NASA Technical Memorandum 4220

NASA Geodynamics Program: Annual Report and Bibliography

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FOREWORD

This Report provides a summary of the major activities of the NASA Geodynamics Program during 1988 and 1989. It includes a bibliography of published reports where the research on which the paper was based was either funded by the Program or was related to the Program by virtue of interagency or international agreements.

Previous annual reports on the Geodynamics Program's progress were issued for 1979, 1980, 1981, 1982, and 1983 (NASA, 1980; NASA, 1981; NASA, 1982; NASA, 1983a; and NASA, 1984a). An overview of the Program was published in 1983 (NASA, 1983b). A report which summarized the Program's achievements from its initiation in 1979 through 1987 was published in 1988 (NASA, 1988a).

The year 1989 marks the tenth anniversary of the formation of the Geodynamics Program. In the past decade, substantial progress has been made in decisive determinations of the motions of the major tectonic plates; in the mapping of crustal deformation near plate boundaries; in the measurement of the Earth's rotational dynamics; in the establishment of an international service based on space techniques for monitoring Earth orientation; and in the modeling of the Earth's gravity and magnetic fields.

In July 1989, the NASA Geodynamics Branch and the NASA Geology Program were brought together to form the NASA Solid Earth Science (SES) Branch.

In August 1989, we were saddened by the passing away of Dr. Edward A.(Ted) Flinn, III, one of the architects of the NASA Geodynamics Program and a principal contributor to the success of its international involvement.

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SECTION I. INTRODUCTION

A. *PROGRAM INITIATION*

The NASA Geodynamics Program was initiated in 1979 to coalesce the emerging technologies of Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR), and Very Long Baseline Interferometry (VLBI) - all having the potential for the detection of tectonic plate motion and crustal deformation - and the use of satellites for mapping the geopotential fields into a coherent program for the study of the solid Earth.

A chronology of major Program activities from 1979 to 1987 was published in 1988 (NASA, 1988a). The chronology for 1988 and 1989 is provided herein (Section III).

B. *PROGRAM OBJECTIVES*

The goals of the Geodynamics Program have been:

- *To contribute to the understanding of the dynamics and evolution of the solid Earth; and in particular, the processes that result in movement and deformation of the tectonic plates;*

- *To obtain measurements of the Earth's rotational dynamics and its gravity and magnetic fields in order to understand better the internal dynamics of the Earth.*

The Geodynamics Program was subdivided into three areas: Earth Dynamics, Crustal Motion, and Geopotential Research.

The objectives in the *Earth Dynamics* area have been to develop models of polar motion and Earth rotation and to relate studies of global plate motion to the dynamics of the Earth's interior. This is expected to lead to an increased understanding of the global structure of the Earth and the evolution of the crust and lithosphere. The research includes studies of the dynamic interaction between different regions of the Earth's tectonic features, as well as the interaction between the solid Earth, atmosphere, and oceans. A significant portion of this includes activities performed under the Crustal Dynamics Project (CDP), through highly accurate measurements of Earth rotation and polar motion.

Field measurements and modeling studies of crustal deformation in various tectonic settings were the primary focus of the *Crustal Motion* research. Activities in this area provide measurements, analyses, and models which describe the accumulation and release of crustal strain and the crustal motion between and within the North American, Pacific, Eurasian, South American, and Australian Plates. A principal result of this research has been the development of quantitative descriptions of geophysical and geological constraints on the motion of measurement sites through refinements of global and regional plate motion models.

Geopotential Research uses space and ground measurements to model the Earth's gravity and magnetic fields. A large part of the effort includes the development of new analysis techniques and software systems. Studies of the Laser Geodynamics Satellite (LAGEOS-I) orbit and the orbits of other near-Earth satellites contribute to the gravity field studies. Other data used in constructing the field models include gravity field data derived from satellite altimetry, satellite-to-satellite tracking and gravity gradiometry; magnetic field data from satellite magnetometers; and ancillary data.

C. CRUSTAL DYNAMICS PROJECT

A major element of the Program, the CDP, was initiated in 1979 to develop the SLR and VLBI techniques and to implement global networks of fixed and mobile SLR and VLBI stations, with the cooperation of many countries, for measurements of plate motion and regional deformation. Although other satellites are used, the SLR measurements rely mainly on ranging to LAGEOS-I which was launched in 1976. LAGEOS-II, which is to be launched in late 1991, is expected to improve further the accuracy and efficiency of SLR. The application of VLBI to precise geodesy has made use of the techniques and global facilities developed for astronomical studies of radio sources.

The management responsibility for the CDP was assigned to the Goddard Space Flight Center (GSFC) with support from the Jet Propulsion Laboratory (JPL). In 1982, Lunar Laser Ranging (LLR) was included in the CDP. In the decade which has followed, the CDP has grown into an international research effort leading toward the understanding of earthquakes and the dynamics of the crust and upper mantle of the Earth. Twenty-three countries are participating in the development and use of these geodetic techniques. Twelve of these countries have formed a consortium, - Working Group of European Geo-Scientists for the Establishment of Networks for Earthquake Research (WEGENER),- which is working with the CDP in the Mediterranean Laser (Medlas) Project to monitor the crustal deformation in the Mediterranean Basin.

While helping to build and deploy SLR, LLR, and VLBI facilities world-wide, the CDP has also developed the technology to improve the accuracy and reliability of the field measurements. Most of the systems which comprise the world-wide network are now capable of measuring the motion of any one site with respect to another with a precision of better than 1 cm/year. This has resulted, for the first time, in the direct measurement of the motion of most of the major plates and the deformation of the Earth's crust in the western U.S., Alaska, and the Mediterranean.

The history of the development of the SLR, LLR, and VLBI techniques and the global networks that currently exist are described in NASA, 1988a. The status and plans of the CDP and the

WEGENER/Medlas consortium, through 1991, are outlined in Section II A and C, respectively.

While the CDP is scheduled to finish its activities at the end of fiscal year 1991, the current measurement program will be continued through 1991, with some changes to reflect the emerging GPS techniques as emboidied in the recommendations of the NASA Geophysics Workshop held in Coolfont, WV, in 1989 (report in preparation). In addition, the CDP is committed to providing SLR tracking for the European Space Agency (ESA) Remote Sensing Satellite (ERS-1) to be launched in 1990 and the NASA Ocean Topography Experiment (TOPEX) to be launched in 1992.

Beyond 1991, NASA has chosen to continue and to improve on the work of the CDP by establishing a new level of effort program. The objectives of the new program, while similar to those of the CDP, will require an expansion of global networks through increased international participation; improved accuracies and greater temporal resolution of measurements; and more detailed studies of the deformation at plate boundaries

D. GLOBAL POSITIONING SYSTEM

NASA development of receivers which use signals from the Global Positioning System (GPS) satellites was initiated at JPL in the late 1970's. In 1983, the U.S. Congress directed NASA to initiate a program for the study of crustal deformation in the Caribbean Basin using GPS. This program now includes developmental experiments in southern California; measurements across the spreading ridge in the Gulf of California; and measurements in Central America, South America, Australia, and New Zealand. These measurement campaigns are coordinated with other countries, with U.S. institutions, and with other U. S. agencies

During the past two years the development and use of the GPS technique has improved rapidly. The precision of the GPS measurements for regional crustal deformation studies is now believed to be comparable to that of mobile SLR and VLBI systems. However, additional data are required to verify that the GPS measurement of global tectonic deformation rates are also comparable.

E. GEOPOTENTIAL FIELDS

1. <u>Gravity Field and Geoid</u>

During the past decade, significant improvements have been made to the accuracy and resolution of models of the Earth's global gravity field and geoid. This has amounted to about a factor of two improvement in gravity field modeling and a factor of about 5-10 improvement in the geoid.

Gravity Field modeling has made extensive use of the SLR data acquired using LAGEOS-I and Starlette (a French satellite) and altimetric measurements using the Geodynamic Experimental Ocean

Satellite (GEOS-3) and the Ocean Dynamics Monitoring Satellite (SEASAT). However, the goal of developing models with an accuracy of a few milligals (mgals) for spatial resolution of 100km or less has not been achieved due to the lack of *in situ* satellite data.

The scientific requirements for these data are discussed in the report of a Gravity Field Workshop that was held in Colorado Springs, CO, in 1987 (NASA, 1987). To meet these requirements there are several planning activities, studies, and instrument developments which are currently underway. These include a spacecraft which will carry a French gradiometer (GRADIO) - the ESA Applications and Research Involving Space Techniques Observing the Earth's field from Low Earth Orbiting Spacecraft (ARISTOTELES) mission; use of GPS and SLR tracking of the Gravity Probe-B (GP-B); and a NASA spacecraft which will carry a University of Maryland cryogenic gradiometer -the Superconducting Gravity Gradiometer Mission (SGGM).

2. Magnetic Field

The first satellite dedicated to mapping the Earth's magnetic field, the Magnetic Field Satellite (MAGSAT), was launched in 1979. MAGSAT provided the first truly global survey of the vector components of the geomagnetic field. Its measurements were used to construct the International Geomagnetic Reference Field (IGRF) for 1980 and to study crustal magnetic anomalies. The geomagnetic field is known to undergo local changes of several hundred nanoTesla (nT) due apparently to motion of the Earth's core. In addition, some ground observatory data indicate a sudden change with time in the third derivative ("magnetic jerk") of the main dipole field. The scientific interest in confirming that the "magnetic jerk" is real, and possibly related to core-mantle interaction, and the need to update the IGRF have generated requirements for a satellite mission capable of long-term surveys of the field. This has resulted in NASA/Centre Nationale d'Etudes Spatiales (CNES) studies of a Magnetic Field Explorer (MFE)/Magnolia mission, and studies by NASA and ESA of the possibility of adapting boom-mounted magnetometers to the ARISTOTELES mission.

F. GEOPHYSICS WORKSHOPS

The first Workshop dedicated to studies of the solid Earth and oceans was held in Williamstown, MA, in 1969 (NASA, 1970). The results of this Workshop formed the basis of the NASA Earth and Oceans Dynamics Applications Program, the predecessor of the Geodynamics Program. The first Geodynamics Workshop was held at Airlie House in Virginia in 1983 (NASA, 1984b). In early 1988, plans were initiated for a second Geodynamics Workshop to be held in 1989, with the intent of developing the Program's details for the next decade. Prior to the 1989 Workshop, NASA supported the participation of U.S. scientists and engineers in an international Workshop held in Erice, Italy, in July 1988 (Mueller and Zerbini).

In response to an impending reorganization, the 1989 Geodynamics Workshop was extended to include geology and was re-formulated to develop the NASA Solid Earth Science (SES) Program for the next decade. This Workshop was held at Coolfont, WV, in July 1989.

The report of the 1989 Geophysics and the SES Program Plan will be published in 1990. This plan outlines five major initiatives for the next decade. These include:

1. The development of Global Geophysical Networks (GGNs) comprised of approximately 200 geophysical stations for studies of plate motion and deformation (this has been named FLINN -Fiducial Laboratory for an International Natural science Network) and regional networks (named DSGS -Densely Spaced Geodetic Systems) for monitoring tectonic activity in active areas.

2. The study of the formation, degradation, erosion, and redistribution of soils; the effects of climatic changes on the land surface; and climate-tectonic interactions.

3. The mapping of the Earth's global land surface topography at moderate resolution, with the acquisition of high resolution data for regional and local areas.

4. The acquisition of gravity and magnetic field measurements with accuracies and resolutions and, for magnetics, duration of measurement period needed to support investigations of the solid Earth.

5. The study of volcanoes to document the interaction of volcanic eruptions with the atmosphere and the short-term climatic effects of volcanic activity.

SECTION II. PROGRESS, STATUS, AND PLANS

A. CRUSTAL DYNAMICS PROJECT

The observing program of the CDP is guided by the Project's scientific objectives. Most of the Project's effort is in understanding the motions occurring in California and Alaska along the plate boundary in western North America, and the determination of global plate motion, especially with respect to North America. The distribution of presently occupied sites in the global SLR network provides a basic framework for the study of plate motion. This is complemented by a network of VLBI observatories, especially between North American sites and those in the northern Pacific and Eurasia. Regional deformation observations in western North America are mainly accomplished with the VLBI systems. In the Mediterranean region, the CDP is participating with WEGENER in a long-term set of SLR measurements. A summary of the CDP activities is reported in Frey and Bosworth, 1988.

During 1988 and 1989, the CDP continued its regular program of fixed and mobile SLR and VLBI measurements. Overall, during the two years, the combined NASA and National Geodetic Survey (NGS) programs involved 23 countries in SLR and VLBI observations using 38 fixed systems and 8 mobile systems, with the latter having completed 84 site visits.

Because of planned upgrades to the Transportable Laser Ranging Systems (TLRS), observations in 1988 with these systems were limited to Cabo San Lucas, Mexico; Westford, MA; Mojave, CA; and Otay Mountain, CA. In 1989 all four TLRSs were in the field: TLRS-1 was in Europe to support WEGENER/Medlas studies of crustal deformation and movement; TLRS-2 and TLRS-3 conducted studies of the relative motions of the Pacific, Nazca, and South American Plates (TLRS-2 shuttled between Huahine, French Polynesia, and Easter Island, and TLRS-3 began measurements at Cerro Tololo, Chile); TLRS-4 visited Ensenada, Mexico, and Cabo San Lucas, Mexico, to study (with the fixed laser at Mazatlan, Mexico) the spreading of the Gulf of California. TLRS-4 also participated in studies of the regional deformation of the North American Plate immediately following the October 17, 1989 Loma Prieta earthquake by making measurements at Mojave, CA.

The mobile VLBI systems (MV-2 and -3) hada banner year in 1988. In addition to measurements of regional deformation in the western U.S. from 18 sites (some 29 site visits) using MV-2 and MV-3, MV-2 participated in studies of the interaction of the North American and Pacific Plates by making measurements across the Aleutian Trench from sites in Alaska and Canada. In 1989, NASA and NGS agreed to exclusive use of MV-3 for NGS programs. However, because of the scientific, and possible societal, importance of the Alaskan studies, the 1988 Alaskan Campaign was repeated. As a consequence, the number of sites in the western U.S. was reduced to 10 (15 site visits).

Following the Loma Prieta earthquake, two mobile VLBI systems were deployed to three previously established VLBI sites in the earthquake area: Fort Ord (near Monterey, CA), the Presidio (in San Francisco, CA), and Point Reyes, CA. From repeated VLBI occupations of these sites since 1983, the pre-earthquake rates of deformation have been determined with respect to a North American reference frame with one sigma formal standard errors of about 1mm/yr. The VLBI measurements immediately following the earthquake showed that the Fort Ord site was displaced 49+/-4mm at an azimuth of 11+/-4^0 and that the Presidio site was displaced 12+/-5mm at an azimuth of 148+/-13^0. No anomalous change was detected at Point Reyes with a one sigma uncertainty of 4mm. The estimated displacements at Fort Ord and the Presidio agree with static displacements predicted on the basis of a coseismic slip model.

During 1988 and 1989, the accuracy of the fixed SLR and VLBI systems was demonstrated at certain sites at the subcentimeter-level. Plans were made for further improvements with the goal of achieving the few mm-level.

Over the past decade, global plate motion studies using data provided by both SLR and VLBI systems have largely confirmed the expected motion for most plates. Figure II-1 shows recent measurements of plate motions along specific baselines, as determined from SLR systems. Figure II-2 shows a similar result for VLBI observations in the Pacific, represented this time as motion of the individual sites with respect to the stable interior of the North American Plate. These direct measurements of plate motion are important: they provide the first proof that the plates move as plate tectonic theory suggests, and that the motion over short time scales is similar to that determined from long-term geologic averages.

Both VLBI and SLR systems are engaged in measurement of the relative motion between the North American and Pacific Plates near the plate boundary in California. Figure II-3 shows vector site motions in the western U.S. with respect to interior North America, as measured by VLBI. For reference, the long-term velocity of the Pacific Plate relative to the North American Plate as estimated by the Northwestern University Velocity Model 1 (NUVEL-1) plate motion model (DeMet, et.al., 1989) is shown. The data indicate that the velocities measured near the plate boundary are several tens of mm/year less than those modeled for the plates as rigid bodies (50mm/year). The difference between the far-field motion and the near-field motion has potentially important implications for the earthquake hazard problem in California, as it may be related to how stress is distributed and stored within boundary zones between two large moving plates. These results are based on solutions developed by GSFC, analyses by other groups, such as NGS, the University of Texas at Austin, and the Smithsonian Astrophysical Observatory, have produced similar results.

Another result documented by the CDP is the regional deformation in the plate boundary zone in Alaska, where the Pacific Plate converges upon, and is consumed under, the North American Plate. Figure II-3 also shows vector site motions in Alaska and the

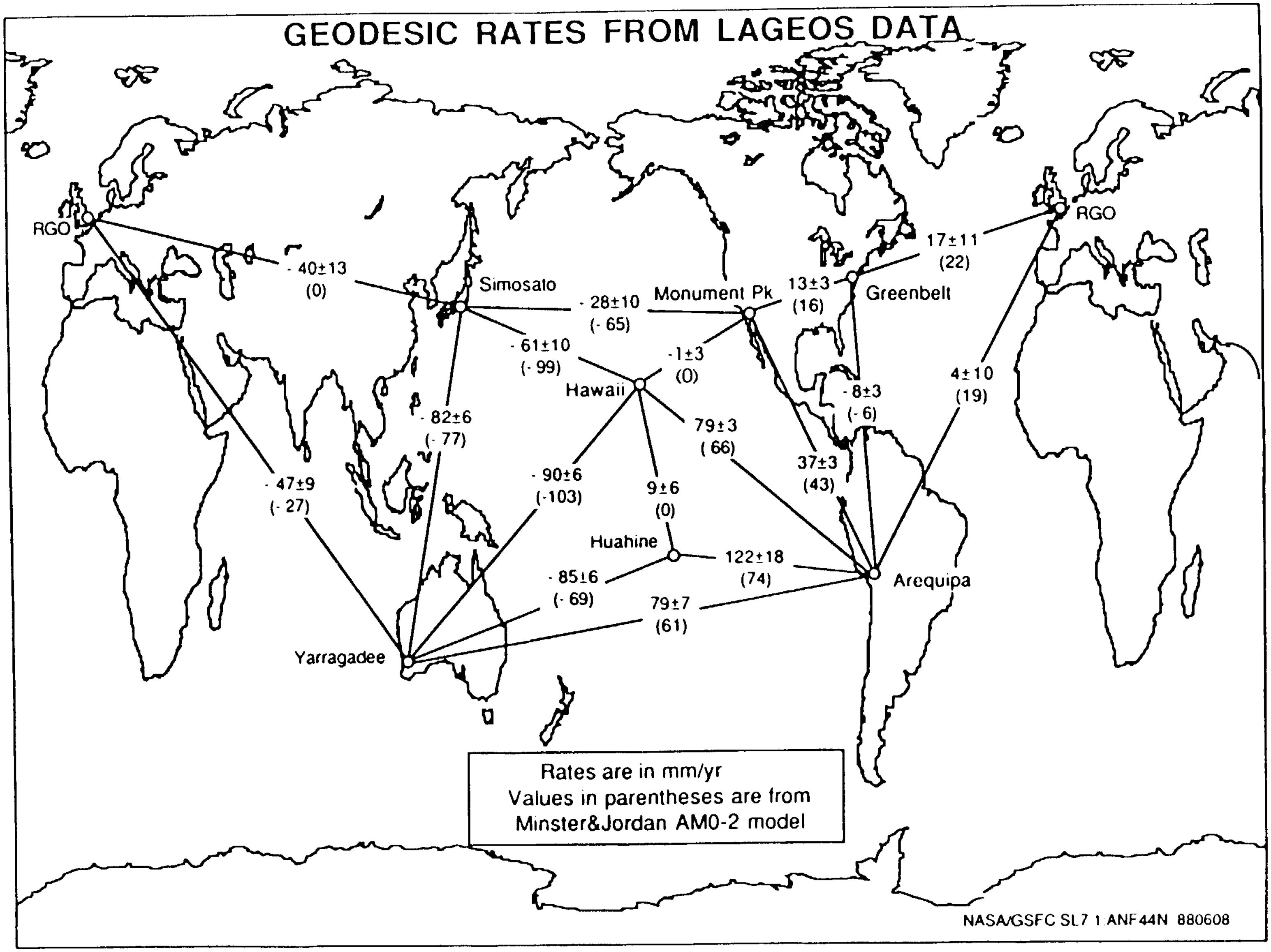


Figure II-1 Rate of change of baseline lengths from Satellite Laser Ranging data for selected baselines between North America, Eurasia, and the Pacific. Rates are in mm/year, in a reference system where the motions are with respect to the underlying mantle. In parentheses are the "predicted" rates based on long-term geological averages.

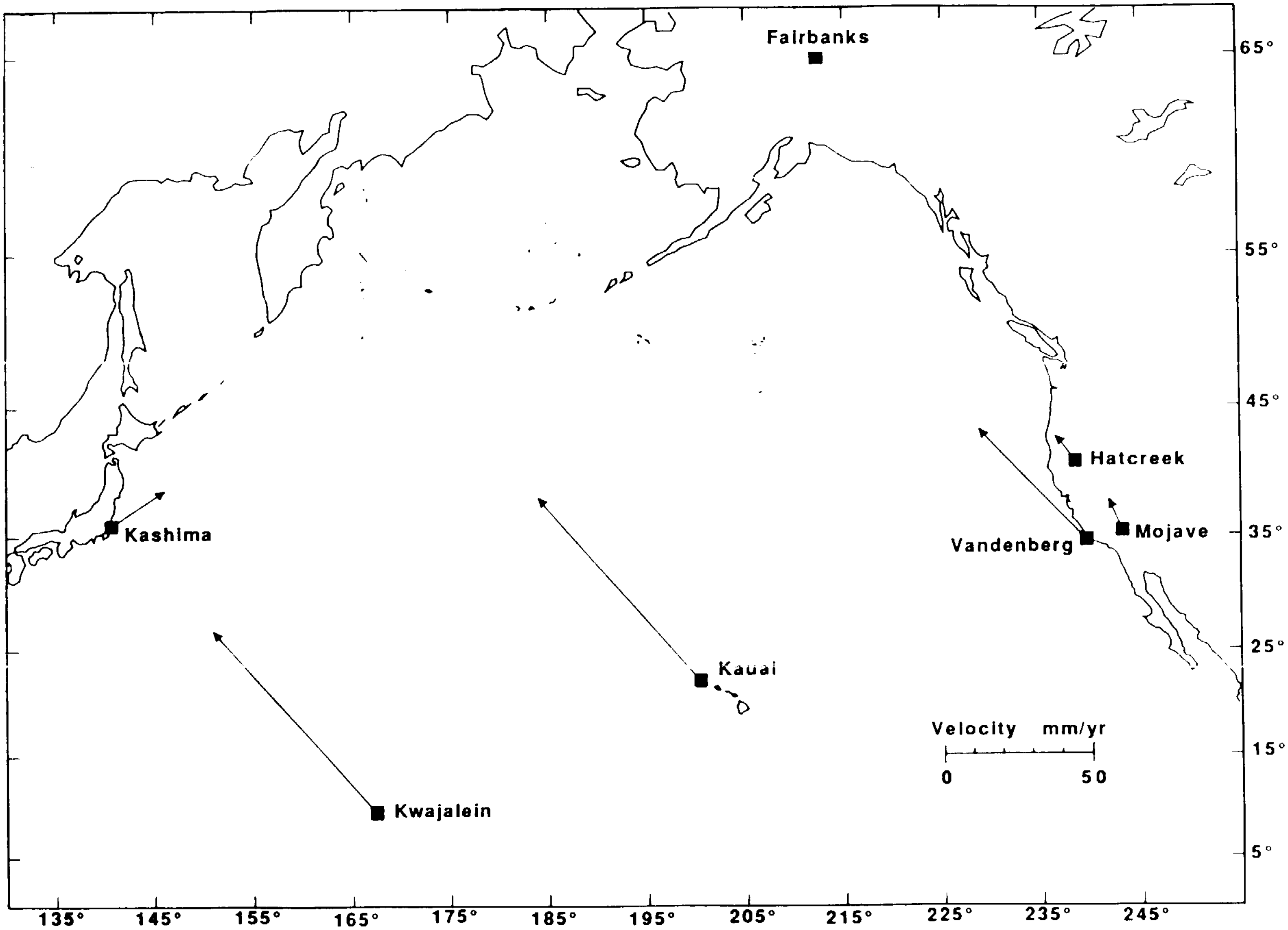


Figure II-2 Observed motions of Very Long Baseline Interferometry (VLBI) sites in the Pacfic. Motions are calculated with respect to an North American Plate site at Fairbanks, AK, assumed fixed. The observed motions for Vandenberg, Kauai, and Kwajalein are very close to the predicted motions based on long-term geological averages, and clearly show how the Pacific Plate is sliding northwestward past the North American Plate.

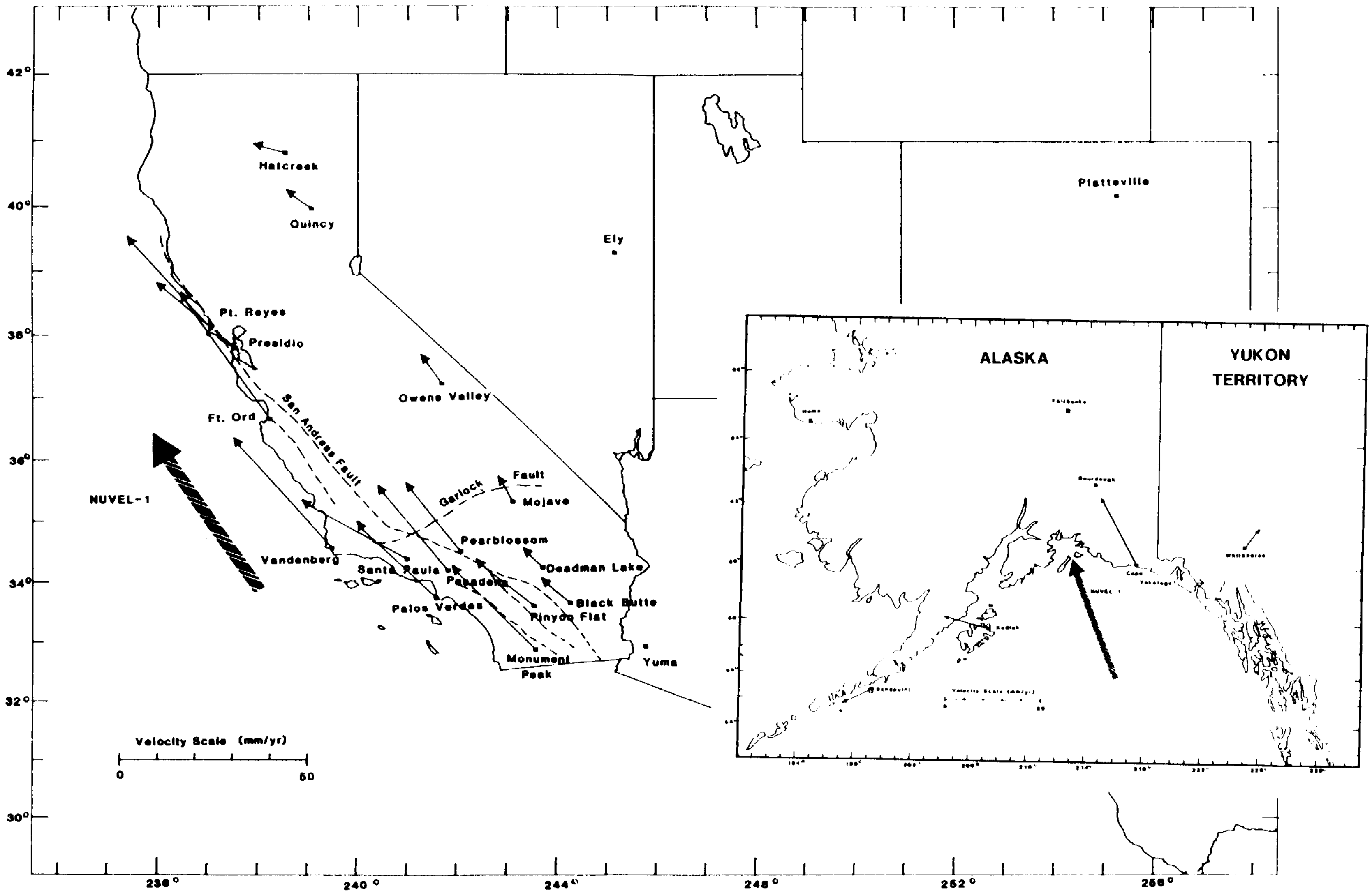


Figure II-3 Motion of VLBI sites along the North American-Pacific Plate boundary in California and Alaska (insert). For comparison, the predicted motion of the Pacific Plate with respect to North America based on NUVEL-1 is shown. Note the departure of the motion of Kodiak and Sand point in Alaska from the expected plate motion.

Yukon Territory with respect to interior Alaska, as determined by VLBI. For reference, the long-term velocity of the Pacific Plate relative to the North American Plate offshore of southern Alaska, as given by the NUVEL-1 plate motion model, is shown. It is clear that several of these sites show relatively large motions of 30-40mm/year, which may be related to the seismic potential of this area. Several of these sites are located in "seismic gaps" where large earthquakes have not occurred in recent times, despite the prolific seismicity in the surrounding areas.

It is planned that most of the current SLR and VLBI measurements will be continued through fiscal year 1991.

B. VLBI/SLR TECHNIQUE COMPARISONS

VLBI and SLR are the two most accurate techniques yet developed for determining geocentric site coordinates on a worldwide scale. Both techniques have been under development for more than twenty years with the aim of providing fundamental data which will lead to an understanding of contemporary tectonic processes. Since 1980, the CDP has undertaken to prove the accuracy of the techniques through blind comparisons of the geodetic information produced by each.

The first comparison results were published in 1985 (Kolenkiewicz et. al.,). Baseline length results for 22 baselines involving 7 sites were compared. The mean level of agreement was 10+/-12mm with an rms scatter about the mean of 52mm. No attempt was made to compare Cartesian station positions directly because of the small number and poor distribution of stations.

By 1989 the number of locations where VLBI/SLR comparisons could be made had increased to 16 and had taken on a worldwide distribution including sites in the mid-Pacific Ocean, Australia, and China. The GSFC VLBI analysis group and the SLR analysis team at the University of Texas agreed to carry out a blind comparison of geocentric site coordinates. Because no effort had been made to make the terrestrial reference frames of the VLBI and SLR analysis systems identical, it was necessary to determine a 7-parameter transformation relating the two reference frames. The transformation consisted of a three-component translation which related the origins of the frames, a three-component rotation which related the orientation of the frames, and a scale factor which related the overall scales of the two frames. After the transformation was applied to the VLBI coordinates they were compared to the SLR values. The weighted rms residual differences for the 16 sites were found to be 19, 26, and 22mm, respectively, in the X, Y, and Z coordinates. These differences are approximately two times the uncertainty in the translation of the coordinate system origin and are consistent with the uncertainties in the individual site components from the two techniques. The results validate the VLBI and SLR techniques for determining Cartesian coordinates at well under the 50mm level achieved for baseline lengths in 1985.

In October 1989, a VLBI observing session was carried out at the Goddard Optical Test Facility (GORF), a location with a monument with well determined SLR coordinates. Thus, a 17th site became available for comparison. When the VLBI coordinates were transformed to the SLR frame using the transformation discussed above and the results compared with the SLR coordinates, the differences were 9, 15, and 2mm, respectively, for the X, Y, and Z components. Considering the 10-15mm level uncertainty in the translation of the origin these are essentially perfect results.

C. WEGENER/Medlas

Medlas was organized in 1981 by a consortium of European countries (WEGENER). The project plan calls for the use of a mix of European fixed and mobile SLR systems and U.S. mobile SLR systems for studies of crustal motion in the Mediterranean Basin. The consortium includes the Federal Republic of Germany (FRG), The Netherlands, the U.S., Austria, Italy, Great Britian, France, Switzerland, Greece, Turkey, Israel, and Egypt. Modular Transportable Laser Ranging Systems (MTLRS) are provided by the Institute fur Angewandte Geodaesie (IfAG) of the FRG (MTLRS-1), the Technical Institute of Delft (MTLRS-2), and NASA (TLRS-1). The Italian Space Agency (ASI) is expected to start construction of two other mobile systems which will join the WEGENER/Medlas studies in the early 1990's. The locations of the fixed and mobile laser sites in Europe are shown in Figure II-4.

The first Medlas Campaign used MTLRS-1 and -2 and was conducted in 1986. This Campaign involved sites in Italy, Turkey, and Greece. In 1987, these systems were joined by TLRS-1. Due to a number of constraints, NASA and WEGENER agreed to revise the Medlas plan to provide for Mediterranean observations on alternate years beginning in 1989 and for MTLRS-1 to visit the U.S. between Mediterranean Campaigns. To implement this plan, MTLRS-1 visited the U.S. in 1988 and acquired observations at VLBI sites in Richmond, FL; Owens Valley, CA; and Platteville, CO. These sites were chosen to support studies recommended by the Commission for Coordination of Space Techniques for Geodesy and Geodynamics (CSTG) of the International Union of Geodesy and Geodynamics (IUGG) and the International Astronomical Union (IAU) Joint Working Group on the Establishment and Maintenance of a Conventional Terrestrial Reference System (COTES). During 1988, MTLRS-2 remained in Europe for observations and upgrades.

In December 1988, MTLRS-1 returned to Europe for the 1989 Medlas Campaign and was joined in early 1989 by TLRS-1. The 1989 Medlas Campaign included 13 sites: 7 by MTLRS-1, 4 by TLRS-1, and 2 by MTLRS-2. In 1990, MTLRS-1 will return to the U.S. for continuation of the COTES measurements. It will be followed later by TLRS-1 which stayed in Europe to complete part of the 1989 schedule.

The next Medlas Campaign is planned for 1992. Meanwhile, WEGENER is developing plans for the extensive use of GPS to densify measurements in the Mediterranean Basin and is exploring

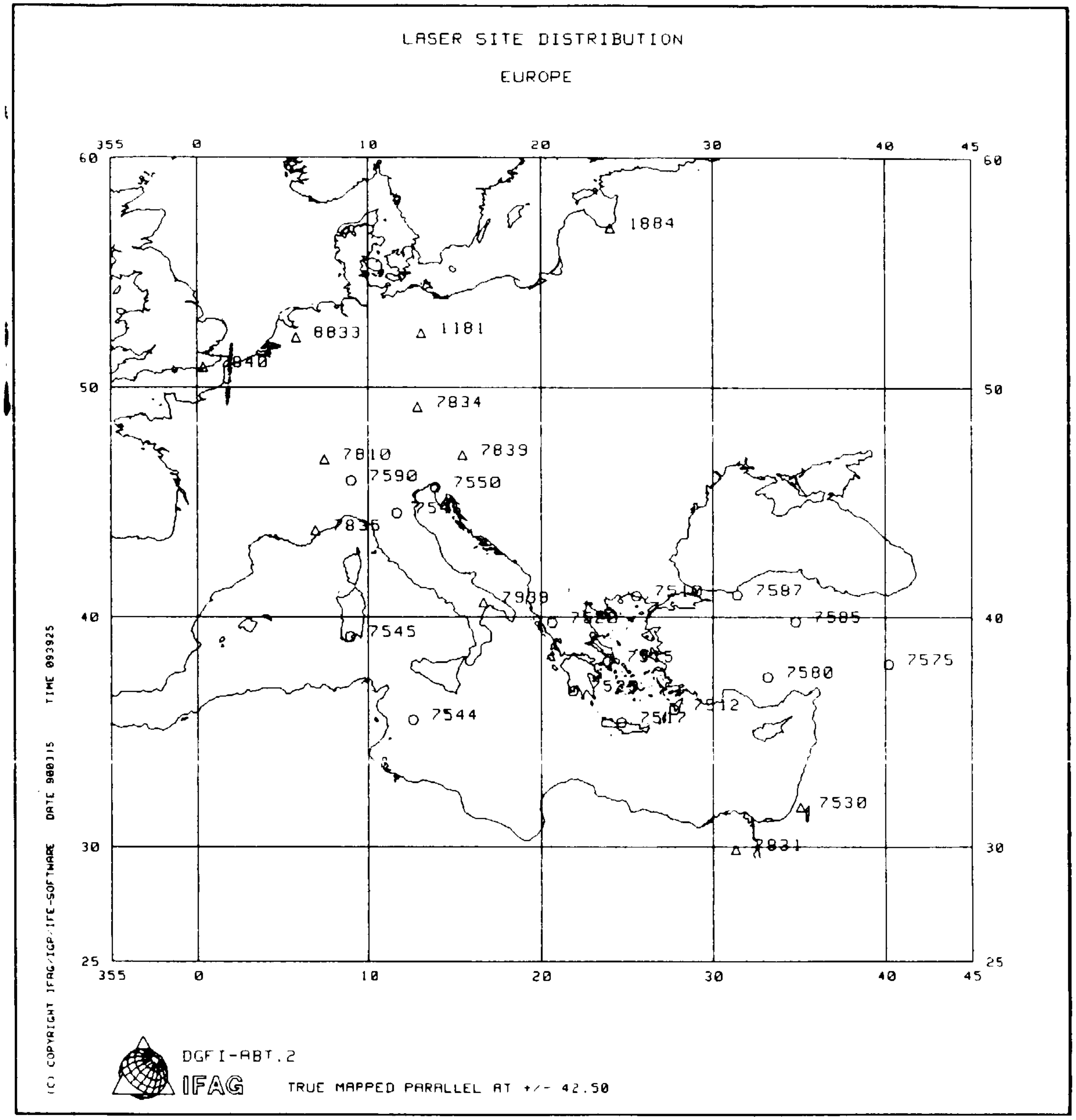


Figure II-4 Distribution of SLR sites contributing regularly with observations to the WEGENER/Medlas Project. Fixed stations identified with triangles. Stations occupied by mobile system identified with circles.

the possibility of extending SLR studies to areas other than the Mediterranean.

Results of the WEGENER/Medlas Campaigns have been presented at several meetings of the CDP Investigators Working Group (IWG), and at special WEGENER/Medlas symposiums held in Bologna, Italy, in 1987 (Baldi and Zerbini, 1988); and in Scheveningen, The Netherlands, in 1988 (Wakker, 1990).

D. GLOBAL POSITIONING SYSTEM APPLICATIONS

In January 1988, JPL coordinated and managed the Central And South America (CASA) Uno 88: a comprehensive GPS data acquisition campaign to monitor crustal deformation in central and northwestern South America. Sites are located in Costa Rica, Panama, Colombia, Venezuela, and Ecuador. CASA Uno 88 required the first implementation of a globally-distributed GPS satellite tracking network to improve orbit determination necessary to compensate for the poor satellite geometry over South America. This was the largest GPS experiment to date to measure tectonic plate motion, acquiring 590 station days of data from 44 GPS receivers in 13 countries. Over 25 different institutions contributed to the success of this campaign.

In October 1988, JPL sent a Rogue GPS receiver to the Deep Space Network (DSN) site in Canberra, Australia and a TI-4100 to Black Birch, New Zealand, in support of a NGS global tracking experiment (GOTEX).

A GPS field campaign in Mexico (GEOMEX 89) was the first reoccupation and extension of GEOMEX 85. This joint experiment with Oregon State University was successfully carried out during two weeks of May 1989. The extension of the network added 7 sites in Mexico which span the Gulf of California, and included a site on Guadalupe Island. In the U.S., 8 additional sites were occupied including sites at Hatcreek, CA; Westford, MA;, and Richmond, FL, where Rogue receivers were deployed.

During August and September 1989, JPL supported a GPS campaign on the island of Sumatra, Indonesia. This support included providing logistical planning and deploying a Rogue GPS receiver to Wellington, New Zealand. The receiver was sent early to New Zealand to also provide fiducial support for the reoccupation of a site in the South Pacific.

Following the October 1989 Loma Prieta earthquake, JPL fielded a team to monitor post-seismic relaxation in the epicentral region. Using the Rapid Static Survey (RSS) technique recently developed at JPL measurements were taken for about 5 minutes every day for 6 days at each of 10 sites with a single roving GPS receiver. Two stationary receivers were operated simultaneously to provide a baseline to which the location of the roving receiver could be referred. The RSS technique involves fast resolution of cycle ambiguities in carrier phase data which depends on the availability of both carrier phase and high precision pseudo-range data. Presently, the Rogue is the only GPS receiver with this capability.

Two major experiments are proposed for 1991: one experiment will attempt to measure the relative plate motion between Tibet and China: and the other experiment will measure the convergence of the Nazca and South American Plates.

GPS data analysis activities in 1988 and 1989 included: final processing and reporting on the experiments of November 1985 in Baja, CA, and June 1986 in the northern Caribbean (see Figure II-5); complete analysis of the January 1988 CASA Uno experiment; and preliminary processing of the Spring 1989 GEOMEX campaign. This now provides data for some baselines which span 4 years (March 1985 - April 1989) and has resulted in direct observation of plate motions which are consistent in magnitude and comparable in precision (both long term and short term) with results from VLBI and SLR. The precision of the vertical components has frequently surpassed that of VLBI both day-to-day and year-to-year.

A study covering a time span of 3.5 years has been nearly completed in which good agreement is demonstrated between VLBI- and GPS-determined rates in southern California, and in which the first rate estimates for an offshore island have been determined.

Overall, the time required to process data from a typical field campaign has been reduced by more than an order of magnitude, and accuracies in horizontal baseline components (as determined by comparison with VLBI) have improved from the typical several parts in 10^8 two years ago to, in many cases, 5 to 10 parts in 10^9. Length precisions of parts in 10^9 have been demonstrated for baselines up to 5,600 km (Lichten, in press).

The Geodynamics Program has supported the development of new GPS receivers capable of range measurements with accuracies at the cm-level and phase measurements with accuracies at the mm-level. Receivers with these capabilities will be needed for the implementation of FLINN and DSGS. The development of the first of the new receivers, Rogue, has been completed, and the technology has been transferred to industry.

Some features that the Rogue receiver has pioneered are:

- Digital tracking (eliminating interchannel bias);
- On-board software which solves for position and clock offset using signals from only two GPS satellites. (Other receivers require at least 4 satellites.)
- The capability to start automatically when power is turned on without *a priori* knowledge of the receiver location, time of day, or satellite ephemerides;
- Excess CPU capacity which allows the future addition of "smart receiver" algorithms;

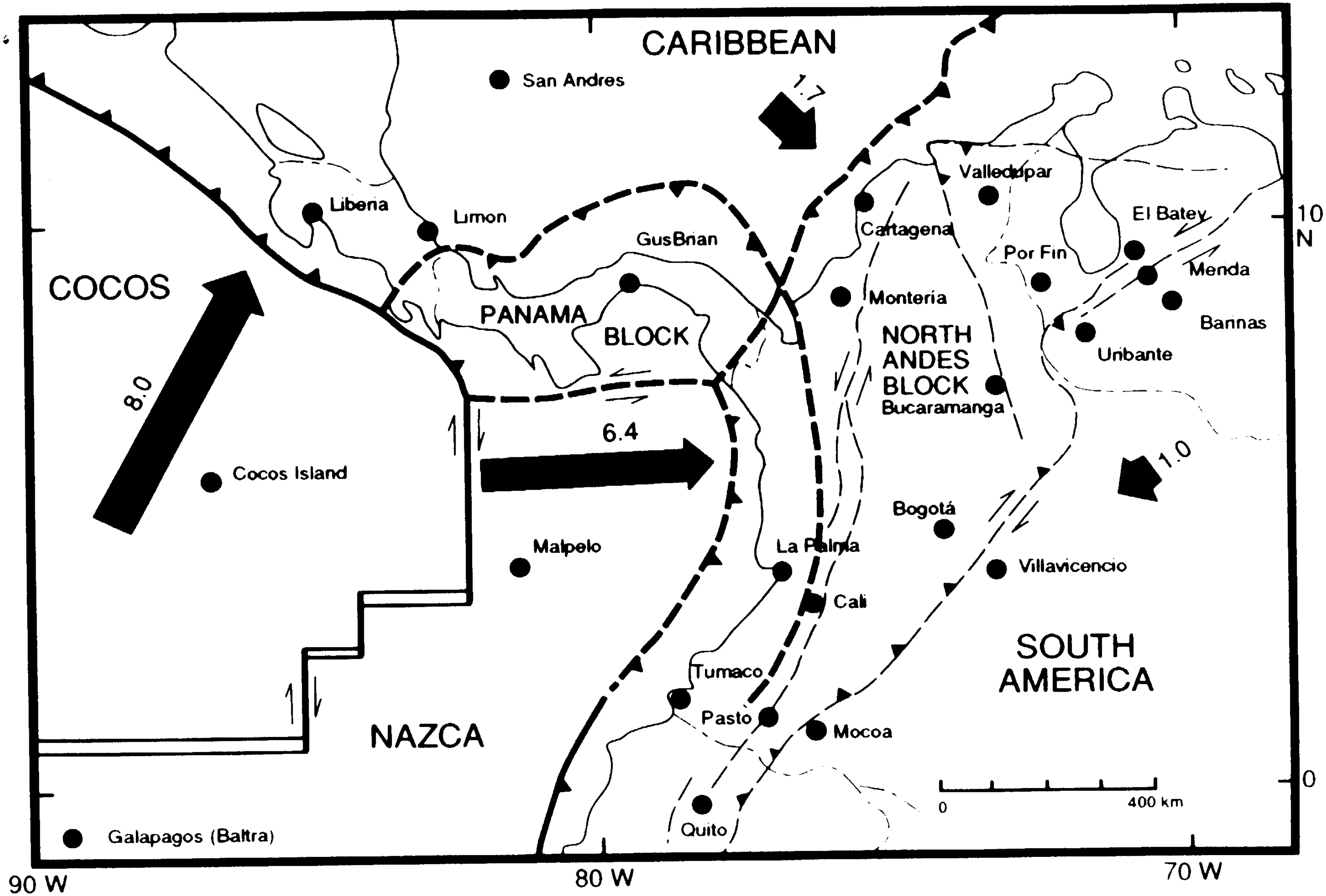


Figure II-5 Central and South America (CASA UNO 1988) GPS site locations.

- Accurate range measurements, allowing the application of automated phase connection algorithms as well as enabling rapid static survey techniques;

- Use of the P-code when available, switching to dual frequency non-code processing when encryption is on;

- Non-code processing which provides full cycle phase ambiguity, in comparison to the half cycle provided by other receivers;

- Low multipath antennas which have demonstrated an order of magnitude reduction of multipath error.

Three Rogues have been fabricated at JPL and three more have been procured from industry. Rogues have been used in CASA Uno, GOTEX, and GEOMEX; and in investigating the post-seismic relaxation following the Loma Prieta earthquake. Four Rogues have also been procured for the DSN. These receivers were used to measure the Earth's ionospheric content during the Voyager/Neptune encounter on August 25, 1989.

The Rogue design is compatible with the new generation of gate array technology, which enables the same level of accuracy to be implemented in a package (TurboRogue) which will be less expensive (targeted at $15K vs. $100K), and lighter (7kg vs. 30kg) and which will require less power (30 watts vs. 180 watts).

The chip design for an advanced Rogue, TurboRogue, has been completed, and simulations are currently being made to validate its performance. Initial contacts have been made with industry to ensure a rapid transfer of this new technology.

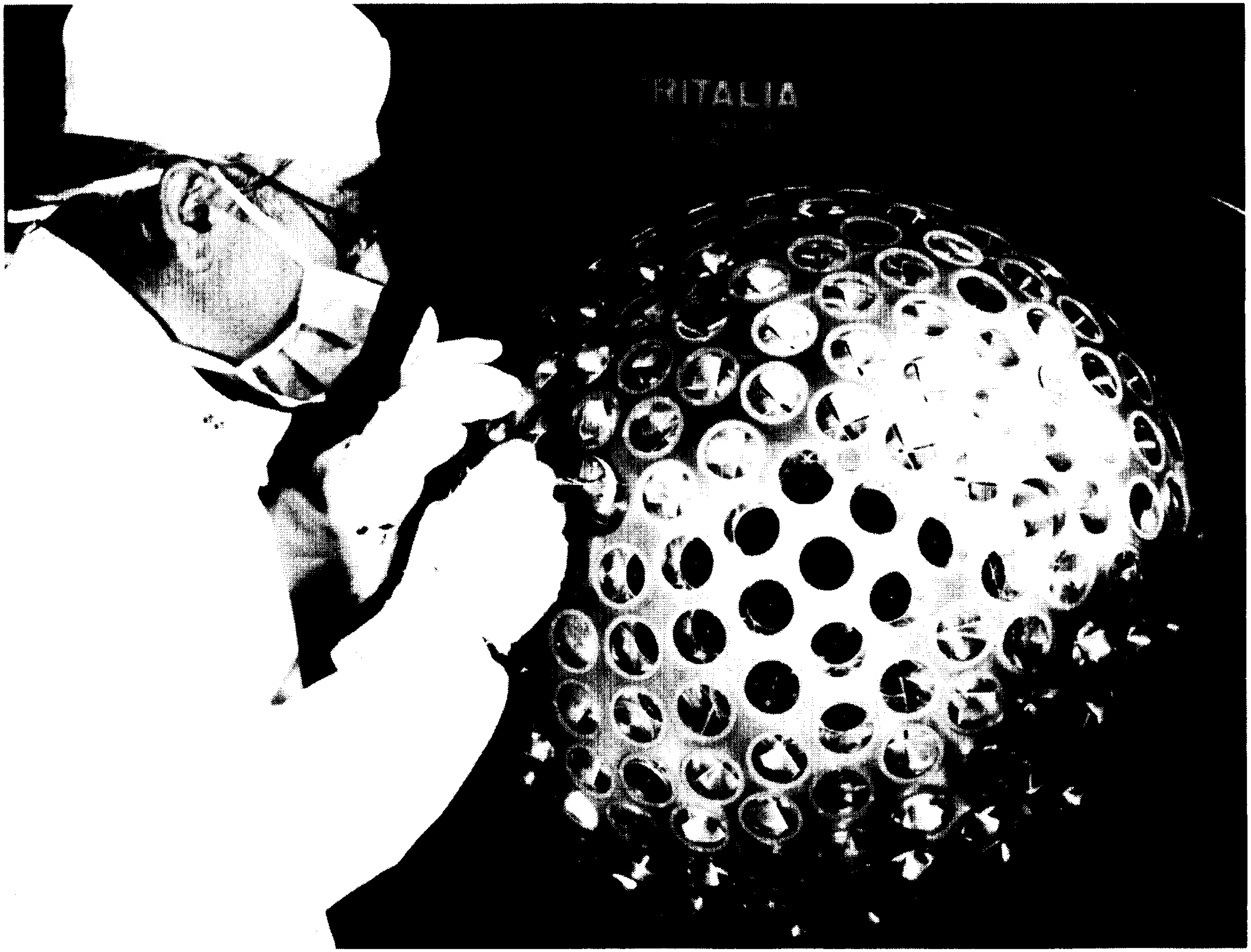
Studies of marine geodesy requires GPS measurements of the attitude of the surface platform to accuracies not previously attained. In order to verify this capability, two Rogue GPS receivers were installed on the NASA DC8 research aircraft and used to demonstrate the measurement of aircraft attitude during flight to an accuracy of 0.02^{0}.

E. FLIGHT MISSIONS

1. <u>LAGEOS-II</u>

LAGEOS-II was initiated in 1984 as a cooperative mission between the Consiglio Nazionale della Ricerche/Piano Spaziale Nazionale (CNR/PSN) of Italy, since renamed Agenzia Spaziale Italiana (ASI), and NASA. It is expected to be launched in 1991 aboard the National Space Transportation System (NSTS) using the Italian Research Interim Stage (IRIS) which ASI is developing as an Italian national space project.

Essentially identical to LAGEOS-I (launched by NASA in 1976), the surface of LAGEOS-II is covered by 426 equally-spaced laser Cube Corner Retroreflectors (CCRs) of which four are germanium and the rest (422) are made of fused silica (Figure II-6).



AERITALIA Space Systems Group

psn

Figure II-6 LAGEOS-II Spacecraft.

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In 1988, Aeritalia under contract to ASI, completed the fabrication of the LAGEOS-II spacecraft. The spacecraft was shipped to GSFC and optical characterization testing was performed on the spacecraft. At the completion of characterization testing the spacecraft was returned to Aeritalia for storage, pending delivery to the Kennedy Space Center (KSC) in 1991 for launch.

At KSC, the LAGEOS-II spacecraft and a LAGEOS Apogee Stage (LAS) will be attached to the IRIS and installed into the NSTS. After release from the NSTS, the IRIS will be used to transfer the LAGEOS-II/LAS to an orbital altitude of 5900km and an orbital inclination of about 41^0. The LAS will provide the impulse to circularize the orbit at 5900km, with an eccentricity of less than 0.02 and to attain the final 52^0 inclination.

ASI will integrate and deliver the LAGEOS-II/LAS/IRIS flight system to NASA; support the NSTS launch, flight, and landing operations; and command IRIS and LAS to insert the LAGEOS-II satellite into the planned orbit. NASA has provided existing ground support equipment, hardware, and software remaining from the LAGEOS-I mission, and performed the optical characterization tests. NASA will also provide technical consultation to support ASI assembly and integration of LAGEOS-II/LAS/IRIS, launch the package on NSTS as a payload of opportunity, determine its orbit, and coordinate LAGEOS-II data acquisition by NASA and other countries' SLR systems.

LAGEOS-II, is a passive satellite dedicated to laser ranging. Along with LAGEOS-I, it is expected to improve by approximately a factor of two the accuracies of the geodetic quantities produced by LAGEOS-I alone. SLR tracking of the two satellites will greatly enhance research in the areas of plate tectonics, regional crustal deformation, geodetic reference frames, Earth orientation, gravity field modeling, and Earth and ocean tides.

In 1988, NASA and ASI issued a joint research announcement requesting proposals for investigations which would use LAGEOS-II data. The announcement provided for investigators in Europe, Africa, and the middle East to submit proposals to ASI: all other countries were to submit proposals to NASA. The proposals received were evaluated separately by the two Agencies. In early 1989: NASA selected 14 and ASI selected 12 LAGEOS-II investigations and investigators. These investigators will be formed into a LAGEOS-II Science Working Group.

2. LAGEOS-III

It has been suggested that placing another LAGEOS spacecraft into an orbit supplementary to that of LAGEOS-I would permit the detection of the Lense-Thirring (frame-dragging) effect predicted by General Relativity. This mission is primarily related to astrophysics. However, since a third LAGEOS would also contribute to a number of SES objectives, it is also of interest to the SES Program.

The geodetic and frame-dragging precessions can be measured via laser ranging to a LAGEOS spacecraft launched into a carefullyoriented Earth orbit. Geodetic precession produced as the Earth moves around the sun and frame-dragging caused by the Earth's rotation combine to precess the line of nodes of the orbit. Orbital measurements of LAGEOS-I would be compared with orbital measurements of a new spacecraft (LAGEOS-III) which will have a supplementary orbital inclination. This combined geometry cancels non-relativistic precession contributions due to the Earth's non-sphericity. The tracking technology required is no different from that presently used for LAGEOS-I, but the accuracy requirement for inserting LAGEOS-III into the correct orbit is very strict if the non-relativistic effects are to cancel at the desired level. This two-spacecraft concept is conceptually similar to an earlier suggestion of using two counter-orbiting satellites in polar orbit to cancel non-relativistic effects and measure the relativistic precession (Van Patten and Everitt, 1976).

After an initial error analysis by the University of Texas at Austin, NASA and ASI formed study groups in May 1988 to conduct a more detailed analysis and to establish feasibility through a comprehensive numerical simulation. At about the same time, NASA Headquarters established a LAGEOS-III Science Advisory Group to provide guidance to the study groups, to monitor the study results for NASA, and to estimate the accuracy of the recovery of the Lense-Thirring effect using this approach.

The report of the Science Advisory Group to be released in early 1990 is expected to conclude that at the 70% confidence level the recovery accuracy would be in the range of 7% to 17%.

3. Magnetic Field Explorer/Magnolia

A combination of the MFE and Magnolia has been proposed as a single NASA/CNES mission for long-term measurements of the geomagnetic field.

A NASA/CNES Study Team was formed to conduct both a conceptual study (Ousley, et. al., 1987) and a system definition study (Ousley and Runavot, 1988). The Study Team recommended that NASA and CNES undertake a cooperative project combining long-term magnetic field measurements with simultaneous electric field measurements. Essentially the report recommended an equitable distribution of effort (launch vehicle, spacecraft, instruments and ground operations) and provided a basic spacecraft/mission concept to accomplish the joint scientific objectives.

Data from the MAGSAT mission provided an accurate description of the main geomagnetic field in 1980 (Langel, et. al., 1985). Another such mission of longer duration is required to obtain a description of the field at a later epoch together with measurements of the temporal variation at the epoch. The combination of data from the two missions would give an estimate of the temporal change between missions. These measurements would greatly enhance our understanding of the physical processes involved in the generation of the magnetic field and of the nature of the source regions, and would provide a valuable set of data for both solid Earth and space plasma physics studies.

A knowledge of the detailed time and space dependence of the geomagnetic field at the Earth's surface can be used to study the properties of the fluid motion in the core. The actual values of the fluid velocity in the upper core may be recoverable from the magnetic data, and a sufficiently long time series may give insight into the forces which drive the dynamo. Current plans for polar orbiting platforms do not include magnetometry until the late 1990's. Thus, in order to maximize chances of obtaining continuous magnetic field monitoring beginning in the mid 1990's, a MFE/Magnolia minimum mission lifetime of 4 years is required.

A MFE/Magnolia mission launched in early 1995 on Ariane 4, initially into a 600km, 86^0 inclination orbit, is needed for the study of the higher harmonics of the core field and meets the mission objectives. The baseline mission includes four magnetometers (two from NASA and two from CNES) and an electric field experiment using six 13-meter extendable antennaes similar to those flown on the Dynamics Explorer Mission. In addition to its basic magnetic field investigation, MFE/Magnolia will investigate large scale electric field structures and their relationship with ionospheric currents, study the global direct current electric field, and carry out a comprehensive investigation of the vector electric field.

The study effort between NASA AND CNES continues and a decision on a cooperative mission is expected in FY 1991.

4. <u>ARISTOTELES</u>

The ARISTOTELES mission is intended to investigate the structure and dynamics of the crust and mantle of the Earth. As planned by ESA, ARISTOTELES will carry a two-dimensional array of highly accurate (one part in 10^{10} g) electrostatic accelerometers which are arranged to measure the gradients of the Earth's gravity field. This mission meets the 10^{-2} E accuracy and 100km resolution measurement requirement needed for many SES studies (NASA, 1987).

Since the structure and dynamics of the crust are reflected in both the gravity and magnetic field data, composite measurements of gravity and magnetic fields at the same spatial resolution should provide a much more complete picture. Consequently, ESA and NASA have discussed the possible contribution by NASA, to the presently planned mission, of scalar and vector magnetometers, a GPS receiver for improved orbital tracking, and the provision of a Delta-2 type launch vehicle.

Under the proposed scenario, ARISTOTELES would orbit the Earth at 200km for 6-8 months before moving to 500-800km for the remainder of the mission duration (3-4 years). Magnetic field measurements at the higher altitude would complement MFE/Magnolia measurements and provide for continuous measurements of the main field until EOS is in orbit.

The initial ESA study for the baseline mission (without magnetometers) has been completed and a new study is underway to determine the mission/spacecraft impact and the additional cost associated with adding the magnetometers.

The solar cycle dictates that the ideal time for launch is late 1996 to mid 1977 to minimize atmospheric drag during the initial low altitude phase of the mission.

5. Gravity Probe-B

The GP-B mission of the NASA Astrophysics Division is planned for launch in 1997 to detect to about 1% the Lense-Thirring effect predicted by General Relativity. The concept is to use an extremely precise set of cryogenic gyros to measure during one year the anticipated frame-dragging of about 42mas. To achieve the needed measurement accuracy, the GP-B is designed to be "drag-free": helium gas boil-off is used to compensate for all non-gravitational forces. It is this "drag-free" feature which makes GP-B of interest to the SES Program. Studies have shown that with its polar orbit and orbital altitude of approximately 600km, accurate tracking of GP-B over a period of several years is capable of significantly improving our knowledge of the intermediate wave-length components of the Earth's gravity field.

The tracking accuracy needed is of the order of a few tens of centimeters, and can be achieved by augmenting the mission by the addition of a GPS receiver and CCRs.

6. Geoscience Laser Ranging System

Knowledge of the strain surrounding regional and local fault zones is fundamental to the understanding of crustal movements. A precise and viable method for rapid and frequent strain measurements can now be achieved due to advances in laser technology and the ability to range with lasers from a stable platform in space. A variation of this method can be applied to acquire altimetric topographical data for studies in several Earth-sensing disciplines. Some examples are: ice sheet volume in oceanography; rift valley delineation in geomorphology; and cloud-top heights in meterology. The ranging and altimetry techniques are combined in the Geoscience Laser Ranging System (GLRS), a facility instrument being developed by NASA/GSFC to fly on EOS.

The GLRS will perform geodetic quality observations to determine the intersite distance and relative height between fixed CCRs arrayed about fault zone surfaces, and to measure vertical height to the Earth surface along the nadir orbital track. In the first mode, the laser beam points at individual CCRs in order and the range time from the generation of the laser pulse to the pulse return is measured. As described below, the range measurements are made by transmitting pulses at both 532 and 355nm. The round trip travel time for the green pulse is measured to provide the basic range measurement. This travel time is measured to 10ps, corresponding to a range precision of 1.5mm. The range measurement is corrected for atmospheric propagation delay by measuring the relative flight times of the green and ultraviolet pulses to an accuracy of 2ps using a streak camera detector. This measurement obviates the need for ground atmospheric sensors. The altimetry profiling is similar, except that it requires no correction; the beam is diffusely reflected off the surface, and the waveform to the return pulse is electronically analyzed.

A conceptual diagram for the GLRS is shown in Figure II-7. The laser transmitter generates pulses at three wavelengths at the rate of 40pps, with a divergence of 0.1mr. The 1064nm infrared pulse is used for altimetry. The 532nm green pulse and the 355nm ultraviolet pulses are used for laser ranging. Laser ranging to a CCR begins when the pair outgoing range pulses trips an event timer. The pulses are aimed at the CCRs with the pointing mirror. They travel to the CCR, are reflected, return in a wide pattern to intercept the instrument, and are then relayed by the pointing mirror into the 18cm receiving telescope. The angle and light intensity of a portion of the green return pulse are detected by an angle tracker for feedback to the controller, which directs the gimbal motion of the beam pointing mirror. When the green light is detected by a photo-multiplier, it stops the time-of-flight measurement. Some green light along with the 355nm pulse is also detected in the streak camera which measures the pulse separation of the returned 532nm and 355nm pulses.

GLRS will have star trackers, and will make use of the EOS three-axis gyro and GPS receiver to provide position and attitude information for the pointing system and to locate the altimeter pulses on the nadir track to 5 arcseconds. Ranging measurement data, target location data, control commands, and software programs for operation are handled by the system computer.

Simulations have been conducted to estimate the accuracy with which baseline lengths, heights, and orbital parameters can be determined using typical GLRS data. Noise-limited calculations indicate uncertainties of 2 to 3mm for a typical CCR grid; the noise-plus-bias uncertainty is less than 1cm for distances up to 250km, with vertical accuracies better than 1.5cm. By tuning the orbital parameters, the orbit error is less than a few tens of centimeters over a 3 to 16 day period.

Conceptual design studies were completed in 1989 and system definition studies are to be completed in 1990. In 1989, NASA selected 13 investigators for the GLRS. These investigators were formed into a team which is guiding the development of the GLRS system.

The GLRS is scheduled to be placed into orbit aboard the second EOS platform.

7. Superconducting Gravity Gradiometer Mission

The development of a cryogenic, three-axis, gravity gradiometer (SGG) has been underway at the University of Maryland since 1980. Initially, it was planned that the Superconducting Gravity Gradiometer (SGG), would have an accuracy of 10^{-2}E. In 1983, a conference on gradiometery for space concluded that an accuracy of at least $3x10^{-3}$E would be needed (NASA, 1984c).

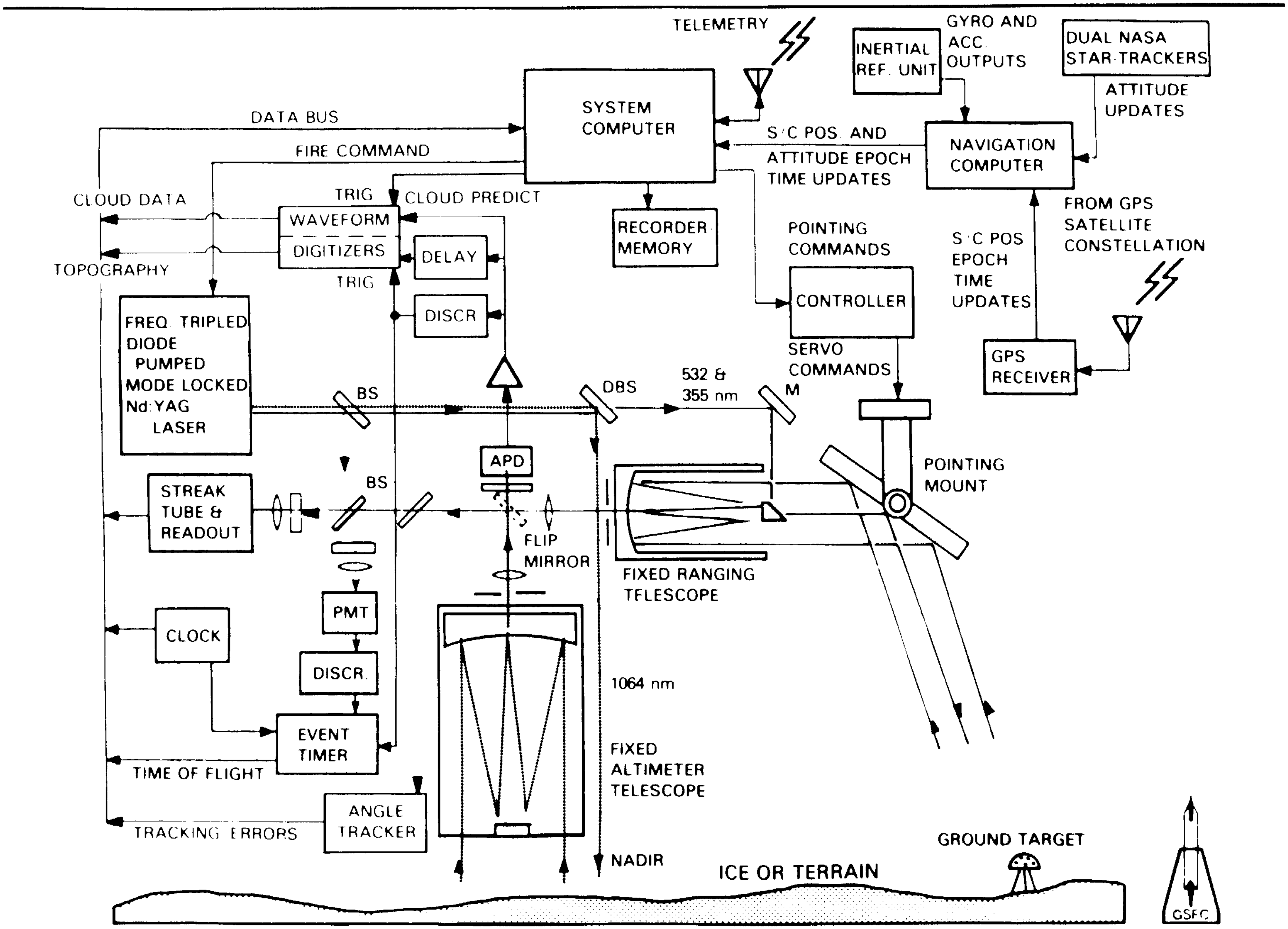

Figure II-7 Geoscience Laser Ranging System.

An interagency study team was formed in 1985 under the direction of the Marshall Space Flight Center (MSFC) to evaluate methods of testing the gradiometer in space and to develop spacecraft design concepts suitable for the SGGM. The principal report of the SGGM Study Team was published in 1988 (NASA, 1988b). An Executive Summary of the report was published in 1989 (NASA, 1989). The Study Team recommended the use of a NSTS-launched free-flyer for testing the SGG. In 1990, studies will be initiated to determine the feasibility of carrying the SGG on a NSTS-supported platform.

In 1988, the first tests of a three-axis SGG instrument (Model-II) were successfully completed, and work was started on an improved version (Model-III). Tests of a single-axis of Model-III were initiated in early 1989. These tests continued through most of 1989, and it is now expected that a fully tested laboratory version of the SGG will be available by the end of 1991.

SGGM will benefit greatly from the experience of the ARISTOTELES experiment and its higher resolution will enable studies of lithospheric phenomena, while the spatial resolution of ARISTOTELES will bring insight to mantle convection processes.

SECTION III. PROGRAM CHRONOLOGY: 1988-1989

A. 1988

JANUARY 1988

- The Haleakala, Hawaii, Lunar Laser Ranging Station was modified to add a path length compensator. With the modification and a new Microchannel Photomultiplier Tube performance was improved to 2cm (rms).

- A GPS receiver was installed at Haleakala, Hawaii.

- The Israeli Space Agency approved funding for the upgrade of the Bar Giyyora SLR Station.

- A report was issued on the gravity workshop held in Colorado Springs in February 1987.

- The GPS CASA Uno 88 campaign was conducted in central and northwestern South America: it involved 44 GPS receivers in 13 countries.

FEBRUARY 1988

- The second VLBI Technology Workshop was held near Monterey, CA.

- First mobile VLBI campaign of 1988 was initiated; data were acquired at nine sites, using three VLBI base stations.

- The first VLBI South Pacific Campaign involved stations at Kokee Park, Hawaii; Kashima, Japan; Shanghai, China; and Tidbindilla, Australia.

- Testing of TLRS-3 was completed and it was deployed to Mojave, CA; TLRS-2 returned to Easter Island.

- A joint PSN/NASA LAGEOS-II Research Announcement was released.

- A NASA VLBI Panel was established by the Geodynamic Program Office: the purpose was to evaluate and recommend the role of VLBI in the 1990's.

- Since the Geopotential Research Mission (GRM) was terminated, the GRM Science Steering Group was disbanded.

- The first test of the Model-II three-axis gravity gradiometer was successfully completed by the University of Maryland.

- A draft of a revised Five-Agency MOU, which superceded the MOU signed in 1981, was distributed to the agencies for review and comment.

MARCH 1988

- The fourteenth CDP Investigator's Working Group meeting was held at JPL.

- The LLR MOWG met to review data from stations in Haleakala, Hawaii; MLRS, TX; and Graz, France (CERGA).

- TLRS-1 was refurbished and shipped to Cabo San Lucas, Mexico; TLRS-4 completed final checkout at the Goddard Optical Ranging Facility (GORF); and TLRS-2 completed its tour at Easter Island and was shipped to Huahine, French Polynesia.

- As part of the WEGENER exchange program, MTLRS-1 arrived in the U.S. for a tour of Richmond, FL; Westford, MA; Owens Valley, CA; and Platteville, CO.

- The first of the new HP A400 computers was installed at the Fairbanks, Alaska, VLBI Station.

- The Washington VLBI Correlator was upgraded to the same configuration as the Haystack VLBI Correlator.

- The MLRS was closed down in preparation for the move to its new site on Mt. Folkes.

- A new agreement was drafted with CNES for continuation of measurements at Huahine, French, Polynesia.

- A NASA Water Vapor Radiometer Panel (WVR) was established by the Geodynamic Program Office to evaluate the effectiveness of WVRs for VLBI. The first meeting was held at JPL.

- NASA/CNES meetings on MFE/Magnolia were held to discuss new start possibilities.

APRIL 1988

- The USGS Brush Station was approved as a replacement for the Fort Ord VLBI site.

- A troublesome VLBI-GPS discrepancy at Mojave, CA, was identified as a survey problem.

- The new Shanghai, China, VLBI station joined stations in Hawaii and Japan in a Pacific Plate Motion Experiment.

- The second mobile VLBI campaign of 1988 was initiated; it included nine mobile sites and four base stations.

- The first meeting of the VLBI Panel was held at NASA Headquarters. The Panel heard reports from NGS, NSF, USNO, and NRAO on their projected needs for VLBI measurements.

- The MFE/Magnolia Phase-B Study Team Report was released.

MAY 1988

- A contract was signed with Universidad Nacional de San Agustin, Peru, for continued operation of the Arequipa SLR Station.

- The CDP was informed that the Wuchang Laser Station in China began tracking and that China was willing to send data to the CDDIS.

- The seventh LAGEOS-II Science Working Group met at Matera, Italy.

- The first geodetic VLBI experiment to use the 34m antenna at Tidbindilla, Australia, was conducted.

- Two Rogue GPS receivers were flown on the NASA DC-8 to verify kinematic attitude determination for submarine geodetic system development.

- The NASA Geodynamic Program initiated plans for a Geodynamics Workshop in the summer of 1989 to develop a program for the next decade.

JUNE 1988

- The JO-3 WVR was sent to Sweden to participate in intercomparison tests with the Onsala radiometer and balloon-borne instruments.

- The CDP was informed that the Hawaiian VLBI Station may be turned over to the U.S. Air Force.

- NGS installed a GPS receiver at Fort Davis, TX.

- TLRS-1 was at Cabo San Lucas, Mexico; TLRS-2 was in Huahine, French Polynesia; TLRS-3 completed its tour at Mojave, CA, and moved to Otay Mountain, CA; and MTLRS-1 was at Richmond, FL.

- A revised CDP site catalogue was released.

- MV-3 was shipped to Israel as a replacement for MV-1, which was scrapped.

- Coolfont, WV, was selected as the site for the 1989 Geodynamics Workshop.

JULY 1988

- The NASA Geodynamics Program investigators participated in an international workshop on The Interdisciplinary Role of Space Geodesy held in Erice, Sicily.

- The fourth Alaskan VLBI Campaign was started: MV-3 went to Hawaii and MV-2 went to Alaska. The Campaign involved five sites: Kodiak, Sand Point, Sourdough, and Yakataga (all in Alaska), and Whitehorse in Canada. Base stations used were Mojave, CA; Fairbanks, Alaska; and Westford, MA.

AUGUST 1988

- The 1988 VLBI Atlantic-Pacific Experiment was completed.

- ASI was established and replaced the previous PSN.

- A VLBI Mark-III system was installed at the DSN Station in Madrid, Spain.

- TLRS-1 was at Haystack, MA; TLRS-2 was at Huahine, French Polynesia; TLRS-3 was at Otay Mountain, CA; and MTLRS-1 was at Platteville, CO.

- NBS WVR tests were underway in Boulder, CO. The purpose was to compare NBS, NASA, and commercial radiometers.

- The Kootwijk SLR Station in The Netherlands terminated operations.

- NASA received 22 proposals and ASI received 10 proposals in response to a joint LAGEOS-II Research Announcement.

- The NASA 1989 Geodynamics Workshop was expanded to include planning for the NASA Geology Program.

SEPTEMBER 1988

- TLRS-2 was shipped to Easter Island; TLRS-1 was at Westford, MA; and MTLRS-1 was at Lampedusa, Italy.

- A meeting was held at Haystack, MA, to develop plans for improving VLBI accuracy.

- Chapman Conferences on GPS and gravity were held at Ft. Lauderdale, FL.

OCTOBER 1988

- The fourth mobile VLBI campaign of 1988 was started: data were acquired at 13 mobile sites and 6 base stations including the first VLBA station at Pie Town, NM.

- TLRS-3 was at GORF in preparation for shipment to Chile; TLRS-1 completed its tour at Westford, MA, and returned to GORF for update; and MTLRS-1 was at Owens Valley, CA.

- NASA GPS receivers were sent to Australia and New Zealand to support the NGS GOTEX experiment.

- The CDP IWG meeting in Munich, FRG, was attended by over 200 participants.

- A LAGEOS-II SWG meeting was held to discuss optical tests and the possibility of thermal testing.

- A LLR Management Operations Working Group (MOWG) meeting at the Centre d'Etudes et de Recherches Geodynamique et Astronomiques (CERGA) reviewed improvements to the CERGA Station and discussed the technical status and development of LLR stations.

- ESA requested that the NASA Geodynamics Program support SLR tracking of ERS-1.

NOVEMBER 1988

- The LAGEOS-II spacecraft laser characterization tests were started.

- VLBI managers of 12 U.S. stations and 5 foreign stations met at GSFC to discuss new developments in hardware, software, and data analysis.

- MV-2 was at JPL; MV-3 was at Presidio, CA.

- MTLRS-1 completed its tour at Owens Valley, CA, and prepared to return to Europe.

- The Superconducting Gravity Gradiometer Mission Study Team Report (Vol. II-NASA TM 4091) was issued: work was started on the Executive Summary (Vol. I-NASA TM 4091).

- The panels for the 1989 Geodynamics/Geology Workshop at Coolfont, WV, were established and invitations were sent to the proposed participants.

DECEMBER 1988

- At the Fall AGU, twenty-five papers were presented by Geodynamics investigators on plate motion, Earth rotation, and crustal deformation.

- A MOU was discussed with the Korean Space Agency.

- NGS installed new GPS receivers at Mojave, CA; Westford, MA; and Richmond, FL.

- VLBI operations at the Owens Valley Radio Observatory were terminated.

- A draft agreement was initiated with the National Technical University in Greece.

- MTLRS-1 returned to FRG.

- The Geodynamics Program established the NASA GPS Panel to recommend criteria for replacing the mobile VLBI, plans for use of GPS, and to define NASA's role in GPS applications. The first meeting of the Panel was held in San Francisco in conjunction with the American Geophysical Union (AGU) meeting.

B. 1989

JANUARY 1989

- The first of the Block-II GPS satellites was launched.

- TLRS-4 was completed and was deployed to Mojave, CA; MV-2 moved to Presidio, CA.

- Plans for the NASA 1989 mobile VLBI observing program were restricted to use of MV-2; MV-3 will be used exclusively for NGS programs.

- The USSR launched the Etalon-1 satellite (similar to LAGEOS-I, but in a 19,000km orbit).

- A NASA team conducted a review of the SLR/LLR Station in Orroral, Australia, and participated in a Critical Design Review of the Saudi Arabian Laser Ranging Observatory.

- NASA and ASI selected 23 LAGEOS-II investigations.

FEBRUARY 1989

- Tests of the Pie Town, NM, VLBI antenna, the first of ten VLBA stations, showed formal uncertainties of 5mm in the horizontal and 20mm in the vertical.

- A meeting was held at JPL to discuss CDP SLR support of TOPEX tracking.

- At a pre-Coolfont meeting of Panel Co-chairs held at GSFC the panel structure for the 1989 Geophysics Workshop (previously Geodynamics/Geology Workshop) and the proposed program objectives were revised.

- NASA announced the selection of 13 investigations for the EOS/GLRS.

- A meeting of the SGGM Study Team was held at the University of Maryland.

MARCH 1989

- A 32-meter VLBI antenna at Noto, Sicily, was completed.

- In support of the 1989 WEGENER Campaign, TLRS-1 was shipped to Athens, Greece.

- At a GPS meeting in Las Cruces, NM, a paper by the University of Berne showed uniform movement of the Yakataga, AK, site at 8cm/yr for the past five years.

- A meeting of SLR network personnel and GSFC electro-optics engineers was held to coordinate improvements in SLR technology.

- The Five-Agency MOU was distributed to the agencies for signature.

APRIL 1989

- The sixteenth CDP IWG was held at JPL: 110 papers and posters were presented. The meeting was held in conjunction with investigators of the NASA Geology Program.

- Global intercomparisons of VLBI and SLR solutions for 16 locations showed an overall rms agreement for all stations of 39mm.

- A pre-Coolfont meeting was held to review initial drafts of position papers prepared by the Panels.

- A VLBI Mark-III system was shipped to Noto, Sicily, to begin preparations for an operational test.

- A MOU was drafted between NASA and the USNO to provide for shared operations and funding for the Fairbanks, AK, and the Kokee Park, HI, VLBI Stations.

- MTLRS-1 was at Lampedusa, Italy; TLRS-1 was at Roumeli, Greece; TLRS-2 completed operations at Huahine, French Polynesia, and was preparing to move to Easter Island; TLRS-3 was at GORF, and TLRS-4 was preparing to leave Mojave, CA, to go to Mexico.

- An Atmospheric Moisture Intercomparison Study was initiated at the Wallops Flight Facility. The comparisons amomg different techniques yielded similar results.

- MV-2 was at Platteville, CO.

- The CSTG Subcommission on Space Geodetic Measurement Sites held its first meeting at JPL. The purpose of the Subcommission is to recommend site catalog and survey standards.

- The WEGENER/Medlas Campaign for 1989 was rescheduled due to TLRS-1 shipping problems and technical problems with the MTLRS-2. In the new schedule, MTLRS-2 and TLRS-1, together, will occupy five sites while MTLRS-1 will occupy four sites.

- A meeting of the LAGEOS-II SWG was held to review results of the laser characterization tests.

MAY 1989

- The GPS GeoMex 89 experiment was conducted: measurements were made across the Gulf of California and on Guadalupa Island.
- A pre-Coolfont meeting of Panel Co-chairs was held to review the revised panel position papers and to finalize preparations for the Workshop.
- A draft of the NASA VLBI Panel Report was mailed to the Co-chairs for the Coolfont Workshop.
- MTLRS-1 was at Lampedusa, Italy; MTLRS-2 remained in The Netherlands due to laser problems.

JUNE 1989

- The Geodynamics Program participated in an Italian workshop held in Trevi, Italy, on the scientific objectives and plans for ARISTOTELES.
- The fourth International Conference on the WEGENER/Medlas Project was held at Scheveningen, The Netherlands, to discuss results and compare data analysis techniques of six independent groups.
- The Program Panel for the Coolfont Workshop met to develop a draft of the program plan for the next decade.
- TLRS-1 completed measurements at the Roumeli, Crete, site and was enroute to Yigilca, Turkey; MTLRS-1 was at Karitsa, Greece.
- MV-3 stopped at GORF on its way to Europe.
- The LAGEOS-II Ground Operations Working Group met at KSC.

JULY 1989

- The 1989 NASA Geophysics Workshop was held at Coolfont, WV, and was attended by 130 participants from 11 countries and 4 other federal agencies.
- The fifth Alaskan Campaign was initiated; MV-2 was at Sand Point, AK.
- At the first stop on its European tour, reimbursed by IfAG, MV-3 was at Helsinki, Finland.
- NGS terminated VLBI operations at Fort Davis, TX.
- NASA Headquarters reorganized the Geodynamics and Geology Programs into the SES Branch.
- TLRS-1 was in Yigilca, Turkey.

- The USSR launched Etalon-II.

- The LAGEOS-II Pre-Storage Review was held at Turino, Italy.

AUGUST 1989

- The Coolfont Program Panel completed a first draft of a report on the major initiatives for the NASA Solid Earth Science Program for the 1990's.

- The Hawaii Kokee Park 9-meter Station was transferred to CDP: the CDP will provide multi-agency support for other investigations.

- MV-2 was at Whitehorse, Canada; MV-3 was at Bergen, Norway.

- MTLRS-1 was at Yozgat, Turkey; MTLRS-2 was at Askites, Greece; TLRS-3 was at GORF for a performance check and for validation of new software; TLRS-4 was at Ensenada, Mexico.

- The first Noto, Sicily, VLBI experiments were performed.

- As part of its Global Sea Level Program, NGS shipped a Mark-III to Tasmania, Australia.

- The final NASA VLBI Panel Report was delivered to Headquarters.

SEPTEMBER 1989

- Analysis of 1989 Alaskan data showed that Kodiak, Sand Point, and Sourdough continue to move relative to Fairbanks in a manner consistent with previous years. An 8 cm "jump" in the Cape Yakatoga data was confirmed.

- MV-3 completed observations at Brest, France, and moved to Grasse, France.

- MTLRS-1 was at Diyarbakir, Turkey; MTLRS-2 was at Askites, Greece; TLRS-1 was at Yigilca, Turkey; TLRS-2 was at Huahine, French Polynesia, and was preparing to move to Easter Island; TLRS-3 was at GORF; and TLRS-4 was at Ensenada, Mexico.

- The WEGENER Management Board held a meeting in Bad Bodenderf, FRG, to discuss future plans.

OCTOBER 1989

- The seventh International Symposium on Laser Ranging Instrumentation was held at Matera, Italy.

- The seventeenth CDP IWG meeting held at GSFC was attended by 145 people, including representatives of seven countries.

- The first meeting of the European Laser (EurLas) Network was held in Matera, Italy.

- MTLRS-1 was at Kattavia, Greece; and TLRS-1 was at Melengiclik, Turkey.

- MV-2 and -3 made post-Loma Prieta earthquake observations at three sites in California: the Presido in San Francisco, Fort Ord, and Point Reyes.

- GPS Rogue receivers were deployed and a Rapid Static Survey technique was used to measure post-seismic relaxation in the epicentral region following the earthquake.

<u>NOVEMBER 1989</u>

- TLRS-1 moved to Xrisokelleria, Greece; MTLRS-1 was at Askites, Greece.

- TLRS-4 completed measurements in Ensenada, Mexico, and was diverted to Mojave, CA, for post-Loma Prieta earthquake observations.

<u>DECEMBER 1989</u>

- Reports on the results of the NASA Geophysics Workshop and the Loma Prieta earthquake observations were reported at the Fall AGU.

- TLRS-1 moved to Punta sa Menta, Italy.

- The upgraded Moblas-2 at Bar Giyyora, Israel, successfully ranged to LAGEOS-II and Ajisai.

- A Mark-III VLBI terminal was shipped to Noto, Italy, to support measurements of Intra-European geodetic ties.

- A major failure occurred in the Moblas-7 slip ring assembly.

- A LAGEOS-II Flight Safety Review was held at JSC.

- A GPS receiver was installed at the Goldstone complex of the DSN.

- A Rogue receiver was mounted in a buoy to test marine operability and multipath environment for submarine applications.

- The VLSI gate array design for the TurboRogue GPS receiver was completed.

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APPENDIX A

GLOSSARY OF ACRONYMS AND ABBREVIATIONS

AGU	American Geophysical Union
Ajisai	Satellite with CCRs (Japan)
ARISTOTELES	Applications and Research Involving Space Techniques Observing the Earths's Field from Low Earth Orbiting Satellite
ASI	Agenzia Spaziale Italiana
CASA	Central And South America (GPS experiment)
CCRs	Corner Cube Retroreflectors
CDDIS	Crustal Dynamics Data Information System
CDP	Crustal Dynamics Project
CERGA	Centre d'Etudes et de Recherches Geodynamique et Astronomiques
cm	Centimeter
CNES	Centre Nationale d'Etudes Spatiales (France)
CNR	Consiglo Nationale della Ricerche (Italy)
COTES	Joint Working Group on the Establishment and Maintenance of a Conventional Terrestrial Reference System
CSTG	Commission for Coordination of Space Techniques for Geodesy and Geodynamics
DSGS	Densely Spaced Geodetic Systems
DSN	Deep Space Network
E	Eotvos Unit (10^{-9} sec^{-2})
EOS	Earth Observing System
ERS-1	ESA Remote Sensing Satellite
ESA	European Space Agency
Etalon	Satellite with CCRs (USSR)
FLINN	Fiducial Laboratory for an International Natural science Network
FRG	Federal Republic of Germany
GEOMEX	Geodesy in Mexico
GEOS	Geodynamic Experimental Ocean Satellite
GGN	Global Geophysical Networks
GLRS	Geoscience Laser Ranging System
GORF	Goddard Optical Research Facility
GoTex	Global Tracking Experiment
GP-B	Gravity Probe-B
GPS	Global Positioning System
GRM	Geopotential Research Mission
GRMSSG	GRM Science Steering Group
GSFC	Goddard Space Flight Center
IAU	International Astronomical Union
IfAG	Institut fur Angewandte Geodaesie (FRG)
IGRF	International Geomagnetic Reference Field
IRIS	Italian Research Interim Stage (Italy)
IUGG	International Union for Geodesy and Geodynamics
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
Km	Kilometer
KSC	Kennedy Space Center
LAGEOS-I	Laser Geodynamics Satellite (U.S.)
LAGEOS-II	Laser Geodynamics Satellite (Italy)
LAS	LAGEOS Apogee Stage

LLR	Lunar Laser Ranging
Magnolia	Magnetic Field Satellite (France)
MAGSAT	Magnetic Field Satellite (U.S.)
Medlas	Mediterranean Laser Project (WEGENER)
MFE	Magnetic Field Explorer (U.S.)
mgal	Milligal (10^{-3} cm sec^{-2}, approximately 10^{-6} g)
MLRS	McDonald Laser Ranging Station
mm	Millimeter
Moblas	Mobile Laser
MOU	Memorandum of Understanding
MOWG	Management Operations Working Group
mr	Millradian
ms	Millisecond
MSFC	Marshall Space Flight Center
MTLRS	Modular Transportable Laser Ranging System
MV	Mobile VLBI
NASA	National Aeronautics and Space Administration
NBS	National Bureau of Standards
NGS	National Geodetic Survey
nm	Nanometer
NOAA	National Oceanic and Atmospheric Administration
NRAO	National Radio Astronomy Observatory
ns	Nanosecond
NSF	National Science Foundation
NSTS	National Space Transportation System
nT	NanoTesla
NUVEL-1	Tectonic Plate Model (DeMets)
OSSA	Office of Space Science and Applications (NASA)
pps	Pulses per second
ps	Picosecond
PSN	Piano Spaziale Nazionale (Italy)
rms	Root mean sum
RSS	Rapid Static Survey (GPS)
SEASAT	Ocean Dynamics Monitoring Satellite
SES	Solid Earth Science
SGG	Superconducting Gravity Gradiometer
SGGM	Superconducting Gravity Gradiometer Mission
SLR	Satellite Laser Ranging
SSG	Science Steering Group
Starlette	Satellite with CCRs (France)
SWG	Science Working Group
TLRS	Transportable Laser Ranging Station
TOPEX	Ocean Topography Experiment
USGS	United States Geological Survey
USNO	United States Naval Observatory
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry
VLSI	Very Large Scale Integrated circuit
WEGENER	Working group of European Geo-scientists for the Establishment of Networks for Earthquake Research
WVR	Water Vapor Radiometer

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3. <u>Geopotential Fields</u>

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