to the systems described above, other space technology systems are being used today in geodesy and geodynamics, for example, in detailed-mapping of the earth's gravity and magnetic fields. The Magnetic Field Satellite (Magsat), launched by NASA in October 1979, successfully measured the geomagnetic field with a scalar magnetometer that has a total-field accuracy of about 3 gamma and a three-axis vector magnetometer with an accuracy of about 6 gamma in each component. Our knowledge of the earth's gravity field has improved enormously since the advent of satellite geodesy nearly two decades ago. Satellite laser ranging and radar altimetry from GEOS-3 have made it possible to construct gravity field representation complete to harmonic degree and order 36. NASA is now studying a dedicated gravity field–mapping satellite (Gravsat) to determine the gravity field with an accuracy of several milligals and a resolution of about 100 km, roughly equivalent to a geoid accuracy of 10 cm for this resolution (*4*).

Laser Ranging

In laser ranging, a short pulse of light is fired from a laser on the ground and reflected back from cube corner retroreflectors mounted on an earth-orbiting satellite. The time of flight is measured, and, since the orbits of the satellites used for this purpose are accurately known, the laser position can be determined (in geocentric coordinates) by measurements made when the satellite is in different parts of the sky, as seen from the laser station.

Lunar laser ranging. The principal use of lunar laser ranging for terrestrial geodynamics is to provide information on long-term changes in the polar motion and rotation rate of the earth. Lunar laser ranging began with the Apollo lunar laser retroreflector experiment. Retroreflectors were placed on the moon by astronauts of the Apollo 11, 14, and 15 missions and by the unmanned Soviet Luna 17 and 21 missions (*5*). The objectives of the Apollo lunar laser ranging experiment were to study relativity, the lunar orbit, lunar dynamics and structure, and terrestrial geodesy; important scientific results have been obtained in several of these areas (*6*). The first lunar laser ranging was accomplished shortly after the landing of Apollo 11, and ranging has been done routinely at the McDonald Observatory of the University of Texas at Austin from 1969 to the present. The mean range accuracy of the McDonald Observatory system over the last 10 years is about 12 cm (*7*).

McDonald Observatory is the only operational lunar ranging station in the world at present, although several other stations have ranged to the moon successfully. The station at Orroral Valley (near Canberra), operated by the Australian Division of National Mapping, is getting returns regularly and should be fully operational in 1981. A laser station at Wettzell, West Germany, is also expected to be operational for lunar ranging in 1981. Lunar laser ranging stations are under development at Dodaira, Japan; Haleakala, Maui, Hawaii; Grasse, France; and the Crimean Astrophysical Observatory, U.S.S.R.

Satellite laser ranging. The geodynamical objectives of satellite laser ranging are to provide information on polar motion, to establish baselines for the determination of plate movement and deformation, to study the earth's gravity field, and to determine precise satellite orbits. Laser ranging to man-made satellites has been done routinely since the middle 1960's with about a dozen satellites equipped with cube corner retroreflectors. Research on the earth's gravity field and on crustal movements was carried out with relatively low altitude satellites until the launch of Lageos into a 5900-km orbit in 1976. Lageos is the principal NASA satellite used for geodynamics; it is a dense passive sphere covered with retroreflectors which should remain in orbit for at least 8 million years.

At present, there are about two dozen laser ranging observatories around the world, with more being constructed or planned. The range accuracy of these stations varies from about 3 cm to about 1 m. NASA operates a fixed laser at Goddard Space Flight Center (GSFC), Greenbelt, Maryland. Its range accuracy is about 3 cm. The Smithsonian Astrophysical Observatory (SAO) operates observatories at Natal, Brazil; Orroral Valley, Australia; and Arequipa, Peru; with a range accuracy to Lageos of 10 to 20 cm. The Institut für Angewandte Geodäsie operates a laser ranging station at Wettzell, West Germany, whose accuracy is about 3 cm; this station should also begin lunar laser ranging in 1981. The Delft University of Technology operates a laser station at Kootwijk, the Netherlands, with a current range accuracy of about 10 cm. The only other high-accuracy laser station now in operation is that of the Groupe de Recherches de Geodesie Spatiale at Grasse, France, with a range accuracy of about 30 cm.

NASA operates eight Mobile Laser stations (Moblas), each consisting of a 76-cm telescope, laser, and surveillance radar. These stations, which were originally designed for precision orbit determination of Seasat-A as well as for geodynamic purposes, are moved from location to location; in 1980, laser data were acquired at GSFC; Owens Valley Radio Observatory, California; the Goldstone Deep Space Network Station, California; Maui, Hawaii; Kwajalein Island; American Samoa; Geraldton, Western Australia; Haystack Observatory, Massachusetts; and Fort Davis, Texas. In 1981, three of these stations will be located at GSFC for upgrading; the other Moblas stations will acquire data at Maui; Geraldton; Boulder, Colorado; and Quincy and Monument Peak, California. The latter three site occupations will be supporting observations of crustal deformation in the western United States. Several experiments were conducted at the 1980 site occupations: a validation and intercomparison experiment between laser ranging and very-long-baseline interferometry (VLBI) methods; plate motion measurements between North America, Australia, and sites on the Pacific plate; and plate stability measurements for these plates (*8*).

The present range accuracy of three of the Moblas units is about 5 cm, and that of the other Moblas units is about 10 cm. A program of upgrading the other five Moblas units to an accuracy of at least 5 cm is under way and should be completed in 1981. Plans are also being considered for upgrading three of the Moblas units to accuracy of 1 to 2 cm in 1982 to 1983.

Several weeks are required to move and set up the Moblas stations at new sites. A much more highly mobile Transportable Laser Ranging Station (TLRS-1) has been constructed by the Department of Astronomy of the University of Texas at Austin (*9*) and is now in operation in southern California. This station is mounted in one self-contained truck, and only 2 hours are required to dismantle or set up at another site. The design range accuracy of the TLRS-1 is 3 cm or bet-

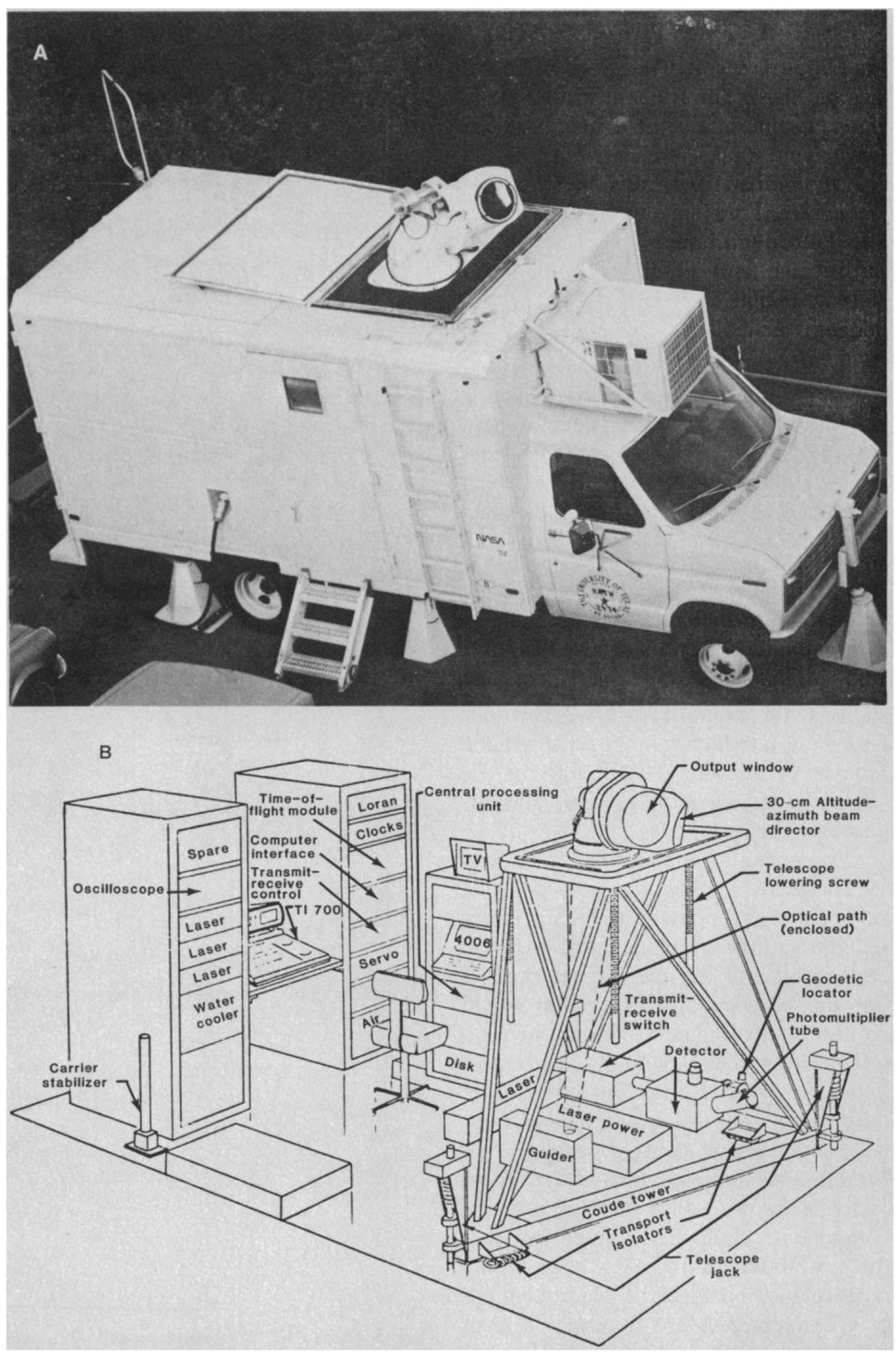


Fig. 1. (A) Transportable laser ranging station, with telescope beam director deployed for ranging. (B) Block diagram of the TLRS interior. [Photograph courtesy of McDonald Observatory, University of Texas, Austin]

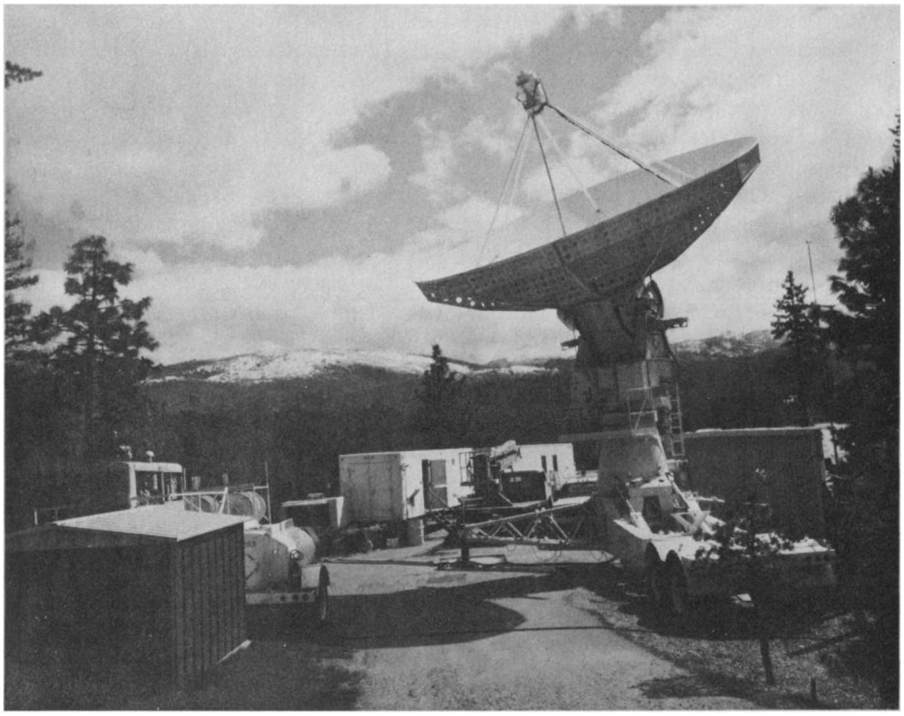


Fig. 2. The 9-m mobile VLBI station (ARIES-1) in operation at Quincy, California, May 1979. [Courtesy of the Jet Propulsion Laboratory, Pasadena]

ter. Figure 1 shows the TLRS-1 and a block diagram of its interior.

A compact, modularized laser ranging station (TLRS-2) is under development at GSFC, and an independently designed, highly mobile station is being developed by the Institut für Angewandte Geodäsie and the Delft University of Technology.

In order to achieve the accuracy goal of 2 to 3 cm, it is necessary to use the highly precise laser stations in pairs to measure relative position. The TLRS stations, for example, will work with a base station (which may be an upgraded Moblas or another TLRS unit) in the same way as the mobile VLBI stations described below.

Spaceborne laser ranging. In 1976 to 1977, NASA studied the possibility of reversing the position of lasers and retroreflectors, that is, placing the laser in earth orbit and the passive retroreflectors on the ground. This system would be useful for rapid surveying of the relative position of sites within a few tens of kilometers of each other but spread over fairly large areas (for example, a tectonically active region such as southern California). The studies indicated that accuracies of the order of 2 cm in all position components could be attained but that the system would be cost-effective only if the relative positions of a large number of ground targets are determined over short periods ("snapshots") a number of times per year in many parts of the world (*10*). These studies were completed in 1980. Further work is awaiting the outcome of studies and prototype development of the Global Positioning System–based radio systems described below, and a decision has not been made on which system, if any, should be further developed for geodetic use (*11*).

Very-Long-Baseline Interferometry

The second basic method of space geodynamics is based on microwave radio interferometry. The idea is straightforward: two radio antennas simultaneously receive radio noise from a distant extraterrestrial radio source. By cross-correlating the output of the two antennas, the time difference between the arrival of the signals at the two stations, and the rate of change of that difference, can be determined. By observing a number of sources repeatedly throughout a day and by combining the resulting measurements in a least-squares adjustment, the vector baseline

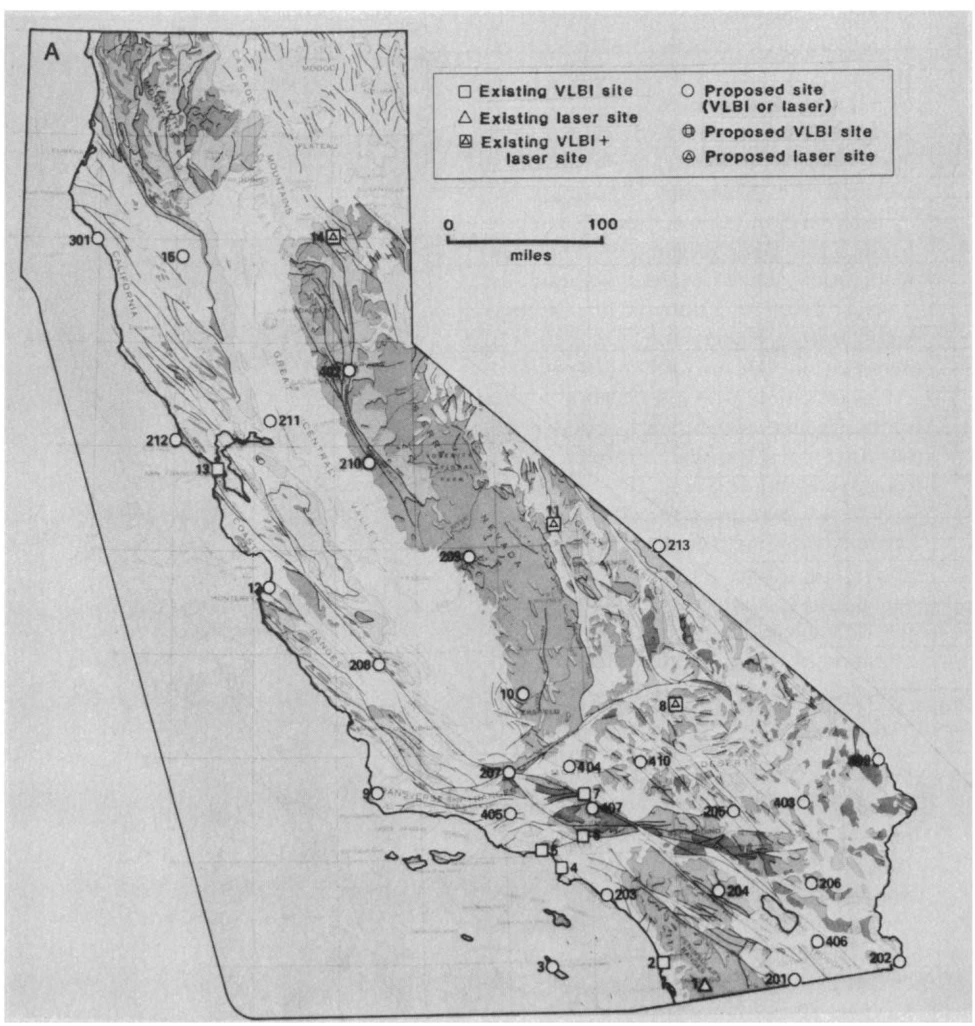
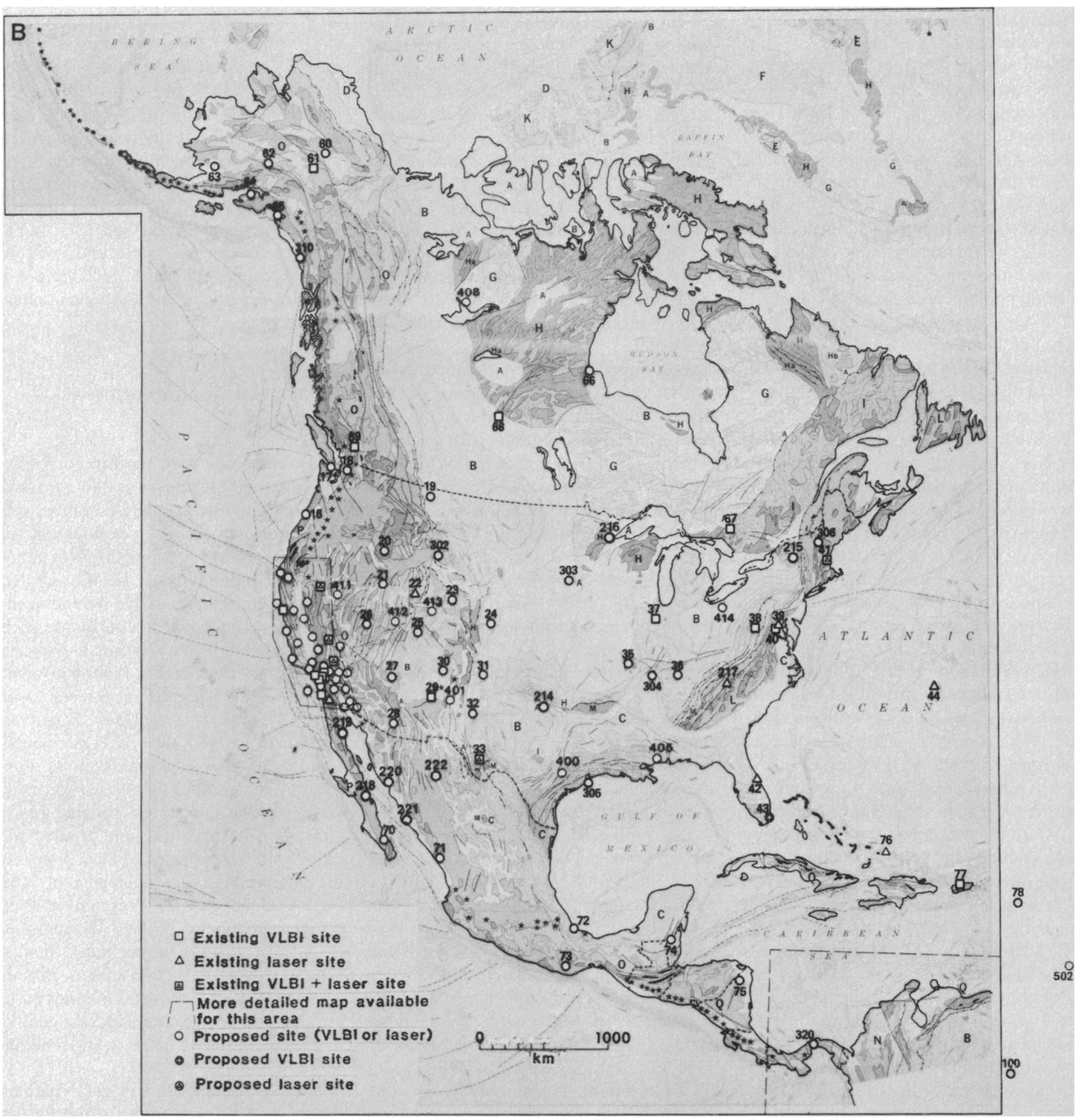


Fig. 3. (A) VLBI observatories and sites planned for mobile VLBI and laser station occupation in California. (B) Observatories and mobile station sites in North America (*24*). Notation used in the figure is explained in (*24*).

between the observing sites can be recovered. The measurements are also sensitive to the positions of the radio sources, the orientation of the earth in an inertial reference system, and the movements of the crust caused by earth tides and ocean loading. Model parameters for these effects are recovered in the least-squares adjustment along with the baseline parameters. The observations are influenced by the earth's ionosphere and troposphere, which affect the speed of the signals through those parts of the atmosphere. These effects can be removed by calibration based on instruments at the observing sites. Thus far, all radio sources used in geodetic microwave interferometry have been extragalactic sources, usually quasi-stellar objects, which have negligible proper motion. Except for source structure effects, which are very small but which can be modeled, these sources may be considered to be fixed points in inertial space.

Historically, radio interferometry was developed by radio astronomers using antennas separated by distances of a few hundred meters to a few tens of kilometers. The signals received at one antenna could be sent to the other by means of a relatively simple communications link, and the cross-correlation information could be generated in real time with no recording required. In geodetic applications, however, the observing sites may be separated by hundreds to thousands of kilometers, and until recently there has been no economically feasible way to transmit the signals received at one site to the other. Instead, the technique of VLBI is used, in which the stations have independent clocks; the signals are independently recorded on magnetic tape at each station and correlated later at a central analysis facility (*12*). To accomplish this, the signals (which are recorded at very high frequencies, typically 3 to 8 gigahertz) must be converted



to some lower frequency by an extremely stable frequency standard. The most successful VLBI programs have used hydrogen maser clocks as frequency standards, and the NASA Geodynamics Program will require hydrogen masers at all VLBI stations. These are expensive and sophisticated devices which are not yet available commercially. The tape recorders required in geodetic-quality VLBI observations have consistently pushed the state of the art: it is necessary to record information at a rate in excess of 100 megabits per second, the equivalent of recording 20 television channels simultaneously. Offsetting these technological difficulties in VLBI is the overriding fact that VLBI stations can be operated arbitrarily far apart, and they can be made small and highly mobile.

Radio signals from Earth-orbiting satellites can also be used for VLBI measurements. Lunar dynamics have been studied in terms of a combination of quasar noise and radio signals from the Apollo instrumentation packages on the moon (*13*). A promising recent development is the use of radio signals from satellites of the Department of Defense Global Positioning System (GPS), which is being implemented for purposes related to the Department of Defense mission, but which offers an opportunity for specialized use in geodynamics research. This is discussed below.

The geodynamical objectives of VLBI measurements are the same as for satellite laser ranging (except that the VLBI results are obtained in an inertial reference frame). In addition, the technological improvement of VLBI observatories required to achieve a baseline length accuracy of 2 to 3 cm is of great interest to radio astronomers because of the significantly greater sensitivity of the new VLBI systems.

Radio astronomers first attempted precise determination of the vector separation between VLBI observatories in the late 1960's, and later many observations were made between Haystack Observatory in Massachusetts and various observatories in California. The repeatability of these measurements has improved from about 16 cm in 1974 to about 4 cm in the most recent measurements (*14*). This improvement has been brought about by the development of the Mark-III VLBI system (*15*) and improvements in the analysis systems.

Measurements have been made with the Mark-III system of intercontinental baselines from Haystack Observatory and the National Radio Astronomy Observatory (NRAO) in Greenbank, West Virginia, to the Owens Valley Radio Observatory (OVRO) in California, the Onsala Space Observatory of the Chalmers University of Technology in Onsala, Sweden, and the 100-m Effelsberg radio telescope of the Max Planck Institute for Radio Astronomy in Bonn (*16*). In addition, observations were made during 1979 and 1980 between Haystack, OVRO, NRAO, and the Harvard Radio Astronomy Station at Fort Davis, Texas, as part of a NASA validation and intercomparison experiment (*17*).

Occasional geodetic VLBI measurements have been made at stations of the NASA Deep Space Network, which operates tracking facilities at Goldstone, California; Madrid, Spain; and Tidbinbilla, Australia. VLBI capability at the 50-cm accuracy level is required for navigation of interplanetary spacecraft, and the necessary equipment is in place at all the Deep Space Network stations. Operational determination of polar motion and earth rotation requires measurements every 1 to 5 days. This almost continuous use of antennas is not possible at large radio observatories whose primary responsibility is unrelated to geodynamics. This problem will be resolved when the Polaris network of three VLBI observatories becomes fully operational in 1983. This network is being constructed by the National Geodetic Survey (NGS) in cooperation with NASA; it will consist of stations at Fort Davis, Texas; Westford, Massachusetts; and Richmond, Florida (*18*). Polaris, which will be operated by NGS, will provide daily estimates of polar motion and the earth's rotation, with expected errors of about 5 to 10 cm in pole position and 100 microseconds in time. These stations will also serve as base stations for crustal deformation measurements made with the use of mobile VLBI stations.

NASA is also building two transportable VLBI Mark-III data systems. These will be used primarily for establishing temporary base stations for plate motion studies and to support mobile VLBI measurements of crustal deformation outside North America.

Two mobile VLBI stations have been built by NASA, one of which has been used since 1974 for measurements at sites in southern California (Fig. 2). Demonstrations of the mobile VLBI system (called ARIES) have shown 6-cm accuracy when compared with NGS measurements in California (*19*). The second station, which will be much more highly mobile, will be in operation in 1981; both stations will be used for crustal deformation measurements in the NASA Crustal Dynamics Project.

Local surveys with Global Positioning System satellite signals. The Department of Defense GPS will consist of at least 18 satellites in high orbits placed so that at least four satellites will always be visible from any point on the earth. Several groups have recognized the possibility of using the radio signals continuously broadcast by these satellites for precise geodetic surveying. The advantages over astronomically based systems are that the ground receivers can be made very small and easily transportable (because of the high signal strength), and that the relative position of two such receivers can probably be determined to 3 cm or better in less than 1 to 2 hours. The limitation is that the receivers must be close enough together (probably 100 to 200 km) that the uncertainty of a few meters in the satellite position does not contribute significantly to the baseline length error (*20*). These systems may make possible frequent measurements of crustal deformation and strain changes over quite large tectonic areas, rapidly and economically. Two different types of GPS-based geodetic systems (*21*) are being developed, and prototypes will be field-tested in 1982 and 1983 before a decision is made on full geodetic application of such systems.

Programs for Geodynamic Use of Space Systems

It is apparent from the foregoing discussion that for the past few years a substantial effort in many countries has been devoted to the development of space technology for application to geodesy and geodynamics. In the United States, a consortium of five federal agencies has been formed to coordinate such efforts: NGS, the National Science Foundation, the Defense Mapping Agency, the U.S. Geological Survey, and NASA. These five agencies signed an agreement in 1980, and an Implementation Plan is now in preparation. A coordinating committee has been formed, with working groups on specific problems such as the selection of sites for mobile station operations, local supporting surveys, and data management. The NASA Geodynamics Program is thus only one segment of the U.S. national activity in space geodynamics. Similar programs are being considered in Europe, and several countries in other parts of the world are also considering geodynamics programs to make measurements at the subdecimeter level.

The NASA activities in geodynamics began in 1972 as the Earth and Ocean

Physics Applications Program, the outgrowth of a conference held in 1969 to discuss possible applications of space technology to earth sciences (*22*). The NASA Geodynamics Program (*8*) was established in 1978 to consolidate the developmental work and prototype measurement programs that had been carried our during the preceding 7 years (*23*). The objectives of this program are to support research in geodynamics, both within the United States and internationally, and to support the U.S. national program in earthquake hazard reduction by conducting research in dynamic processes related to earthquakes. In 1980, a NASA Crustal Dynamics Project was started at GSFC to carry out the observational and developmental activities in the program.

Accomplishment of these geodynamics program objectives necessitates repeated measurements of position and position changes at global, continental, regional, and local scales. As part of the federal program and in cooperation with the governments of other countries, NASA is helping to establish a worldwide network of laser ranging and VLBI observatories that will measure polar motion, the earth's rotation, and tectonic plate movement, and will also serve as base stations for mobile stations measuring crustal deformation at regional distance scales.

It is important that both the laser ranging and VLBI systems be used in parallel, with considerable overlap of the network of observation sites for the two types of stations. The reason is that it is necessary to check the validity of the observations, which, as pointed out above, cannot be done with ground surveys. The sources of error and bias in laser ranging and VLBI are almost certainly independent, and so cross-checking of the two methods can be done by continued comparison of the measurements.

The observing strategy at the fixed observatories is simple: to make as many VLBI observations and perform laser ranging on as many satellite passes as budgetary and other constraints allow. The strategy for the measurement of crustal deformation in tectonically active areas, however, is very much more complex. The number of mobile stations is small and the number of geophysically important problems that might be studied with such equipment is large, as is the number of areas where crustal deformation is known or inferred to be taking place at rates large enough to be seen at the present accuracy levels.

A major effort of the program is to decide priorities for deployment and operation of the mobile VLBI and laser ranging stations. After consultation with NASA advisory groups, the other federal agencies, and committees of the National Research Council, a plan for site occupation by the mobile stations has been established. The first priority is on observation of crustal movements in the western United States, because of the economic and social importance of the earthquake hazards there. The mobile stations will be used in this region through 1981, concentrating on the San Andreas fault system. Figure 3 shows VLBI and laser observatories in California and the rest of North America and planned sites for mobile station occupation (*24*). Less frequent observations will be made in the rest of North America, primarily to determine the stability of the North American plate, to establish initial epoch baselines in the Basin and Range Province and the seismic region in Missouri, to monitor uplift in the eastern United States and Canada due to glacial rebound, and to measure crustal deformation in Alaska.

The first foreign operations under the present plan will include observation of the relative movement of the Pacific, North American, Australian, and South American plates. These will be followed by observations of the movement of the Nazca plate and of crustal movements in Andean South America, Central America and the Caribbean, and the north coast of South America. Later, observations will probably be made in Australia, New Zealand, and elsewhere in the Pacific. When the European and other space geodynamics programs begin, it is expected that close cooperation will evolve naturally through existing international activities such as the International Lithosphere Program and the International Association of Geodesy's recently established Commission on International Coordination of Space Techniques for Geodesy and Geodynamics. An exchange of laser ranging and VLBI data is already being accomplished under international agreements such as Project MERIT of the International Astronomical Union and the International Association of Geodesy and Geophysics, and the joint International Union of Geodesy and Geophysics–Committee on Space Research Project EROLD (*25*).

The funding level for space geodynamics in the United States can be estimated from the budget for the NASA Geodynamics Program, which in fiscal year 1980 was about $21 million (about $6 million of which is used to support research in institutions outside NASA). The prospects for continued support of research in this aspect of geodynamics appear to be bright, and there is good reason to believe that these programs will make important contributions to geodynamics.

References and Notes

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7. The specification of accuracy figures is somewhat complicated. For both lunar and satellite laser ranging, the accuracy given is the estimated uncertainty of a "normal point," which is the average of observations during a short segment of a single satellite observing pass (about 10 returns for lunar work and about 100 returns for Lageos); for further information, see R. I. Abbot, P. J. Shelus, J. D. Mulholland, E. C. Silverberg, *Astron. J.* **78**, 784 (1973). Both random and systematic errors are considered in determining the estimates of normal point uncertainties. Range accuracy translates into station position accuracy in a complicated way, but the uncertainty in each component of position is of the same order as the systematic error contribution to the range uncertainty, and generally somewhat larger.
8. *Application of Space Technology to Geodynamics and Earthquake Research* (Technical Paper 1464, NASA, Washington, D.C., 1979). This is the NASA Geodynamics Program plan.
9. E. C. Silverberg, in *Proceedings of the 9th Geodesy/Solid-Earth and Ocean Physics Research Conference* (Department of Geodetic Science Report 280, Ohio State University, Columbus, 1979, pp. 41–46.
10. *Report of the Workshop on the Spaceborne Geodynamics Ranging System* (Report TR-79-2, Institute for Advanced Study in Orbital Mechanics, University of Texas, Austin, March 1979).
11. NASA is providing funding in 1981 for further studies of local surveying by laser, because the possibility of placing the laser in an aircraft instead of a spacecraft appears to be both technically feasible and economically attractive.
12. For a review, see I. I. Shapiro, in *Proceedings of the 9th Geodesy/Solid-Earth and Ocean Physics Research Conference* (Department of Geodetic Science Report 280, Ohio State University, Columbus, 1979), pp. 29–34. The first geodetic results were reported by H. F. Hinteregger *et al.*, *Science* **178**, 396 (1972). See also the following: M. H. Cohen, D. L. Jauncey, K. I. Kellermann, B. G. Clark, *ibid.* **162**, 88 (1968); W. E. Carter, A. E. E. Rogers, C. C. Counselman, I. I. Shapiro, *J. Geophys. Res.* **85**, 2685 (1980). Low-frequency Doppler measurements, although important in several applications, appear to have an inherent accuracy limitation of about 20 cm, which means that this system cannot be effectively used in geodynamics. The earliest space method, photography of satellite tracks against a star background, is also too inaccurate to be useful in geodynamics.
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20. The uncertainty in satellite position is reduced by a factor of which the numerator is the station separation and the denominator is the satellite altitude, 20,000 km.
21. One system, being developed by the Jet Propulsion Laboratory, uses the GPS signals in the same way that conventional VLBI uses the quasar noise [P.F. MacDoran, Bull. Geodesique 53, 117 (1979)]. The other system measures the GPS reconstructed carrier phase difference between pairs of receivers [C. C. Goad, Eos Trans. Am. Geophys. Union 60, 233, (1979); C. C. Counselman et al., in Proceedings of the Conference on Radio Interferometry for Geodesy (Conference Publication 2115, NASA, Washington, D.C., 1980), pp. 409–416; J. D. Bossler, C. C. Goad, P. L. Bender, Bull. Geodesique, in press]. See also R. A. Preston et al., Science 178, 407 (1972).
22. The Terrestrial Environment: Solid-Earth and Ocean Physics (Report CR-1579, NASA, Washington, D.C., April 1970).
23. An example of research accomplishments in the program is given by D. E. Smith, R. Kolenkiewicz, P. J. Dunn, and M. H. Torrence [Tectonophysics 52, 59 (1979)].
24. Crustal Dynamics Project Plan (NASA Goddard Space Flight Center, Greenbelt, Md., 1980).
25. MERIT is an acronym for Monitoring of Earth Rotation and Intercomparison of Techniques. The MERIT Project sponsored a coordinated campaign of observations of polar motion and earth rotation in August through October 1980; a full 1-year campaign will be carried out in 1983. EROLD is an acronym for Earth Rotation by Lunar Distances; it is primarily a mechanism for data exchange.
26. Interested readers may be handicapped by not having readily available the titles of the citations used in this article; a copy of the references which includes the titles will be sent upon request. I am grateful to P. L. Bender, W. E. Carter, R. J. Coates, C. C. Counselman, B. Douglas, T. L. Fischetti, J. M. Flinn, P. F. MacDoran, I. I. Mueller, W. E. Melbourne, and D. E. Smith for critical reviews.

State of Stress and Intraplate Earthquakes in the United States

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Although the central and eastern United States is generally thought to be a tectonically stable intraplate region, a number of major earthquakes have occurred there in historic times (*1*). Most significant are (i) the 1811–1812 New Madrid, Missouri, earthquakes; (ii) the 1886 Charleston, South Carolina, earthquake; (iii) the 1638 and 1755 earthquakes off Cape Ann, Massachusetts; (iv) the 1663 and 1925 St. Lawrence Valley earthquakes; and (v) the 1929 Grand Banks earthquake (offshore Nova Scotia). An understanding of the tectonic processes responsible for these earthquakes is needed if one is to place the assessment of seismic hazard throughout the central and eastern United States on a firm geologic basis. The major reason that progress in the geologic characterization of sites of historic seismicity has been slow is that both the structures associated with the earthquakes and the tectonic forces responsible for them are poorly understood. In this article we highlight recent progress in understanding the tectonic stress field in the central and eastern United States and the interaction of the stress field with specific geologic structures, primarily in the New Madrid region. In keeping with the intended purpose of this special issue of *Science*, we also attempt to point out areas where research can be focused to accelerate progress in understanding seismicity and tectonism in the central and eastern United States.

Summary. Recently compiled data on the state of stress have been used to define stress provinces in the conterminous United States in which the orientation and relative magnitude of the horizontal principal stresses are fairly uniform. The observed patterns of stress constrain mechanisms for generating intraplate lithospheric stresses. Coupled with new information on geologic structure and tectonism in seismically active areas of the Midcontinent and East, these data help to define some characteristics common to these areas and to identify key questions regarding why certain faults seem to be seismically active.

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The main point of departure for this article is a recent compilation of contemporary stress field indicators (*2*) derived from in situ stress measurements at depth, relatively well constrained earthquake focal mechanisms, and young geologic data (the sense of fault offsets in the eastern United States and detailed fault slip information as well as the orientation of volcanic feeders in the western United States). In considering the geologic evidence pertinent to the current stress field, for the western United States we used only feeder dike and fault offset data less than 5 million years old. For the eastern United States where similar tectonic forces are thought to have been acting throughout Cenozoic time (that is, for 63 million years), only faults offsetting Eocene (55 million years) or younger strata were included and most faults used offset Miocene (24 million years) or younger strata.

A map showing the relative magnitude of the horizontal principal stresses in the conterminous United States is shown in Fig. 1. The country is subdivided into stress provinces in which the orientation and relative magnitude of the principal stresses are fairly uniform. In Fig. 1 regions of relative horizontal compression and extension are distinguished by the inward- and outward-pointing arrows. The delineation of province boundaries was based on both the stress data and information on young faulting (*3*); the boundaries were drawn so as to be no more complicated than required by the data. In some cases the areas of transition between stress provinces is probably much broader and more complex than indicated in Fig. 1. In some parts of the country where few data are available, there may be a tendency to give unwarranted significance to isolated data points.

In general, the selection criteria estab-

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