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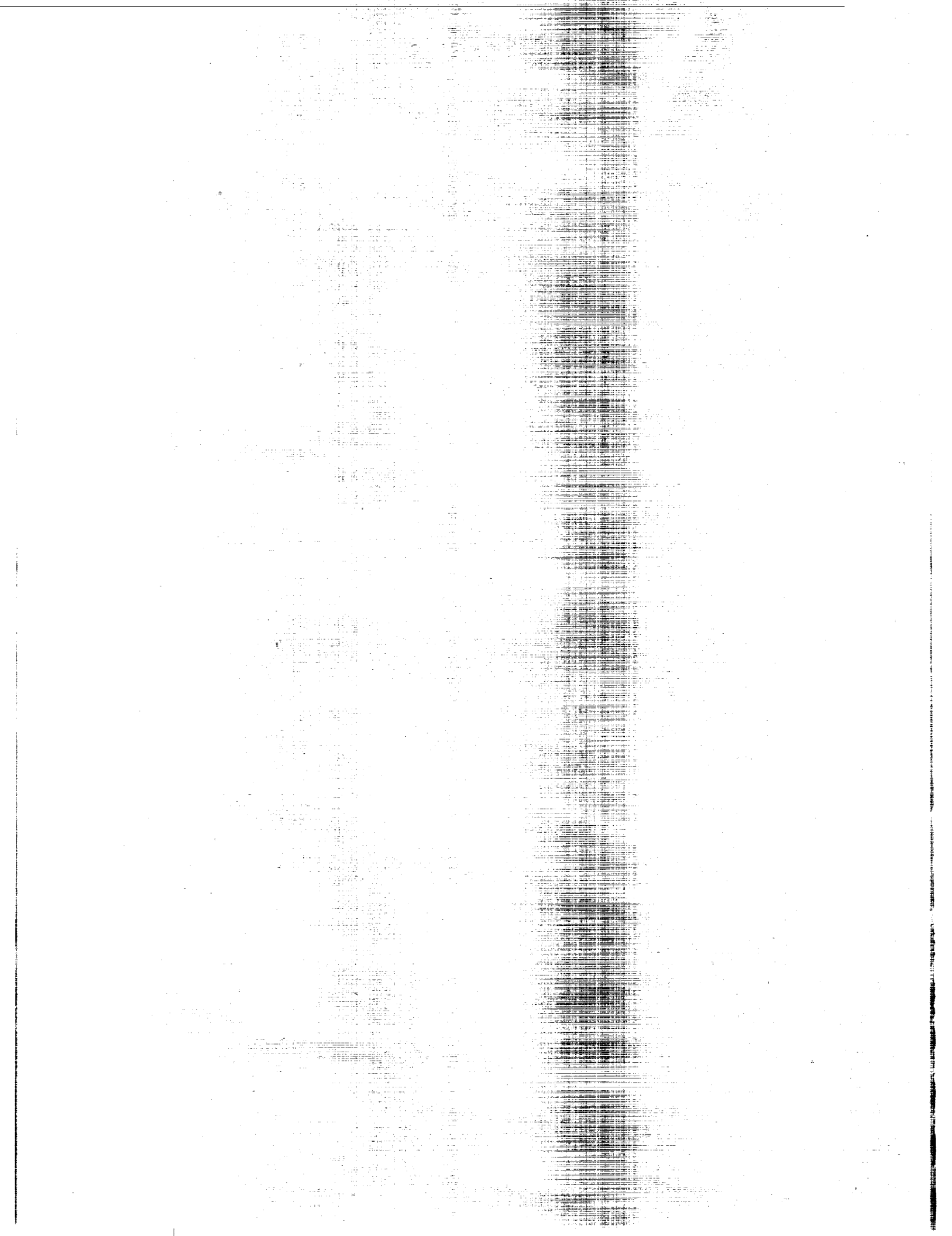
## Solid Earth Science in the 1990s

### *Volume 3—Measurement Techniques and Technology*

FEBRUARY 1991

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## Solid Earth Science in the 1990s

### *Volume 3—Measurement Techniques and Technology*

*NASA Office of Space Science and Applications  
Washington, D.C.*



National Aeronautics and  
Space Administration  
Office of Management  
Scientific and Technical  
Information Division

**1991**



## FOREWORD

With the 1980's came the first widespread recognition that an understanding of the Earth requires a global perspective of the numerous interacting dynamical systems operating at a range of spatial and temporal scales. This has led to the recognition of the urgent need to understand the Earth as a planet and to assess the impact of both natural change and human interaction. From this has arisen the novel concept of the "Mission to Planet Earth". The solid Earth is a crucial element of the global interplay of dynamic systems, and the Solid Earth Science Program of NASA for the coming decade builds upon the new paradigm of Earth System Science.

To help plan its Solid Earth Science Program for the 1990's, NASA sponsored a workshop at Coolfont, WV, from July 22 to July 28, 1989. The workshop was attended by over 130 people from universities, research institutions, and government agencies in the United States and 13 countries. In this the third volume of the set of reports generated by the workshop, the measurement techniques and technologies needed to satisfy the data requirements from the science panels are addressed.



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# 1. INTRODUCTION

The Measurement Technique and Technology Panel was tasked with identifying measurement systems for each of the measurements required for the Geodynamics/-Geology Program that would fall under the NASA purview. For each technique, the Panel was to provide:

1. The pertinent measurement requirements from the Science Panels.
2. Alternative approaches to meet the measurement requirements.
3. Present measurement capability in terms of: accuracy, spatial resolution, and temporal resolution.
4. Present limitations in performance.
5. Required support measurements such as: meteorology, eccentricities, footprint surveys, local environment, etc.
6. Developments required to improve performance of current systems and new systems which may be built.
7. Projected performance over the next decade with assumptions used.
8. Present and projected level of data flow and flow limitations.
9. Mode of data storage and user access.

The Panel was also to develop a technology plan on how to bring the measurement techniques to the level of capability required to meet the scientific objectives. This plan was to include:

1. Strategies, tradeoffs, and issues.
2. Development program
3. Validation
4. Schedule
5. Cost

The Panel was to identify measurement needs that cannot be met using current techniques with projected capabilities, and try to identify other techniques that could satisfy these needs. In the data area, the Panel was tasked with providing:

1. Description of current data storage and management systems in use for the current NASA Geodynamics and Geology Programs.
2. Description of the current data stored and the method of user interface.
3. Limitations of the current system.
4. New capabilities and capacity anticipated over the next decade (CDDIS, PLDS, Eos, etc.)
5. Shortcomings anticipated.

The members of the Panel are listed in Table 1.1.

To facilitate the activities, the Panel was divided into subpanels, each responsible for the material in a particular measurement area. These included:

SUBPANEL	MEASUREMENT AREA
Geodetic Techniques	Baselines, Station coordinates, Orientation/Rotation, Underwater Geodetic Measurements
Remote Sensing Techniques	Thermal IR Mapping, Visible Mapping, Topography (Land and Ice), Spectrometry
Field Measurement Specialized Ground- Measurements Data Systems and Techniques	Gravity Field, Magnetic Field Based Gravity Field, Earth Rotation CDDIS, PLDS, EOS.

The memberships in the subpanels is reflected in the authorship of the chapters.

**Table 1.1. Panel membership**

Mike Abrams	JPL
Peter Bender	U. Colorado
Tom Clark	GSFC
Steve Cohen	GSFC
John Degnan	GSFC
Francis Everitt	Stanford University
Clyde Goad	Ohio State University
Robert King	MIT
Tom Herring	CfA/MIT
Anne Kahle	JPL
Ron Kolenkiewicz	GSFC
Fuk Li	JPL
Henry Linder	GSFC
Cary Noll	GSFC
Ho Jung Paik	U. Maryland
David Sandwell	U. Texas
Michael Pearlman	CfA
Alan Rogers	MIT/Haystack
Peter Shelus	U. Texas
Ed Smith	JPL
Fred Spiess	Scripps Inst.
David Sonnabend	JPL
Byron Tapley	U. Texas
Cathy Thornton	JPL
Nancy Vandenberg	Interferometrics

## 2. GEODETIC TECHNIQUES

This section on Geodetic Techniques is concerned with measurements of: baseline length (changes in length), station positions (3 dimensional), and Earth rotation (nutation, polar motion, and length of day). The most stringent requirements from the Scientific Panels are summarized as follows:

### Earth Orientation

Accuracy of measurement:	0.1 mas (for polar motion), 0.01 mts (for length of day)
Frequency of measurement:	Four times per day
Distribution of sites:	8-9 sites uniformly distributed

### Crustal Motion(Global)

Accuracy of measurement:	1.0 mm per year
Frequency of measurement:	1/year for 1 mm system 12/year for 5 mm system
Distribution of sites:	2-3 per plate

### Crustal Motion(Regional)

Accuracy of measurement:	1.0 - 10.0 mm per year
Frequency of measurement:	Continuous to once per 2 years
Distribution of sites:	30-1000 sites in 25 regions (assume 1000-2000 sites)

The techniques discussed in this section include:

- Satellite Laser Ranging (SLR)
- Lunar Laser Ranging (LLR)
- Spaceborne Laser Ranging (SBLR)
- Global Positioning System (GPS)
- Very Long Baseline Interferometry (VLBI)
- Other Radio Techniques (PRARE, DORIS, GeoBeacons)

Each of the techniques supports a number of measurement applications as shown below: (an X means applicable, P means possibly applicable—insufficient data are available currently to determine)

	SLR	LLR	SBLR	GPS	VLBI	RADIO TECH
Polar Motion	X	X		P	X	P
Length of Day	X	X		P	X	
Plate Motion	X	X		X	X	X
Regional Motion	X		X	X	X	X

Each technique however has its own unique characteristics involving: visibility, reference frame, susceptibility to environment, modeling errors, measurement errors, etc. As such, each has its own strengths and weaknesses for particular geodetic measurements, plus its own special synergies for other measurements in the Program.

## 2.1 Groundbased laser ranging techniques

M. Pearlman, T. Varghese, J. Degnan, P. Shelus, R. Kolenkiewicz

This section deals with Satellite Laser Ranging (SLR), and Lunar Laser Ranging (LLR) and reviews the current status of each, the current limiting factors, work in progress, progress and performance anticipated over the next decade, and issues of data management.

The Williamstown Conference in 1969 projected a requirement on laser ranging of 2 cm. This was presented as range accuracy or systematic error on a pass-by-pass basis. The community saw the need for doing better, but with range accuracies then about 1 meter, they tried to put their requirement on a practicable basis. Unfortunately, with  $\pm 2$  cm range accuracy, measurements of crustal movement would require long integration times, and high frequency, low amplitude structure would be impossible to measure.

From the International Workshop on "The Interdisciplinary Role of Space Geodesy [Mueller and Zerbini, 1989], the most stringent requirements for SLR measurements come from long term dynamics of the solid Earth where: (1) motion along interplate baselines "must be resolved to an accuracy of about 1 mm/yr"; (2) variations in rates must be studied for "signals averaged over 1 hour to 100 years"; and (3) "the most significant departures from rigid plate motions occur in zones of 100 to 1000 km width." In addition, requirements from Earth rotation and Earth tides project needs for measurement accuracies of "0.3 cm" and "an order of magnitude better than present space techniques can achieve," respectively.

Over the past several years, lasers and other techniques have surpassed the Williamstown requirement, having reached measurement accuracies of 1 cm, and still offering promise of considerably better performance. Based on this, and the evolving need to see smaller structure over shorter observation times, the Laser Ranging community is now striving for measurement accuracies of 1mm with occupation times of a week or less.

Satellite and Lunar Laser Ranging use short pulse lasers to make range measurements from the ground to retroreflectors on artificial satellites or the moon. The quantity of interest is a time-of-flight corrected for ranging system internal delay (calibration), atmospheric refraction (delay), retroreflector offset to the spacecraft center-of-mass (or lunar reflector position), and network epoch synchronization. SLR measurements are referred to the Earth's center-of-mass, and geodetic and geophysical quantities are measured by aggregating data over a number of satellite passes. For the past decade, satellite targets include one high satellite LAGEOS (5900 km) for measurements of crustal motion and a complex of low satellites, used mainly for gravity field determination. In early 1989, an additional satellite, Etalon (19000 km), was launched by the USSR for measurements of crustal motion and Earth dynamics.

SLR is currently used at interstation separations of 100 km to intercontinental distances. Station position determinations are typically computed from 4-6 weeks of data, but this limitation has been imposed by the limited number of appropriate satel-

lites. Over the next three years, additional satellites to be launched in both high and low orbits will significantly enhance tracking coverage and geometry, thereby appreciably reducing required data integration time.

LLR measurements are referred to the planetary reference frame, which is nearly identical to the inertial reference frame; lunar and geophysical quantities are measured by aggregating data from one or more of the four arrays over a number of lunar transits.

### 2.1.1. Systems in Operation or Under Development

Worldwide there are approximately 30 fixed SLR stations, of which 20 have high performance and routine or scheduled operation. A list of the stations providing data during the last year is included in Table 2.1-1. In addition, there are systems under development in Japan, PRC, USSR, Saudi Arabia, Italy, and India. At the moment, density of coverage varies with geography: there are many stations located in Europe, the U.S., and the Orient; there is no coverage in Africa, Indochina, and the Indian Ocean. Many groups tend to keep their fixed SLR systems "close to home." There is also considerable variation in the technology from system to system: Some are at the state-of-the-art, using mode-locked lasers, microchannel plate photomultiplier tubes, constant fraction discriminators, 20 ps resolution timing electronics, and either internal or very close range target calibration. The very oldest vintage systems are still using Q-switched lasers, conventional diode chain photomultipliers, threshold discrimination, 1 ns resolution timing electronics, and billboard target calibration. Fortunately, some of these older systems such as those in Arequipa, Matera, and Bar Giyyora are now in the process of being upgraded or replaced.

**Table 2.1-1 Satellite laser ranging stations (providing data during the last year)**

Arequipa, Peru	Bar Giyyora, Israel (Moblas 2)
Borowiecz, Poland	Chang Chun, PRC
Grasse, France	Graz, Austria
Greenbelt, MD (Moblas 7)	Helwan, Egypt
Herstmonceux, UK	Matera, Italy
Mazatlan, Mexico (Moblas 6)	Metsahovi, Finland
Monument Peak, CA (Moblas 4)	
Mt. Fowlkes, TX	Mt. Haleakala, HI
Orroral Valley, Australia	Potsdam, GDR
Quincy, CA (Moblas 8)	Riga, USSR
Santiago, De Cuba, Cuba	Shanghai, PRC
Simosato, Japan	Wetzell, FRG
Yarragadee, Australia (Moblas 5)	Zimmerwald, Switzerland

There are presently seven mobile SLR systems:

<u>SYSTEM</u>	<u>OWNED/OPERATED</u>
MTLRS-1	IFAG/FRG
MTLRS-2	DUT/Holland
TLRS 1-4	NASA/USA
HTLRS	Hydrographic Office/Japan

Additional systems are under development in Italy and the USSR. Typically, mobile systems occupy sites for periods of 8–12 weeks and then require 3–10 days for relocation, depending upon distance and logistics. Since the mobile laser systems are fairly new, they tend to be of recent technology and at the higher end of the performance spectrum. Sites currently available to accommodate mobile SLR are listed in Table 2.1–2.

Worldwide, there are six laser ranging stations which are capable of ranging to the moon: Mt. Fowlkes (Texas), Mt. Haleakala (Hawaii), and Grasse (France) which are in routine operation; and the Crimea (USSR), Orroral Valley (Australia), and Wettzell (Federal Republic of Germany) which are in engineering status. One other potentially lunar capable station is under development in Japan. In the longer run, activities in Saudi Arabia and in China may lead to stations which also have lunar capability.

The LLR data which the operational stations obtain contribute significantly to Earth science. Over the past five years, intercomparisons of LLR-derived UT–1 with other techniques show agreement to 0.1 millisecond; it is presently the only such product which can serve as an adequate check on VLBI UT–1 over extended periods of time. Observations of the lunar rotation axis and free librations give information relevant to the formation of the Earth–moon system. Nutation results provide valuable insights into the internal structure of the Earth. The LLR data set, now 20 years in length, permits the determination of corrections to the standard IAU model for the 18.6 year terms as well as the precession constant.

LLR is also important in the unification of reference systems since most of the lunar capable stations are artificial satellite ranging stations as well, allowing the straightforward tying of the geocentric artificial satellite reference system with the dynamical reference system defined by the solar system. Finally, LLR data has made major contributions to testing the foundations of gravitational physics. These contributions are described in several reports of the National Academy of Science and in the recent NASA report "Space Science: 1995–2015."

**Table 2.1-2 Mobile SLR sites**

---

**WEGENER:**

Switzerland	Monte Generoso
Italy	Lampedusa
	Punta sa Menta
	Basovizza
	Bologna
	Medicina
Greece	RoumeliI
	Karitsa
	Xrisokellaria
	Askites
	Kattavia
	Dionysos
Turkey	Yozgat
	Diyarbakir
	Yigilca
	Melengiclik

**Crustal Dynamics Project:**

Westford, MA  
Richmond, FL  
Bear Lake, UT  
Mojave, CA  
Flagstaff, AZ  
Platteville, CO  
Vernal, CA  
Yuma, AZ

Cerro Tololo, Chile  
Santiago, Chile  
Arequipa, Peru  
Cabo san Lucas, Mexico  
Easter Island  
Tahiti

**Japanese Marine Geodetic Control:**

Ishigaki-shima  
Titi-shima

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### 2.1.2. System Performance

Ranging performance for typical SLR systems is shown in Table 2.1-3. Although it is common to quantify ranging machine performance in terms of single shot range noise, the most relevant quantity is accuracy, taken here as systematic excursions seen on a pass-by-pass basis. In practice, these error signatures are observed either through careful ground-based measurements designed to isolate individual error components, such as range variation with signal strength or azimuth (see Figures 2.1-1 and 2.1-2), or through side-by-side collocation or ranging by two systems (see Figure 2.1-3). These collocation tests which have involved several of the fixed lasers in the U.S. and Europe, and all six of the MTLRS and TLRS systems, have recovered interstation coordinates using long-arc techniques to less than 1 cm, and in many cases a few millimeters, using data sets of 20-30 Lageos passes.

The recovery of station positions or other geophysical parameter involves orbital computations in which data is averaged over a number of passes and, therefore, sky geometry. The newer ranging systems with 1 cm quality data are producing station positions of accuracy 2 cm with about 100 passes of data. Older systems, even those with accuracies of 3-6 cm are producing station positions only a factor of two worse owing to the strength of data averaging.

The LLR stations have very significant differences in design, but all are using recent technology. An overview of the LLR System Performance is shown in Table 2.1-4.

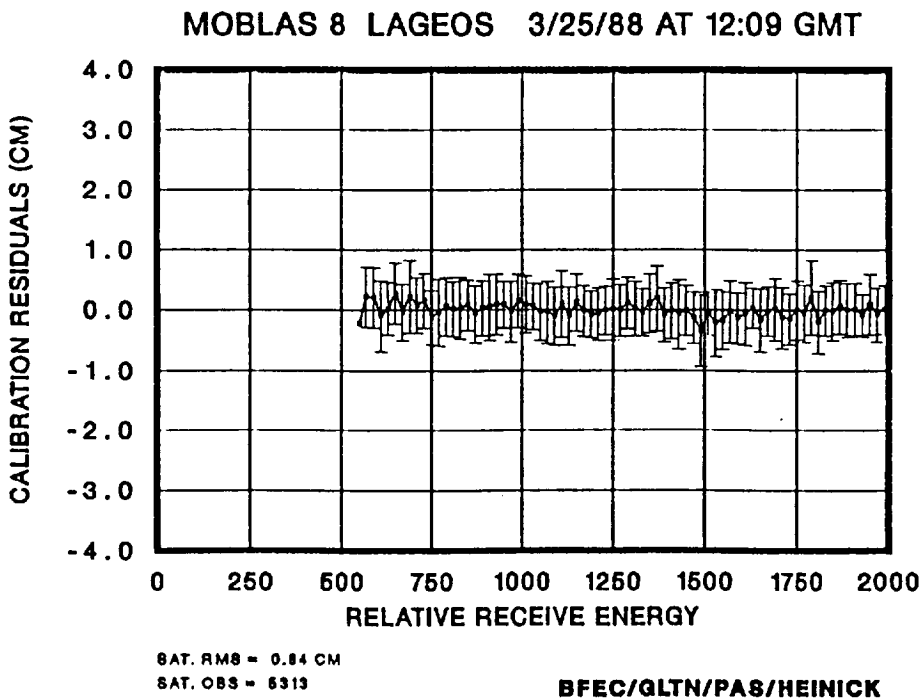


Fig. 2.1-1 Receive energy dependence

**TABLE 2.1-3 SLR System performance**

	<u>Current technology</u>	<u>Older vintage technology</u>
Single shot noise	0.7 – 3.0 cm	10 – 15 cm
Normal point noise	0.2 – 0.4 cm	5 cm
Ranging machine accuracy	0.5 – 1.0 cm	3 – 6 cm
Systematic errors per pass		
Range modeling errors (Refraction, C/M correction)	0.5 cm	0.5 cm
Station position recovery (100 passes/3 months)	2 cm	4 cm
Baseline change (Monthly solutions with several years of data)	± Few mm/yr	± Several mm/yr
Polar motion	3 – 6 cm	
Length of day	0.2 ms	

**TABLE 2.1-4 Lunar Laser Ranging system performance**

Single shot noise	2–6 cm
Normal point noise	1–3 cm
Ranging machine accuracy	2–4 cm
Systematic errors	
Range modeling errors (refraction)	0.5 cm
UT1	0.1 ms
Variation of latitude	5 cm
Geodetic precession (Moon)	2%
Nordtvedt effect	<5 cm

# M7 IC VS. EL

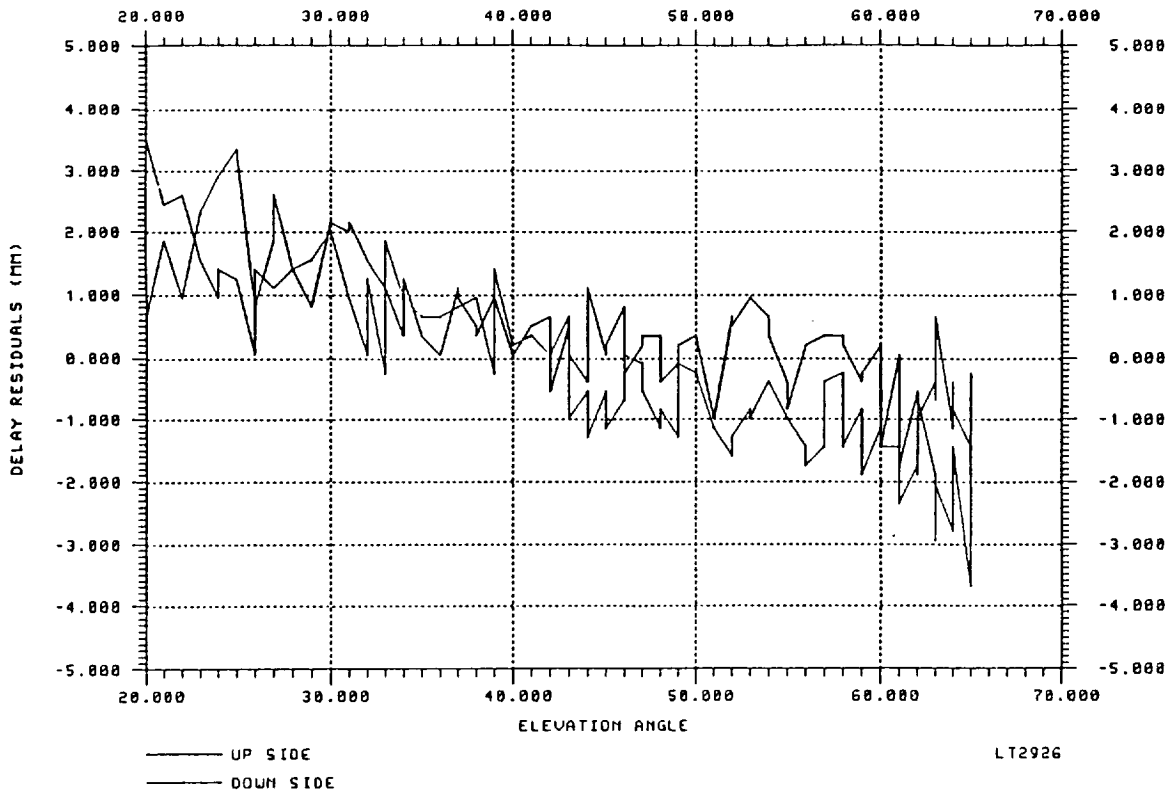
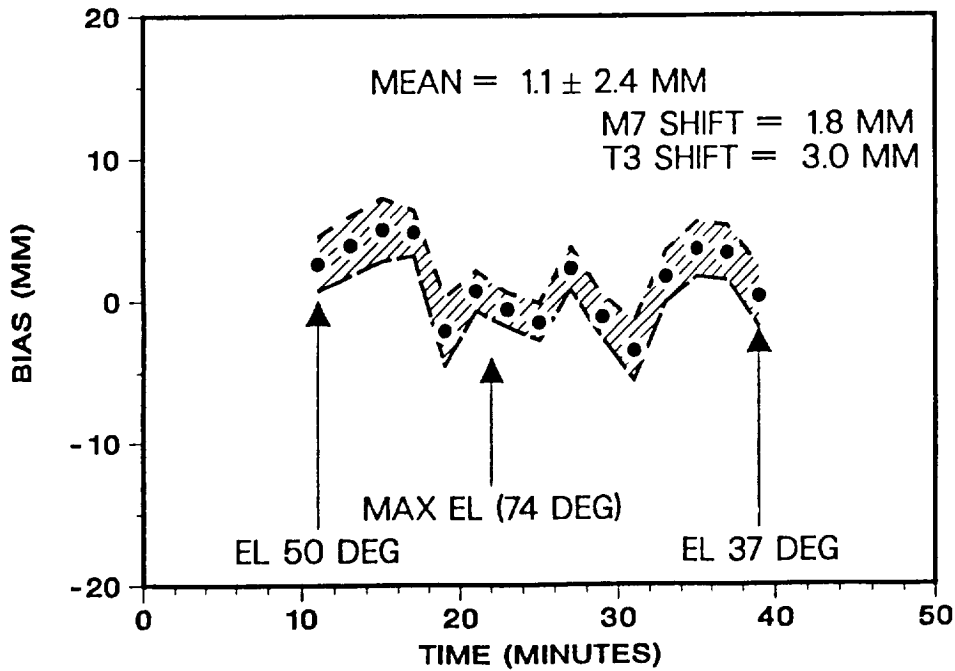


Fig. 2.1-2 Internal Calibration versus elevation angle



ALLIED SIGNAL

BENDIX  
VAN B. HUSSON

Fig. 2.1-3 TLRS-3 minus Moblas 7 colocation

### 2.1.3. Current Limiting Factors and Activities Underway

#### *Satellite Laser Ranging*

##### *Limited Number of Satellites*

For measurements of crustal motion and Earth rotation, the Williamstown Report recognized the need for a complex of three retroreflector satellites in high orbit to provide sufficient geometry and opportunity for observations. As of the end of 1988, there is a complex of satellites at lower orbital altitudes but only one satellite, LAGEOS, at a higher altitude. As a result, it has taken several months to acquire sufficient data to accurately determine station positions and changes in position.

In early 1989, two higher altitude satellites, Etalon I and II, were launched by the USSR. In addition, a number of satellites will be launched over the next five years, radically changing the situation. These satellites to be launched include:

High Satellites		Low Satellites	
LAGEOS II (Italy/US)	1991	Stella (France)	1990
LAGEOS III (Italy/US)	1992 (?)	ERS-1 (Europe)	1990
ACRE (US)	1992 (?)	TOPEX (France/US)	1991

The dramatic increase in the complex of higher satellites will provide both the orbital geometry and nearly continuous opportunity for observation which should allow SLR site occupations to be reduced to a week or less. Those in lower orbits will be used to further refine the gravity field models.

##### *Refraction*

The commonly used Marini and Murray model [Marini and Murray, 1973] for refraction delay correction has an estimated accuracy of 0.5 cm or better at 45° elevation. The error is much worse at lower elevations, but the symmetry of the passes provides considerable benefit through data averaging.

Efforts are underway now to adapt some of the improvements developed in the CfA 2.2 refraction model for VLBI [Davis *et al.*, 1985] to the optical region. Since the optical region is less influenced by water vapor, the improvements may not be as dramatic, but may still offer considerable benefit.

Both of the above atmospheric models, and their associated error estimates, assume that the atmosphere is made up of spherically symmetric shells which obey the hydrostatic equation in the vertical dimension. No allowance is made for horizontal gradients in the surface meteorological parameters such as pressure, temperature and humidity. In recent VLBI data analyses, a parameter associated with horizontal atmospheric gradients was included in the analysis along with the station coordinates and used in the atmospheric delay correction for the VLBI signals. The validity and ultimate accuracy of this approach should be studied further with an eye toward possible

application in single color satellite laser ranging systems. The validity of such a model correction, if one is possible for SLR, should be established by comparison with direct measurement of the atmospheric refraction correction.

The most promising technique for directly measuring the refraction corrections in the optical region is multiple frequency ranging. The technique uses the difference in round trip arrival time of frequencies selected to accentuate the dispersive effects of the atmosphere, and thereby gives a direct measure of the amount of intervening atmosphere. Work is currently underway at CNES with 1.06 micron/5300A and at GSFC with 5300A/3533A. Other groups are pursuing similar systems, and satellite ranging is anticipated within the year.

Because of the differential dual wavelength nature of the measurement, dispersion measurements must be made to sensitivities of 10–20 times greater than the required accuracy, *i.e.*, millimeter accuracies require dispersion measurements of 0.05–1 mm. Fortunately, commercially available streak cameras are already providing subpicosecond resolution (.1mm), and the technology is evolving very rapidly.

At the moment, it is not clear that multiple frequency ranging machines would be required at every site. The first priority is to develop the machines and use them for model evaluation and development. Once the limit of refraction corrections based on groundbased data can be evaluated at a variety of sites and conditions, then the economics and the value for going to multiple frequency systems could be evaluated.

#### *Spacecraft Center-of-Mass Correction*

Spacecraft center-of-mass correction is measured in the laboratory before launch. For a geometrically simple spacecraft like LAGEOS, the correction is taken as independent of aspect, and constant over lifetime. For more complex spacecraft, such as TOPEX, the correction depends upon aspect and even internal fuel consumption. The most accurate correction determined to date is that of LAGEOS which is estimated at about  $\pm 3$  mm, and this limitation was imposed by the laboratory equipment used in 1976 prior to launch. More elaborate equipment, including multiple frequency measurements with streak camera technology, are being used for tests on LAGEOS-II, which should give us improved corrections for both LAGEOS-I and LAGEOS-II.

Until the LAGEOS II measurements are properly analyzed, we will not know the ranging accuracy limitations imposed by the temporal spreading and the polarization dependence resulting from the multiple cube corner response of the array. However, it is thought to be in the range of 1–3 mm, depending upon the period of averaging. New receiver strategies and/or algorithms must be developed to extract the optimum range and differential range measurements from multiple color streak camera waveforms obtained at low signal levels. In addition, a parallel effort to develop new space targets more suited to millimeter accuracy ranging should be pursued. One approach might be spherical satellites having fewer but larger cube corner reflectors which would further restrict the number of cubes contributing to the return signal while maintaining a high optical radar cross section. A recently proposed approach based on a modified cats-eye reflector would potentially provide a polarization-insensitive "point" target response and a more circularly symmetric far field target response than is currently obtained with LAGEOS and Starlette type targets.

### *Geodetic and Orbital Modelling*

In spite of the fact that the ranging machines have demonstrated centimeter accuracies, it takes a considerable amount of data to reach 1 cm accuracy baselines and station coordinates. This is partially due to the geometry limitation and partially due to the quality of the geodetic and orbital models.

Historically, this modelling has been driven by the data quality and quantity. As the 1cm data base grows and additional satellites are introduced, we anticipate the evolution of model quality to continue. In particular, the 1cm data has been available from a fairly wide network for only a couple of years, and as a result, model development which relies on the historical data base is dependent upon a considerable amount of lower quality and quantity data. This situation, however, is changing rapidly.

### *Operational Limitations*

Limitations are imposed on the performance of the global SLR Network as a result of operational and technical differences among stations. For the most part, SLR stations are locally built using the same general philosophies, but differ in configuration, components and subsystems, calibration, operating procedures, and software. In addition, these independently built and operated systems are operated with very different budget and manpower constraints which lead to differences in temporal coverage, system reliability, and implementation of upgrades for improved performance. As a result, there are differences in: data quality, data quantity, daylight ranging capability, and data turnaround.

Considerable effort is being made within the international community through organizations such as the CSTG to introduce more standardization, particularly in: calibration, data handling procedures, and specialized components (such as the micro-channel plate tube). There is a strong tendency for new stations to be built by a few manufacturing groups (such as BFEC, TPD, EOS, and Intercosmos) that are now following much more common paths. In addition, the older, more unique and problematic SLR systems are tending to fall into disuse or are being totally replaced by new systems.

An example of activities presently underway to foster standardization is the development of UNIX-based software for common use on site for:

- Data Evaluation
- Machine Performance Evaluation
- Orbit/Prediction Update
- Normal Point Generation
- Multisatellite Tasking/Interleaving
- Communications

### *Geographic Distribution*

There are some areas of the world, such as Africa, the Indian Ocean, South America, and Indochina, where there is little or no SLR coverage for spacecraft tracking, global crustal motions, or local measurements. This situation will be relieved somewhat

over the next five years through fixed systems now under development in/for: Japan, China, USSR, Saudi Arabia, Italy, and India. In addition, mobile lasers now under development in Italy, France, and the USSR should provide greatly enhanced coverage.

### *Limitations in Manpower*

With the additional satellites and the demand for more comprehensive spatial and temporal coverage, stations will be required to extend hours of operation and reduce downtime. Since manpower is already the greatest expense at most stations, operations are limited to 1–2 shifts (40–80 hrs.) per week. The tendency now is to implement more automation, first for preparing and validating data to speed throughput and monitor system performance, and second for reducing manpower during data acquisition. Some systems now under development envision hands-off operations for at least part of the daily data acquisition and maintenance activities.

### *Lunar Laser Ranging*

Many of the issues and activities discussed under SLR, such as refraction, modelling, and operational considerations, are pertinent to LLR. In addition:

#### *Limited Number of Stations and Geographic Coverage*

At the moment, there are three LLR stations in routine operation and no southern hemisphere coverage; this places limitations on global kinematics and lunar science. The addition of operating stations at the Crimea, Orroral Valley, Wettzell, and Tokyo will provide comprehensive longitudinal coverage and some data from the southern hemisphere. This will constitute a very significant improvement in geographic coverage. There would still be a very strong desire for a second Southern Hemisphere site in either South America or Africa.

#### *Limited Data Yield*

Lunar ranging is difficult, requiring a highly optimized system for routine success. This, coupled with data limitations due to phase of the moon, daylight conditions, cloud cover, and seeing condition (atmospheric propagation), means that only groups with adequate technical and financial support will be active and successful participants. The threshold for success has been very high, and in the past LLR groups have been required to do considerable sophisticated technical development on their own.

The availability of commercial companies now willing to furnish part or all of the LLR system may relax the development requirement on individual groups. Some economies based on sharing software and hardware design/fabrication will be forthcoming. On the other hand, the low data yield is pressing for more and more sophistication to expand data yield and data quality.

#### 2.1.4. Required Support Measurements

Aside from calibration data required to measure system delay, the laser ranging systems require groundbased measurements of pressure, temperature, and humidity at prescribed locations around the site to model the columnar delay due to atmospheric

refraction. The most sensitive of these parameters, barometric pressure, models into a delay of about 4 mm per millibar at an elevation of 45°. Experience has shown that validation of this groundbased data, probably through regular comparison trips with portable standards, will be required for millimeter accuracy.

Range measurements with SLR and LLR must be extrapolated to reference geodetic ground markers. This accounts for the offset between the system reference (such as the intersection of axes) and the local geodetic network. Measurement of this offset, or "system eccentricity", must be made whenever there is reason to believe that shifts have occurred in system position (vertical or horizontal).

#### 2.1.5. Future Improvements in Ranging System Performance

The available technology has evolved beyond the stage of current SLR and LLR equipment in the field. To reach 1 mm ranging accuracy will require an order of magnitude improvement in hardware performance, but even with modest projections based on current technology, it does not appear that the ranging machine itself will be inhibited from reaching this capability.

The main areas where improvements will be implemented are: (1) laser pulse width, (2) time-of-flight electronics, (3) detectors, (4) calibration, (5) epoch synchronization, and (6) laser pulse repetition rate. Lasers in the field are currently operating with 200 ps pulse widths at 5–10 pps. Reduction in pulse width reduces range rms, but more importantly, it allows more detailed observation of systematic signatures. Field-durable lasers are currently available with 50 ps pulse widths, and an addition factor of 2–3 seems quite reasonable based on laboratory systems.

Field time-of-flight electronics, have resolutions of 20 ps (4 mm). Hardware with 5 ps precision has been developed in prototype. This and upgrades planned by vendors indicate that considerable improvement is underway in this area, with the ultimate limitation being imposed by the discriminator. The use of newer, high speed AlGaAs technology should improve timing resolution by at least a factor of four.

The best detectors in the field now for SLR and LLR are the MicroChannel Plate (MCP) tubes. The impact of the MCP is to reduce the internal system delay dependence on focal spot position and return signal strength. Tubes now in the field with 12 micron channel width constrain the range dependence on amplitude to about 3mm with a quantum efficiency of 10%. Tubes are now being built with 6 micron channels and quantum efficiencies of 20%, and additional timing improvements may be possible with improved anode designs. Other classes of photodetectors, such as the geiger mode avalanche photodiode, also offer promise of improved performance but mostly in LLR where further improvements in quantum efficiency (as high as 50%) would help the current weakness in data yield.

The most accurate ranging systems in the field today are using either internal calibration or the close "Nelson Pier" external calibration target. At millimeter accuracies, measurements will be corrupted by temporal, spatial, and environmental variations, requiring full environmental monitoring including real-time or shot-by-shot monitoring of internal delay, plus system eccentricity within a local, stable reference frame. No



new technology will be required to perform this monitoring, but the system configuration may have to be modified to accommodate the additional measurements necessary.

Epoch synchronization through GPS is currently at 100 nsec with improvement to 50 nsec or better within the current capability. This is sufficient to meet the 1mm accuracy requirement.

With the large complex of satellites to be available within the next five years, interleaving of passes will become necessary during data acquisition. It may be advantageous to increase the data rate to as much as 25–50 pps and reduce the time span for each normal point. A LAGEOS normal point might be reduced from two minutes to, perhaps, 15–30 seconds. The impact of this on the system would be the requirement for higher pulse repetition rate lasers and faster data recording systems.

Lunar ranging would also benefit greatly from higher repetition rate for increased data yield. In addition, the next five to ten years should see increases in laser output power and higher detector quantum efficiency in LLR systems.

#### 2.1.6. Projections of System Performance

Projections of ranging system capability depend upon our estimates of how the hardware and modelling upgrades and development will evolve. After examining each of the issues and activities underway, we developed a projection of capability for the next decade assuming that development is actively pursued. Table 2.1–5 shows some of the key parameters with overall ranging accuracy reaching 1–2 mm by 1998. The dominant error sources are the atmospheric refraction and orbital modelling.

#### 2.1.7. Present and Projected Data Flow

The SLR field stations produce tracking data in two forms: full rate data which includes all points, and quick–look data which is sampled at the rate usually of 50 points per pass. Full rate data is sent from the station periodically (few days to a week) by storage medium to the operator's processing center, and then forwarded to the CDDIS in 60–90 days. The quick–look data is sent daily by communications to BFEC where the data is reviewed and redistributed for those users requiring rapid data. Full rate data is available from the CDDIS by request or by terminal access. Processing centers are also furnishing the CDDIS with aggregated data in the form of normal points along with their full rate submission.

The global network is currently producing about 10,000 passes of data per year on LAGEOS, Starlette and Ajisai. This equates to about 12,000,000 full rate data points or about 1.5 billion characters per year. The quick–look data amounts to about 500,000 points or about 50 million characters per year.

**TABLE 2.1-5 Ranging capability**

	Present	1993	1998
Single shot noise (mm)	7-30	2-3	1
Normal point noise (mm)	2-4	1	<1
Ranging machine systematic errors (mm)	5-10	2-5	1
Atmospheric refraction			
Model (mm)	5	4	3
Multicolor (mm)		2	1
S/C Center of mass correction (mm)	3	1	1
Epoch	100 ns (5 mm)	50 ns (3 mm)	10 ns (<1 mm)

Measures are now underway to have stations compute normal points on site. It is anticipated that within two years most stations will submit both quick-look and normal points by communications. The quick-look data will remain the basis for engineering review, while a set of normal points (of similar or smaller size) will be available for rapid data use. The intention is to provide normal points from the field of sufficient quality to satisfy the Crustal Dynamics requirements. There is, however, no illusion that the requirement for archiving full rate data at the CDDIS will disappear in the foreseeable future.

By 1992-3, the increased satellite tracking load, the additional stations projected to be in operation, and the need for extending tracking schedules to provide better and more rapid temporal and geometric coverage, will increase the data volume by a factor of 6-10. Based on this projection, the SLR Network will be producing as much as 10-15 billion characters of full rate and about 500 million characters of quick-look data per year. This, coupled with scientific desire for more rapid availability of results, will pressure the community to use the field generated normal points as primary data. This, of course, requires that the SLR stations provide sufficient supporting information and performance validation to convince the scientific community of the normal point data quality.

The LLR field stations at Mt. Fowlkes, Mt. Haleakala, and Grasse produce about 600 normal points of lunar ranging data per year, each point an aggregation of 5-200 individual photons accumulated over 5-45 minutes. The normal points are formed by each group and submitted as the primary data to the CDDIS where it is available to user. The data and information record for each normal point is about 300 characters. With the operations in Orroral Valley, the Crimea, Tokyo, Wettzell, and possibly other stations, the data yield would probably double.

The estimated cost and manpower for these activities are tabulated in Schedule 2.1-1 which is discussed in the next section.

### 2.1.8. System Development Plan

The SLR system development plan focusses on: (1) the evolution of technologies to bring the current SLR network stations to the limit of their capabilities in a systematic low risk approach; and (2) the development and implementation of newer technologies and configurations that will lead to the next generation systems with even greater ranging capabilities. This plan includes:

1. Development and demonstration of upgrades to the laser network from its current instrument accuracy of 1 cm to a few mm. This approach will include a phased upgrade of MOB LAS 7 to demonstrate the improved capability and to identify the components and procedures required for the rest of the network (MOB LAS, TLRS, and the cooperating network stations).

Once the upgrade capability is demonstrated on MOB LAS 7 it will be implemented on the other SLR and LLR systems within the network: the technology and system plans will also be made available to the overseas groups for implementation into their systems.

2. Development and demonstration of the newer technologies such as: newer high performance lasers streak cameras and optical delay line calibration techniques to enable SLR to reach mm accuracies and multiple wavelength operation. The newer techniques will be developed on the 48 inch telescope facility at GSFC to:
  - a. Demonstrate the capability of the newer technologies.
  - b. Study and develop refraction models to test the limits of single frequency ranging operations.
  - c. Develop a basis for configuring the design of the next generation SLR system.
3. Once the newer technologies have been demonstrated a mobile prototype of the next generation system will be built for use as a portable standard for: (1) collocation and high accuracy baseline tests with the 48 inch telescope test facility; (2) performance evaluation of the other network lasers; and (3) evaluation of refraction models at a typical distribution of sites.
4. The new systems based on the prototype technology would then replace some of the SLR systems in the field as required by the program.

### *Upgrading of the Current Systems*

The upgrading required to bring the ranging machine accuracy of the current SLR stations to a few millimeters is based on: (1) modifications that maintain the present systems configurations; (2) components already commercially available; (3) modifications to commercial items that have already been tested in the laboratory; or (4) modifications to commercial components that appear within the current capability of manufacturers.

This activity includes:

- Reduction of the laser pulsewidth from 200 ps to 50 ps by changing some components on the current laser table.
- Development and testing at a selected manufacturer of MCP tubes with narrower channels to reduce jitter and range aliasing and begin tests of newer tubes with 6 micron channels and higher quantum efficiencies and higher speeds.
- Reconfiguring the time interval unit (TIU) to use it as an interpolator in an event timer configuration with a high frequency external oscillator as a coarse reference; this will require support to one of the TIU manufacturers to upgrade their electronics for higher resolution and to reconfigure their system to use the same circuits for both the start and stop channels.
- Upgrading the meteorological sensor system to read automatically conditions at several locations in and around the system for both refraction correction and internal monitoring of system performance.
- Completing development of the internal calibration system using an internal optical path to measure system delay in real time.
- Completing the development and demonstration of the on-site data processing and interface system which was recommended by the SLR Computer Panel and is now underway.
- Upgrading the station timing system with a disciplined oscillator for better short term timing stability.
- Upgrading the controller hardware and software to: (1) replace hardware items that are becoming very difficult to spare and maintain; (2) replace software that is cumbersome and difficult to maintain and upgrade due to age; (3) introduce automation to enhance data yield and reduce operator intervention; and (4) provide on-site computer redundancy.

This program will be undertaken to bring the SLR Network to the highest level of performance practicable within the constraints of current system configuration. The anticipated ranging machine accuracy is in the neighborhood of 2–4 mm.

The ultimate limitations on the current SLR systems will be imposed by their basic configuration. These systems which were originally built for decimeter accuracies have been upgraded to centimeter and now even subcentimeter capability. At millimeter accuracy however it may be necessary to make some fundamental changes in configuration in order to incorporate the streak camera and its associated components. In addition, it is doubtful that the current laser telescopes are stable to one millimeter nor that they would lend themselves to real or near real time monitoring of system eccentricity.

The estimated cost and manpower for both development and subsequent implementation in the network stations are tabulated in Schedule 2.1-1. In all of the following schedules the costs are given in current K\$. As discussed above the development phase includes the implementation and demonstration in MOBLAS 7.

**SCHEDULE 2.1-1. Upgrade of the current SLR systems (\$K)**

FY	90	91	92	93	94	95	96	REPL
Laser	60							60
Detector								
First Unit	25							40
Development	75	75	75					
TIU	50	75	100					60
Met. Sensor	25							25
Internal Cal.	*							
Data system	*							35
Timing system		25						25
Controller		100	100					50
Automation		25	25	25				15
Control Elect.		50	100	50				
<b>TOTAL</b>	<b>235</b>	<b>350</b>	<b>400</b>	<b>75</b>				<b>310</b>
Manpower (my)	2	3	2	2	2			2
<u>Replication (12 units)</u>								
Hardware (\$K)		305	610	915	915	915		
Manpower		2	4	6	6	6		

*Development of New Generation Systems*

The next generation SLR systems will be designed for 1 mm accuracy. At issue with these systems is whether such capability requires multiple frequency operation for refraction correction or whether atmospheric models can be refined to satisfy this need. Under this plan a prototype of the next generation system will be developed jointly by Code 601 and Code 723 at GSFC on the 48 inch telescope facility. This facility has been made available as an R&D site and is supported in part by Center funding. The prototype will be built to provide millimeter accuracy for ranging and multiple frequency operation for refraction analysis. The specific frequencies and their number will be selected to optimize the refraction correction procedure.

The system which is already in the early stages of development in the laboratories at both GSFC and BFEC is based on the following:

1. Higher performance lasers
  - a. 10-15 ps pulsewidth

- b. 20–50 pps
  - c. multifrequency output
2. Streak cameras for detector and epoch timing interpolator and baseline tests.
  3. Optical delay line for calibration
  4. Automated guidance and control system.

The new technology on the 48 inch telescope facility will be analyzed through collocation at GSFC and then used for testing and development of refraction models for range correction. Once the concept has been satisfactorily demonstrated a mobile prototype will be built as a portable standard for: (1) collocation and precision baseline tests with the 48 inch telescope facility; (2) validating performance of the other stations in the current SLR Network; and (3) development and validation of refraction models. This network and model validation process is a critical aspect of reaching the 2–4 mm level performance of the upgraded SLR stations in the current network (see 2.1. above).

The estimated cost and manpower for these activities are tabulated in Schedule 2.1–2.

Once the performance of the new generation prototype system has been carefully assessed there is a major decision point on whether and how to proceed with the implementation of a new generation network and the design of its stations. This decision will depend upon:

1. The latest requirements from the scientific community at that time.
2. The demonstrated performance of the upgraded stations in the current SLR Network.
3. The results of the refraction and spacecraft modelling activities.
4. The performance of the prototype system in both single and multiple frequency modes.
5. The extent to which the existing stations can accommodate the new system components.

It is assumed that the improved capability will be required to meet the long term scientific objectives of this program and that a major reconfiguration or replacement of the SLR systems may be required.

**SCHEDULE 2.1-2. Development of prototype on 48" telescope facility**

FY	90	91	92	93	94	95	96	97	98	99
Laser	150	50								
Streak camera	200	20	20							
Optical TIU/CAL		100								
Controller & S/W	50	75	75							
Data system		50								
Automation	50									
GPS/INMARSAT			60							
Control elect.		100	50							
Support	100	100	100	100	100	100				
Gen. Devel.	100	200	300	400	500	500	500	500	500	500
<b>TOTAL</b>	<b>650</b>	<b>695</b>	<b>605</b>	<b>500</b>	<b>600</b>	<b>600</b>	<b>500</b>	<b>500</b>	<b>500</b>	<b>500</b>

**Development of portable standard and new generation prototype**

FY	90	91	92	93	94	95	96	97	98	99
Laser		100	100							
Streak camera		200	20							
Optical TIU/CAL			50	50						
Controller & S/W			75	75						
Data system		50								
Automation		50								
Met. Sensor			25							
Telescope			200	200	200					
Structure			50	150	300					
GPS/INMARSAT					60					
Control Elect.		50	50							
<b>TOTAL</b>		<b>450</b>	<b>570</b>	<b>475</b>	<b>560</b>					
Manpower (my)	5	5	7	7	7	2	2	2	2	2
Replication (12 units)										
Hardware (\$K)						4500	4500	4500	4500	4500
Manpower (my)						5	5	5	5	5

### *Model Development*

Improvement in range accuracy to 1 mm will require continued development in the models for refraction correction and spacecraft center of mass.

Refraction: It will be necessary to continue work on the verification and/or possible improvement of the: (1) Marini and Murray Atmospheric Model; and (2) CfA Refraction Model using ground based data and columnar information derived from both ground and satellite sensors.

Models have already been developed for extraction of refraction correction from multiple frequency ranging. Once data is forthcoming from the prototype on the 48 inch facility and from the subsequent field version we anticipate considerable development and refinement for both single frequency and multiple frequency models.

This activity includes manpower to continue the development of single and multiple frequency refraction models and to analyze multiple frequency range data for performance evaluation and model development.

Spacecraft Center-of-Mass: The laboratory measurements on LAGEOS II showed that center-of-mass corrections with the current field lasers can be made to an accuracy of several mm on a single shot basis and 1–2 mm on an aggregated basis over a pass. As laser pulse widths are reduced with commensurate improvement in receiver performance it will become possible to discriminate returns from individual cubes and cube arrays on the satellite. It is anticipated that analysis of the return signals will allow us to improve the center-of-mass correction by using information on satellite orientation.

In addition to this analysis approach there are also several new ideas on design of future retroreflector spacecraft that could support submillimeter ranging.

This activity includes manpower and equipment to continue the refinement of center-of-mass corrections on current satellites and to study future spacecraft and retroreflector designs with submillimeter capabilities.

The estimated cost and manpower for these activities are tabulated in Schedule 2.1–3.

### *Upgrade for Current LLR Capable Stations*

Under current plans to upgrade the entire NASA/SLR network the lunar capabilities of Haleakala and MLRS will not be significantly affected. The current number of days on which observations can be obtained by the Haleakala and McDonald stations and their accuracies although useful in producing the above-mentioned results are marginal and sometimes inadequate for meeting future scientific goals.



**SCHEDULE 2.1-3. SLR model development**

---

FY	90	91	92	93	94	95
Refraction						
Manpower (my)	0.5	1.0	1.0	1.5	1.0	1.0
Center-of-mass						
Equipment	10	10	10	10	10	
Manpower (my)	0.5	1.0	1.0	1.0	1.0	1.0

---

It is highly likely that substantial improvements in data yield (in the lunar mode) can be obtained if adequate guiding capability is provided to keep the transmitted beam on any given reflector as well as the atmospheric "seeing" permits. With automatic off-set guiding a small circular crater almost anywhere on the moon which is well illuminated can be used for guiding. The image of the crater would be modulated across the detector and used to lock the guiding system. The signal-to-noise ratio will be high. Therefore the design construction and testing of automatic guiding systems for the Haleakala and MLRS transmitters will increase the return signal level and there by allow measurements to be obtained on several times as many days per year.

The system design is based upon the following:

1. Use of a field-of-view covering the entire moon;
2. Inclusion of an image rotator to compensate for image rotation at the Coude focus as the telescope drives across the sky;
3. Computer control of the guiding position offset to permit the use of any desired small crater;
4. One arc-second stability of the offset angle and azimuth over periods of at least 20 minutes.

One system would be designed initially for use at Haleakala and then installed and tested. A set of narrower band but better transmitting optical filters and other optical component upgrades would be provided at the same time. The same auto-guiding system (but with system modifications specific to the MLRS) would then be built, installed, and tested at the MLRS with a similar optical filter and associated optical component upgrade. The time scale for this effort is expected to be two years for Haleakala plus one additional year after that for the MLRS.

After completing the automatic guiding system installations and testing in 1993, replacement of the lasers at both Haleakala and the MLRS with improved high power units together with general electronic and timing system upgrades will be done. That work should require an additional two years.

The estimated cost and manpower for these activities are tabulated in Schedule 2.1-4.

**SCHEDULE 2.1-4. Lunar specific upgrade of the current LLR capable systems**

<b>FY</b>	<b>90</b>	<b>91</b>	<b>92</b>	<b>93</b>	<b>94</b>	<b>95</b>
<b>Optical system</b>						
<b>Modifications</b>		50	100	100		
<b>Image rotators</b>		25	50	50		
<b>Automatic guiding</b>						
<b>Electronics and detectors</b>		25	50	50		
<b>Controllers</b>		25	75	25		
<b>Data system upgrades</b>				50	75	50
<b>High power lasers</b>					150	150
<b>TOTAL</b>		125	275	275	225	200
<b>Manpower (my)</b>		2	2	2	2	2

## 2.2 Spaceborne Laser Ranging Techniques

S. Cohen

### 2.2.1. Statement of Requirements

Spaceborne laser ranging systems have been designed to provide millimeter to centimeter accuracy geodetic observations on spatial scales ranging from a few kilometers to several hundred kilometers. This scale of observations is required in order to study the accumulation and release of strain in seismically active zones, the deformation of tectonic plates at their boundaries, the relationships between crustal movements and changes in sea level, and the mechanisms of strain build-up and release in volcanoes. A typical seismic zone, for example, will have several hundred sites located along-strike and orthogonal to the fault. Observations over a wide range of temporal scales is required in order to examine the details of interseismic strain accumulation, precursory deformation, and postseismic rebound. Thus, spaceborne laser ranging systems are designed to provide both repeated scheduled surveys and on-call capability to respond to specific events. Vertical motions of a few millimeters accuracy are also required over a wide range of horizontal scales. Millimeter to centimeter accuracy range observations are also required to apply spaceborne laser ranging data to plate boundary deformation, volcanic strain accumulation, postglacial rebound, and other local and regional scale geodynamic studies.

Spaceborne laser ranging systems are particularly appropriate for conducting measurements that require a high density of sites, nearly simultaneous observation of a network, or an on-call survey capability. They are well suited for logistically difficult locales where power may not be available, where lightweight packages are required for easy deployment, or where maintenance, if needed at all, can be conducted by local personnel. In principal the passive targets can be quite inexpensive. Once installed, they can be observed as frequently as desired without mounting extensive field campaigns.

Depending on the spacecraft height, platform stability, and orbital configuration such ranging system can also be used for satellite-to-satellite tracking, gravity field modeling, non-conservative force field modeling, and satellite self-tracking to aid other sensors. Reflectors can be placed on ice sheets to monitor ice flow. A precision onboard clock can be used to transfer time from location to location and to conduct experiments in special and general relativity. Spaceborne laser rangers designed with nadir looking or pointable altimetric capabilities can also be used to measure land and ice topography, determine cloud top heights, measure atmospheric pressure, determine geoid heights, and measure wave heights.

### 2.2.2. Description of Measurement System

Engineering studies of a spaceborne laser ranging system started in 1975 [Fitzmaurice *et al.*, 1975] and continued with a variety of simulations and experiments being conducted in the late 1970's and early 1980's. In the mid-1980's consideration began for inclusion of such a system as a facility instrument onboard the planned Earth Observing System (Eos), a set of multisensor platforms being developed for

integrated, multidisciplinary Earth science observations. Presently the Geoscience Laser Ranging System (GLRS) [Cohen *et al*, 1987] is being developed by NASA as part of Eos. The performance specifications for GLRS are shown in Figure 2.2-1 and a conceptual block diagram of the system is shown in Figure 2.2-2.

The key features of GLRS are a dual-color laser ranging function and the ability to conduct both laser ranging to passive retroreflector targets and altimetry to natural surfaces. Under current design plans, the laser transmitter consists of a Nd:YAG laser which will be pumped by a long-lived laser diode array. Its output pulse is frequency doubled and tripled to produce pulses at 1064 (infrared), 532 (visible), and 355 (ultraviolet) nm. The visible and ultraviolet pulses are used for laser ranging and the infrared pulse is transmitted at nadir for altimetry. The ranging signal is collected by an 18 cm diameter telescope. A portion of the return green pulse is used in the range receiver consisting of a microchannel plate photodetector, constant fraction discriminator, and time interval unit. This subsystem has a timing resolution of 10 ps. A 2 ps resolution streak camera is used to detect the difference in the arrival time between the green and ultraviolet pulses and thereby make the atmospheric delay correction. A variable optical delay is used on the transmitted or received signals to assure that both of these pulses return within a single sweep of the streak camera. The heritage for this system can be found in existing operational laser ranging systems and laboratory experiments on prototype components for GLRS.

#### GLRS Technical Specifications

<b>LASER:</b>	<b>ND:YAG, diode pumped, frequency doubled &amp; tripled, Q-switched, mode locked, cavity dumped</b>
<b>POINTING CAPABILITY:</b>	<b>50 degrees</b>
<b>MAXIMUM PULSE RATE:</b>	<b>40 pulses/sec</b>
<b>BEAM DIVERGENCE:</b>	<b>0.125 millirad (532 nm); 0.1 millirad (355 nm) 0.10 millirad (1064 nm; 80 m footprint)</b>
<b>TELESCOPE DIAMETER:</b>	<b>18 cm (ranging function) 50 cm (altimetry function)</b>
<b>WEIGHT:</b>	<b>380 kg</b>
<b>POWER:</b>	<b>650 W (peak)</b>
<b>LASER LIFETIME:</b>	<b>&gt; 1 billion shots (5 years)</b>
<b>PULSEWIDTH:</b>	<b>100 picoseconds (FWHM)</b>
<b>ENERGY:</b>	<b>120 millijoules (1064 nm) 60 millijoules (532 nm) 40 millijoules (355 nm)</b>
<b>RANGER POINTING PREC.:</b>	<b>0.01 milliradians</b>
<b>ALT. POINTING KNOWLEDGE:</b>	<b>0.25 milliradians</b>
<b>TIMING RESOLUTION:</b>	<b>10 picoseconds (coarse range receiver) 2 picoseconds (streak camera receiver) 300 picoseconds (surface altimeter receiver). 500 nanoseconds (cloud altimeter receiver)</b>
<b>DATA RATE:</b>	<b>800 kilobits/sec</b>

Fig 2.2-1 GLRS technical specifications

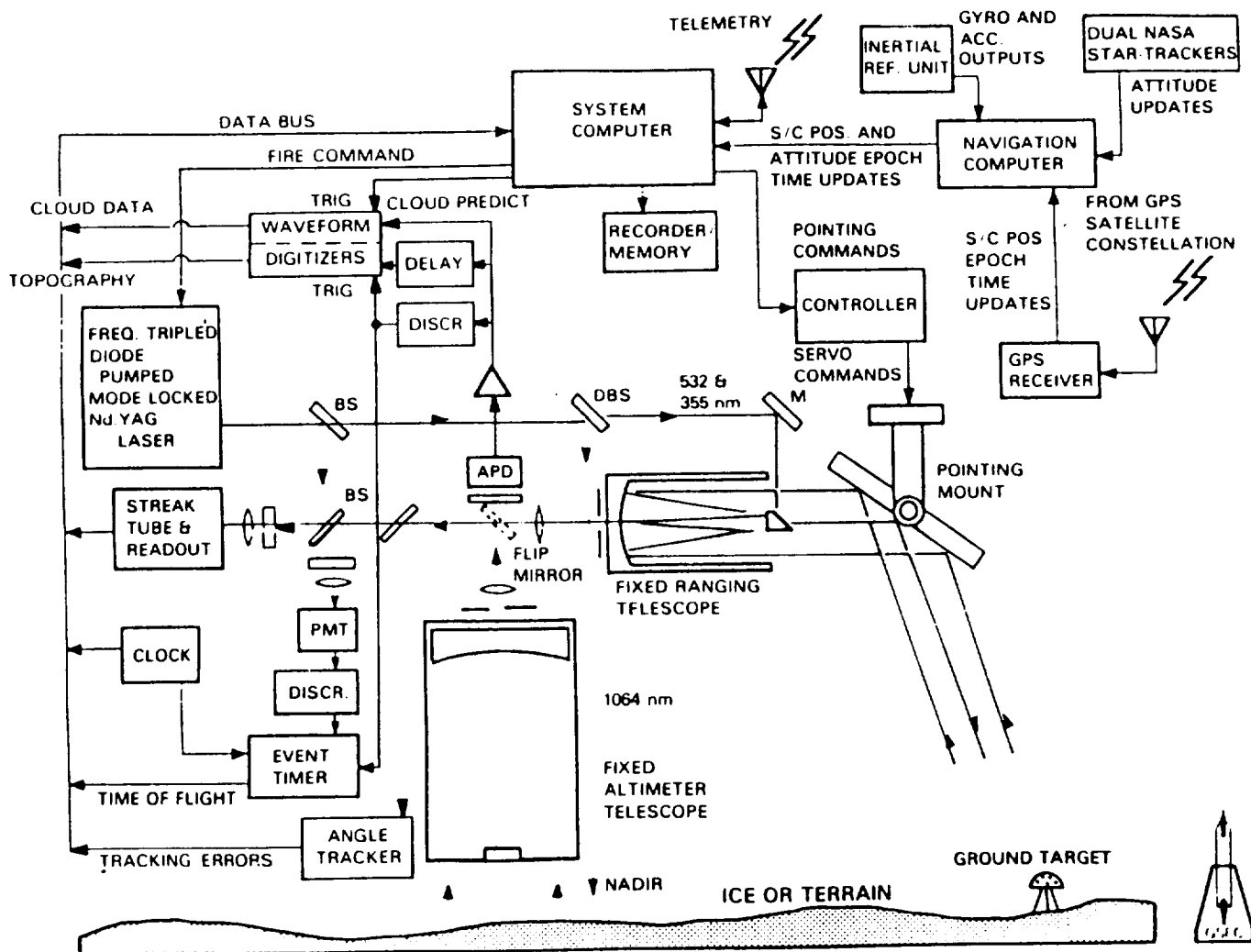


Fig 2.2-2 Block diagram of GLRS

The altimeter is designed to provide both surface and cloud-height observations. The reflected light is collected by a 50 cm diameter telescope and detected by an avalanche photodiode, timing circuitry, and waveform digitizers. For surface altimetry, the range accuracy will be 10 cm over smooth surfaces and the surface roughness will be quantized at 20 cm resolution over a dynamic range of several tens of meters. These specifications are driven by ice-sheet topography requirements. One of the major goals of the observations is to detect subdecadal changes in ice sheet thickness and topography. Such changes are intimately tied to global climate change and are affected

by the coupled interaction of the oceans, the ice-sheets, and the atmosphere. Changes in climate can manifest themselves in a myriad of ways including ice-sheet melting, enhanced snowfall in the polar region, and changes in atmospheric flow patterns.

For cloud-tops the return signal will be digitized into 75 m range bins over a range from the ground to at least 30 km altitude. The ground-spot position uncertainty is expected to be about 20 m, corresponding to an attitude uncertainty of 5 arcsec. The cloud top measurements not only provide important information for energy balance models, but also provide direct vertical cloud distribution data, which can be used to validate somewhat ambiguous, passive retrievals.

The system is pulsed at 40 pps. It has a ranging system pointing capability of 50° both along track and across track. Approximately 120, 60, and 40 mJ are transmitted at the 1064, 532, and 355 nm wavelengths, respectively. The divergence for the 532 nm beam is about 0.125 mrad, as dictated by eye safety considerations. The divergence of the 355 nm beam is somewhat less to assure adequate photon density on the target, and hence in the return beam. The 1064 nm altimeter beam divergence of 0.1 mrad produces surface spots of approximately 70 m from the Eos altitude of 705 km. The along-track altimeter spot spacing is about 150 m. Position and attitude information for GLRS are provided by an onboard GPS receiver, dual star-trackers, and a 3 axis-gyro. The detailed design of GLRS is in progress, thus, it is likely that some of the system specifications and design details will be changed as further progress is made in technology and design. For example, it may be possible to reduce the pulse width in order to improve the timing for the atmospheric propagation delay correction.

Several key aspects of spaceborne laser ranging systems distinguish these systems from traditional laser ranging systems. These systems must operate in an unattended mode for many years. In addition they must be designed with economy of space and mass in order to fit within a reasonable envelope on a space platform, they must be engineered to withstand the rigors of launch and deployment and they must operate in a space environment.

### 2.2.3. Required Support Measurements

In order to acquire the ground targets as efficiently as possible, real time orbit position at the several meter accuracy level is desirable. GLRS will either include a collocated GPS receiver or utilize a GPS receiver onboard the Eos platform to obtain knowledge of its position. Startrackers and gyros will be used to establish and maintain attitude knowledge of the system. In processing GLRS data, it is likely that a precise orbital ephemerides, provided by GPS observations, will be available to constrain the spacecraft orbital parameters. Consideration is also being given to verifying and calibrating GLRS range data by performing ground-based laser ranging measurements to a retroreflector target located on the GLRS package. The installation of GLRS targets will include determination of the site coordinates to at least several meter accuracy, most likely using GPS. The relative position of nearby reference sites will be determined to assure that the location of damaged sites can be recovered.

#### 2.2.4. Developments to Improve Performance

The major requirements on the laser are high reliability and long life and high electrical and thermal efficiency. Since ground meteorological data will not be available at the GLRS sites two color ranging is used.

The most power efficient candidate lasers utilize a Nd:YAG rod pumped by an array of AlGaAs laser diodes. Diode array lifetimes in excess of  $3 \times 10^9$  shots have been demonstrated and lifetimes in excess of  $10^{10}$  shots are likely to be achieved. The implications of these lifetimes are quite significant; a system with a lifetime of 10 billion firings would operate continuously for a decade at 30 pps and for 5 years at 60 pps. Laser pulsewidth can be narrowed to several tens of picoseconds via active modelocking techniques.

The current design for GLRS involves sequential acquisition of individual targets rather than multibeam tracking, the pointing system must be capable of providing: (1) tracking of a given target with few arcsecond accuracy; (2) rapid slewing between targets; and (3) rapid settling into the tracking mode of newly acquired targets. Prototype pointing systems having this slew and settling capability were developed in the early 1980's. A typical prototype system can slew and settle over a 50 degree pointing angle change in 0.5 seconds leaving more than 1 second for target observations. Longer dwell times on targets can be achieved or more sites surveyed by combining data from successive passes in which only a portion of a grid is viewed in a single pass.

Several modes of operation are possible for the dual-color receiver. In one mode, the differential time of flight between the visible and ultraviolet pulses is measured by, for example, a streak camera. This data is used to correct range data for atmospheric propagation delay only. This mode, which is the currently planned mode for GLRS, is capable of providing absolute range accuracies of about 5–10 mm. In a second mode the streak camera is used to provide a vernier timing correction to the coarser range measurements. The total round-trip of flight of each of the pulses is measured. This mode, although more technically difficult and risky, can potentially, provide an enhanced range accuracy of a one or two mm. Most of the residual atmospheric propagation error is due to different dispersion properties of the water vapor and dry components of the atmosphere. Correction for this term may require the use of multicolor, or possibly, combined laser and microwave instruments.

For determination of the differential time of flight in either mode, a timing resolution of a few psec or better is required. Available streak cameras and recently developed timing units can achieve this resolution.

#### 2.2.5. Projected Performance

GLRS is expected to provide absolute range measurements to an accuracy of 5-10 mm. Assuming such accuracy, it will be possible, in principle, to determine intersite distances to an accuracy of a few millimeters at distances up to a few hundred km or more. Figure 2.2-3 shows the computed accuracy in baseline length and relative height in a local tangent plane coordinate system. The distances are measured

relative to a fixed origin near the center of the grid. The results are based on a random 10 mm single shot range noise and a network of 157 sites separated by 50 km from one another in California. Ten independent arcs of satellite data are simulated in the analysis. Other parameters affecting the results include 1.5 sec dwell time on the targets, and a 50° along and across track pointing capability of the instrument. No systematic biases are included in this analysis.

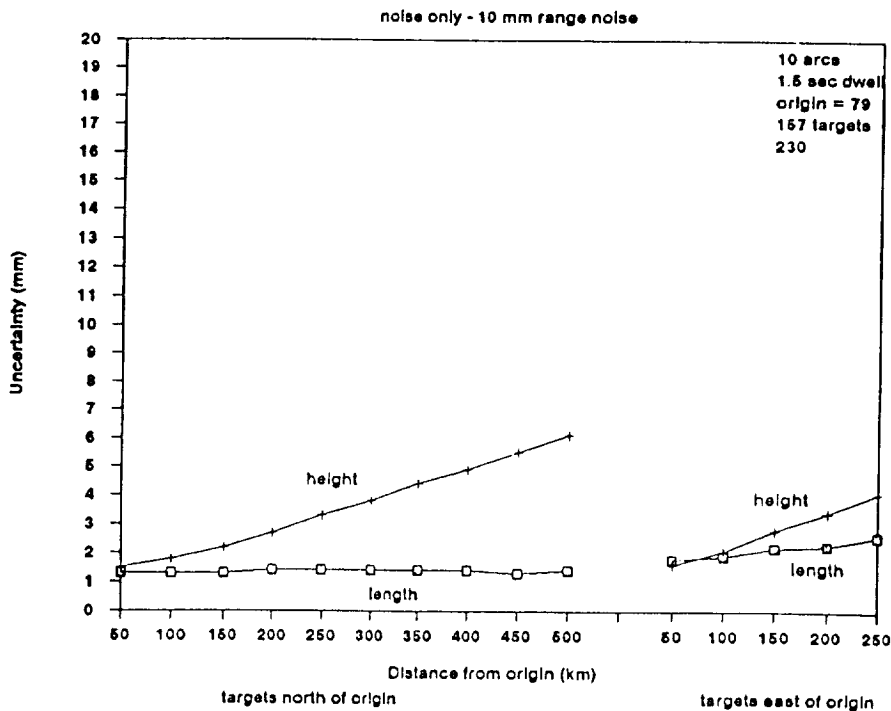


Fig 2.2-3 Length and height errors for GLRS

Covariance analyses of the effects of gravity field uncertainty for the same network indicate that these effects become increasingly more significant with increasing baseline length. However, in the Eos era it is likely that the satellite orbit will be well determined by an onboard GPS receiver. In this case, gravity field uncertainties will have a much reduced, and possibly negligible effect. The GPS orbit data will also be used to enhance the ability of GLRS to determine long baseline length and in determining the site coordinates in a geocentric coordinate system. Alternatively, improvements in the gravity field model, including the incorporation of GLRS range data, will substantially reduce gravity field aliasing. At the millimeter accuracy level, the stability of the benchmarks may be a limiting factor. Other limiting factors may be residual atmospheric delay effects and other systematic biases. GLRS accuracy will also depend on the number of stations surveyed, their geometry, and the number of arcs of data used in the solution. If, in the previously cited example, the number of data arcs is reduced from ten to seven, the noise only solution degrades approximately in proportion to the square root of the reduced number of observations (*i.e.*,  $\sqrt{10/7}$ ). Solutions based on fewer passes show greater dilution of precision due to loss of geometric strength. Given the Eos altitude of approximately 700 km and the GLRS pointing capability of 50°, targets can generally be acquired in two passes a day at mid-latitudes. The detailed trade off between accuracy and temporal resolution depends on the number of targets surveyed.



A spaceborne laser ranging system constellation could be based on GLRS hardware and be upwardly compatible. It could provide total global monitoring at the few mm level.

Subpicosecond time transfer would be possible with future laser ranging systems. Such a capability would be quite useful for communications particularly in view of the fact that the time measurements could be completely integrated with position. Navigation and anticollision systems are possible.

A continuous wave laser interferometer system could be used for satellite-to-satellite relativity experiments. Range rates of  $0.01 \mu\text{m/s}$  are possible.

#### 2.2.6. Data Flow, Storage and User Access

The data for GLRS will be part of a large data system for the Earth Observing System known as EosDIS. Permanent archives of raw, calibrated, ancillary, and processed data (station coordinates, satellite orbits, etc) will be maintained. Under EosDIS policy all data collected by GLRS will be available to all users with no exclusive data rights. The data will be input in the system as it is processed with an emphasis on the rapid deposition of raw and processed data. Data will be available, on line, to authorized users through an electronic communications system.

GLRS is expected to operate at a maximum data rate of 800 Kbs, determined primarily by the altimeter digitizer and the streak camera. Data will be downlinked through TDRSS to the EosDIS (see below). In routine operation, it is expected that data will be transmitted to the ground within one revolution of data collection. With a time averaged duty cycle of approximately 20 percent, GLRS is a relatively low data rate system on Eos. Observation schedules will be generated by the GLRS science team, and be transmitted to the system through EosDIS. Both routine observation schedules and high priority-specific event observations schemes will be accommodated. The time required for uplinking new observational schedules is not yet fully determined.

Currently VLBI and SLR data products are routinely deposited in the CDDIS. GLRS data will consist of raw data, calibration corrected data, and derived baselines and target coordinates. Under Eos data policies, the data processing will be implemented on the Eos Central Data Handler and the data archived in the Data Archive and Distribution Systems. Plans must be made to assure that the GLRS data can be easily merged with Crustal Dynamics data, GPS data, and other geodetic data. To the extent that it is practical, common formatting of the data sets should be used. This will require the development of communications networks for data transfer between EosDIS and other geodetic data bases.

#### 2.2.7. Plans for System Development

##### *Ongoing and planned activities*

GLRS is being developed for implementation on one of the NASA Polar Orbiting Platform (NPOP) of Eos. At present NPOP-1 is scheduled for launch in the fourth quarter of calendar year 1996 and NPOP-2 in the fourth quarter of 1999. The two

platforms will carry a different set of instruments and, according to current plans, they will be replaced at 5 years intervals. The Eos mission is planned for at least 15 years. Conceptual design studies (Phase-A) for GLRS have been completed. These design studies cover both laser ranging and altimetry. The Phase-B studies will consider the design in more detail, conduct tradeoff evaluations of alternative designs, and examine risk issues. These studies are scheduled for completion in 1990. The Phase C/D efforts which will include detailed design, building and testing of engineering and flight packages are expected to last at least 4 years. The major technical challenges include the development of a reliable, unattended system with a five year replacement lifetime, assuring adequate signal strength under a variety of atmospheric visibility conditions, and development of a reliable, inexpensive, and logistically simple ground target. With regard to reliability of operation, the key technical issues are the development, testing, and space qualification of the laser system and characterization and space qualification of the streak camera. Reliability of the electronics and mechanical devices must also be carefully maintained and will require the implementation of redundant and backup components where possible. The data collected by GLRS will be processed and archived within the Earth Observing System Data Information System (EosDIS).

### *Cost*

The development of the GLRS space flight hardware and ground package is being supported by the Eos Project. Operational and data processing cost will also be borne by Eos; however, the cost of manufacturing and deploying the ground targets will require support from the Solid Earth Science Program. GLRS targets are anticipated to cost about \$1000; therefore, an initial purchase of 500 targets, for example, would cost 0.5 million dollars and an ultimate deployment of 5000 targets would cost 5.0 million dollars. It is possible that many of these costs will be borne by the Eos Project for official Eos investigators and by foreign institutions for experiments conducted by their personnel. Although GLRS is being developed as an Eos facility instrument, neither the Eos Project nor the GLRS have been confirmed for flight at this time. Selection of instruments for flight on the Eos platforms is expected in the early 1990's.

## 2.3 Global Positioning System

C. Thornton, R. King, C. Goad

### 2.3.1. Current Capabilities

For some applications GPS already competes in accuracy and cost-effectiveness with more mature technologies. For others, improvements in hardware, analysis techniques, and the satellite constellation will be necessary to establish its role. The evidence for GPS capabilities is greatest for static positioning over baselines from 50 to 1000 km, where the alternative technologies are mobile VLBI and SLR. However, GPS measurements are or soon will be useful for applications ranging from attitude determination (baselines of only a few meters) to monitoring the Earth's rotation (baselines of thousands of kilometers). Because of today's limited GPS constellation, in assessing current capabilities, it is important to take into account the location and extent of the region to be studied.

In the past four years, baselines have been measured with high precision GPS techniques between over 150 sites in the western U.S. alone, an order of magnitude more than with mobile VLBI. The evidence to date suggests that the repeatability and accuracy of the GPS and VLBI measurements, for comparable observing times, are not significantly different for baselines up to 1000 km in length (Figures 2.3-1 and 2.3-2).

Figures 2.3-1 and 2.3-2 provide a concise indication of current GPS performance relative to VLBI. Figure 2.3-1 illustrates the differences between GPS and VLBI measurements of baselines in the western U.S. The VLBI values are taken from the GSFC global analysis GLB 223; the GPS values are from analyses of three different groups, using different software packages. The mean differences between GPS and VLBI values are about 5 mm + 1 part in  $10^8$  in the horizontal components and 20 mm in the vertical. Figure 2.3-2 presents comparisons of repeated measurements by GPS and VLBI of the lengths of the baselines from Vandenberg to Mojave and Palos Verdes. For the Vandenberg-Mojave line, the difference between the rates estimated from VLBI and GPS measurements is less than 3 mm/yr.

The internal consistency of the GPS system is typically equivalent to the agreement with VLBI, and in some cases it is noticeably better. Figure 2.3-3 illustrates GPS system precision at the 1-2 mm level on the OVRO to Mojave baseline (245 km). These recent results were obtained by Lindqwister and Blewitt at JPL using the GIPSY software.

The high signal-to-noise ratio of the primary (L1) GPS signal allows carrier phase to be measured with millimeter precision with less than one second averaging. Recent experiments have used this capability to monitor the attitude of aircraft and ships with a precision of better than 1 mrad [Purcell *et al.*, 1989; Seeber and Wubben, 1989]. Similarly, single-frequency measurements of short (<1 km) static baselines have demonstrated repeatability and agreement with EDM measurements at the (one) millimeter level [Svarc *et al.*, 1989; Meertens and Rocken, 1989]. For longer baseline measurements requiring the second (L2) GPS frequency to calibrate ionospheric effects (up to  $10^{-5}$  of baseline length), higher noise levels and unmodeled antenna

phase-center variations have thus far limited accuracy to several millimeters [e.g., *Meertens and Rocken, 1989*]. Kinematic positioning has been demonstrated at an accuracy better than 10 cm, providing, for example, an important tool for control of photogrammetric surveying [*Mader and Lucas, 1989*]. Kinematic surveying at the centimeter level has been reported by *Remondi [1986]*; and very recent tests by *Goad et al. [1989]* suggest 5 mm capability.

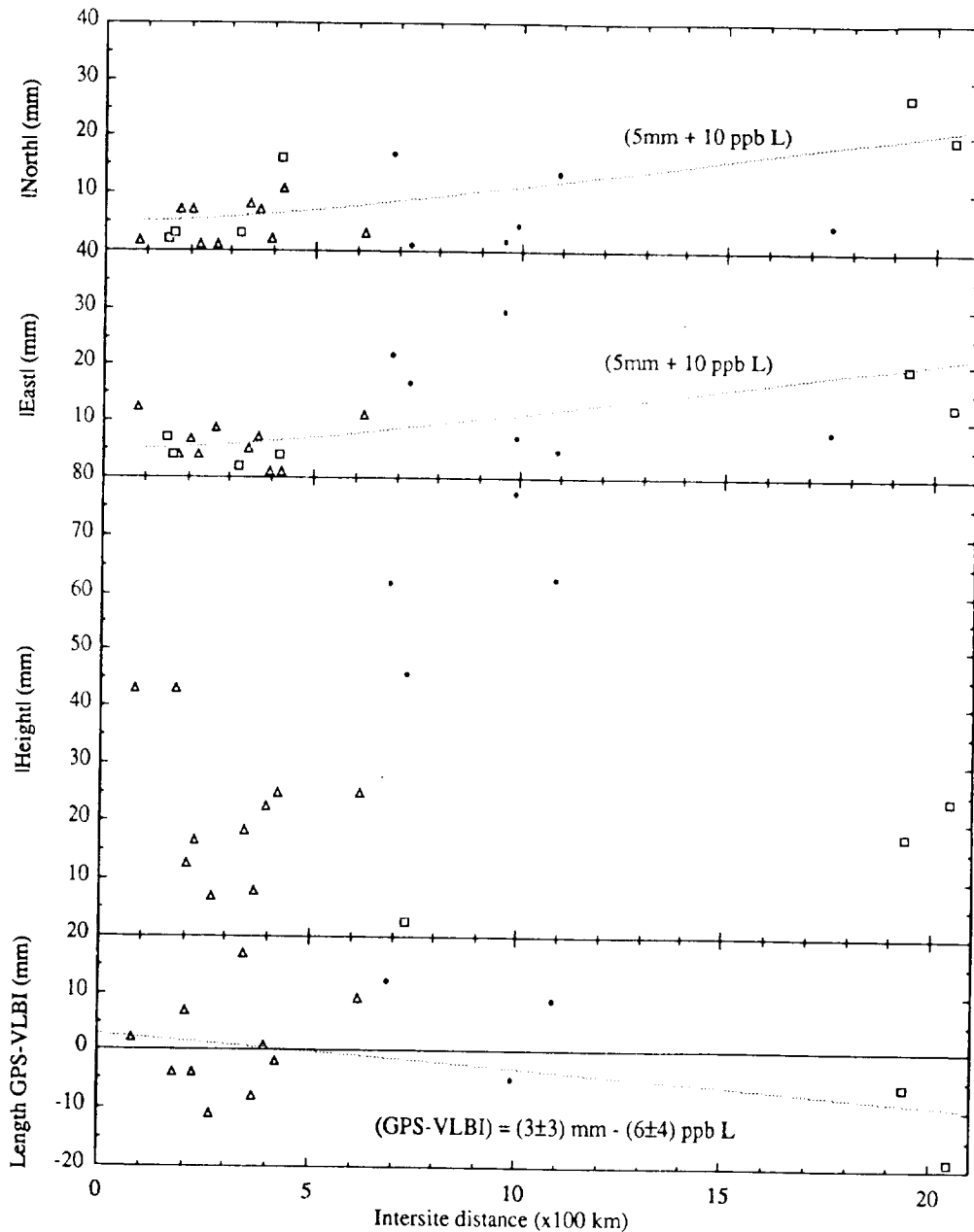


Figure 2.3-1. Differences between GPS and VLBI determined baselines in the United States, adapted from *Herring and King [1989]*. The different symbols refer to the number of 3- to 8-hour sessions that have been averaged before being differenced from the VLBI estimates: dots 1-3; triangles 4; squares >4.

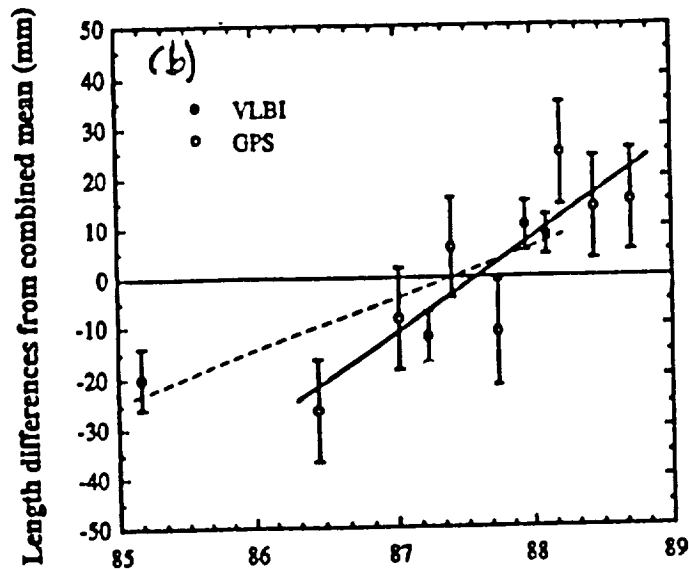
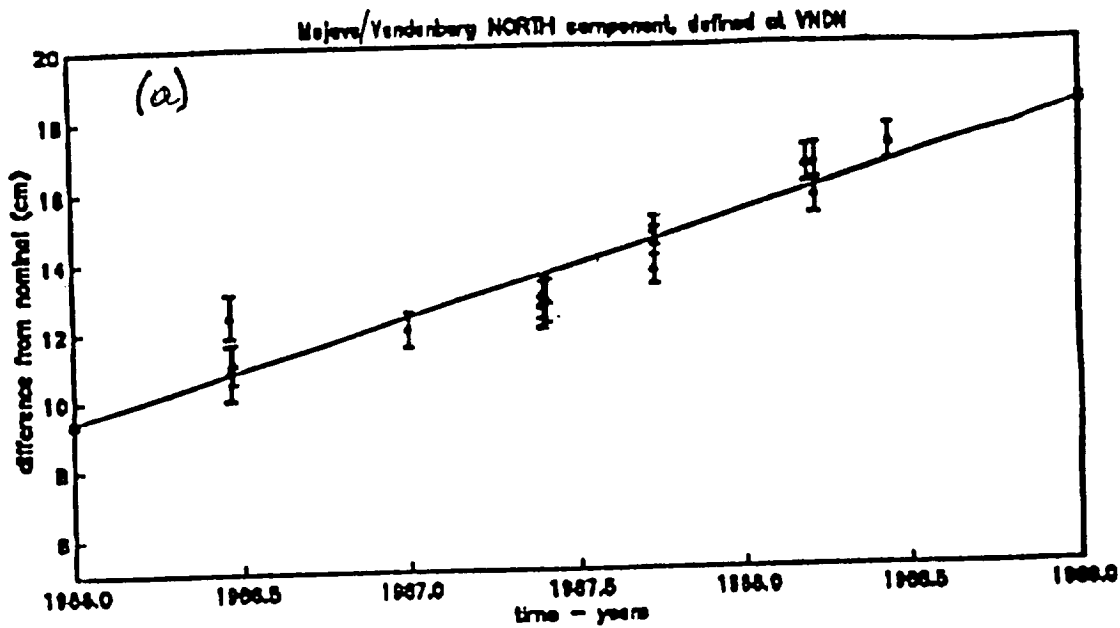


Figure 2.3-2. GPS and VLBI measurements of the baselines from Vandenberg to Mojave (a) and Palos Verdes (b). The VLBI results are taken from the GSFC global analysis GLB223. The analysis of the Vandenberg-Mojave observations was performed by K. Larson at Scripps using the GIPSY software. For this line the difference in the inferred motion from the two techniques is  $3 \pm 2.6$  mm/yr, and the rms scatters of the individual measurements about the mean slopes are 7.5 mm for GPS and 7.1 mm for VLBI. The analysis of the Vandenberg-Palos Verdes observations were performed by Davis and Prescott at the USGS using the Bernese software. The difference in the inferred motion from the two techniques is  $9 \pm 6$  mm/yr, and the rms scatters are 10 mm for GPS and 8 mm for VLBI.

Applications requiring relative position measurements over long baselines are limited by the inherent lack of a stable GPS reference frame. Nevertheless, when a terrestrial frame is provided by VLBI and SLR sites, GPS measurements can extend in time and space the capabilities of these other techniques. For a few baselines in North Amer-

ica, GPS and VLBI results have agreed at the level of 10 mms over a thousand kilometers (1 part in  $10^{-8}$ ) [Lichten and Bertiger, 1989; Blewitt, 1989]. GPS measurements of short-period variations in the Earth's rotation are currently better than 1 part in  $10^7$  (0.5 ms in LOD, 10–20 cm in pole position), limited by the small number of GPS satellites and poor distribution of tracking sites [Swift, 1988].

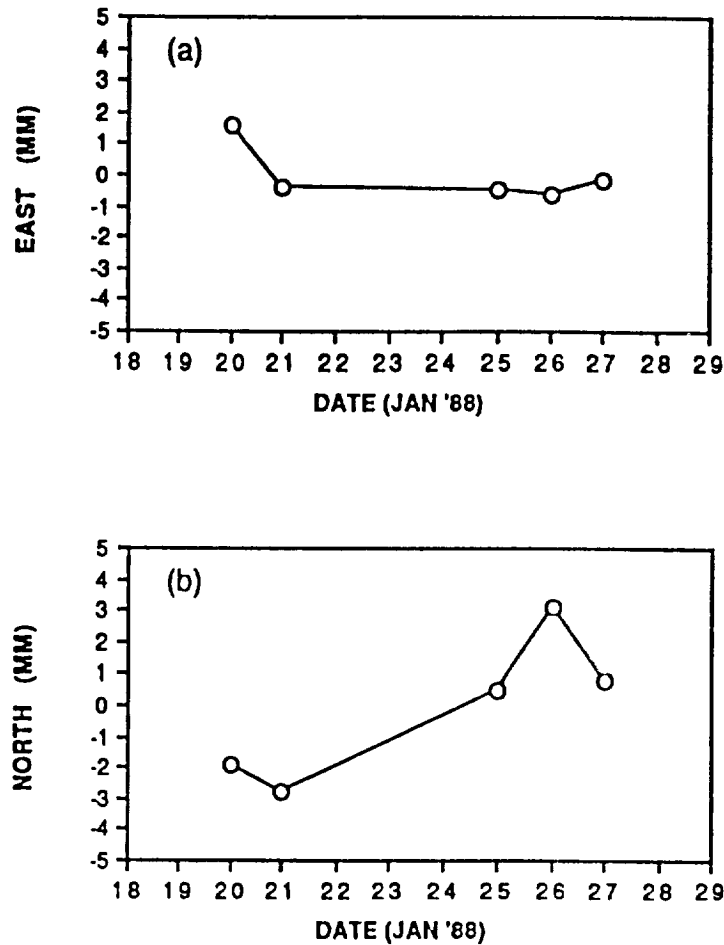


Figure 2.3-3. Repeatability of GPS solutions for the OVRO-Mojave baseline. The RMS scatter about the mean is 0.9 mm in the East component and 2.3 mm in the North. These results were obtained by Lindqwister and Blewitt using the GIPSY software.

Several special characteristics of system design and techniques of data analysis have proven particularly advantageous in high performance GPS geodesy. These include: (1) carrier cycle ambiguity resolution or "bias fixing" (and the algorithms and careful geometric arrangement of the network of receiving sites that make it possible), (2) stochastic modeling of zenith tropospheric delay and the nongravitational forces acting on the GPS satellites, (3) judicious use of water vapor radiometers to calibrate the wet tropospheric delay at humid sites having high spatial and temporal variability, (4) multi-day GPS orbit solutions for measurements of long baselines, and (5) the combined use of dual frequency carrier phase and pseudorange data. Resolution of carrier phase ambiguity has now been achieved over distances of up to 2000 km. This

has been accomplished using algorithms that formally reflect the integer character of the cycle ambiguity problem and an arrangement of receiver sites permitting short and intermediate baseline resolution as preliminary steps to long baseline resolution [Blewitt, 1989; Dong and Bock, 1989]. For baselines of a few hundred kilometers, solutions after ambiguity resolution are typically 3-5 times more accurate than solutions treating the carrier phase bias as a continuous variable. Carefully tuned random walk troposphere models have proved effective in reducing tropospheric contamination, improving baseline repeatability by as much as a factor of two over constant delay models and surface meteorology calibrations.

The use of high precision pseudorange data in combination with carrier phase confers a number of benefits. These include: (1) greatly simplifying data editing and recovering from cycle breaks, (2) improving the speed and reliability of ambiguity resolution, (3) improving solutions for clock offsets between receivers, (4) improving the carrier phase bias solution when the ambiguity cannot be resolved, (5) enabling precise kinematic tracking of moving platforms, and (6) generally reducing the system sensitivity to data outages and other operational problems. Several studies have shown that pseudorange of subdecimeter accuracy achieved by the new high performance receivers and antenna systems, when used together with ambiguous carrier phase, can yield baseline accuracies approaching those currently achievable only with resolved carrier phase.

Receivers themselves are only one component of the elaborate data collection, calibration, modeling, and analysis systems needed for today's cm baseline measurement accuracies. Data must first be gathered with a well-planned network of receivers extending over a sizeable geographic area, and a portion of the collected data must be used to improve the ephemerides of the GPS satellites. Several different approaches to system design and data analysis have proved successful. In one approach, three or more receivers placed at well known reference ("fiducial") sites are held fixed during a grand simultaneous solution for all other receiver locations and GPS ephemerides. In addition, parameters for stochastic effects such as zenith tropospheric delay, solar radiation pressure, and other unmodeled GPS satellite accelerations are also adjusted. In a variation on this approach, fiducial data are processed first to produce accurate GPS ephemerides which are then held fixed during a second solution for the baselines of geodetic interest. Experiments have shown the latter (somewhat simpler) approach to be virtually as accurate as the full simultaneous solution, so long as the geodetic baselines are within or close to the fiducial set. In both of these approaches, the fiducial network defines the reference frame in which the GPS ephemerides and baselines are determined. An alternative approach, in its most extreme form, frees up all receiver coordinates except (necessarily) the longitude of one reference receiver, allowing the considerable strength of the GPS data and a fixed value for the GM of Earth to determine all orbits and receiver positions in a self-consistent, properly scaled reference frame. This eliminates dependence upon predetermined fiducials, at the cost of introducing potential differences with the reference frames established by VLBI and SLR techniques. Myriad variations and hybrids of these techniques, in which different numbers of fiducial parameters are freed and constraints of varying levels of severity are applied, are also being investigated. Identifying a quasi-optimal strategy for establishing a globally consistent geodetic reference for all investigators at all times will be an important pursuit in the next decade.

### 2.3.2. Systems Presently in Operation

#### 2.3.2.1 Hardware

Most high-precision surveys performed to date have used TI 4100 receivers. However, this receiver is expected to be phased out in the next 1-2 years due to its size, weight and power requirements; the ability to track only four satellites; antenna phase center variations and multipathing at the 10 mm level on carrier phase and about 1 meter level on pseudorange, and the high frequency of cycle-slips in the phase data. Other receivers (MACROMETER II, MINI-MAC 2816, prototype Rogue, SERIES-X, Trimble 4000 SL, and WM-102) have been used in a more limited way for high-precision surveys but have not been subjected to the extensive field testing and analysis of the TI 4100.

Several light-weight field receivers are now available or will be by Fall, 1989. Three of these (MINI-MAC 2816, Trimble 4000STD, and Ashtec XII) currently do not have P-code pseudorange and use codeless tracking of the L2 GPS signal, features which make resolution of phase ambiguities more difficult. Tracking site receivers such as the WM-102 and the Rogue SNR-8 receivers have both P-code and codeless capability. The Rogue has exceptionally low pseudo-range noise, an important feature for kinematic applications and rapid recovery from data outages. It also has robust tracking loops which enable continuous carrier phase measurements during high dynamic applications and strong ionospheric disturbances.

#### 2.3.2.2. Data Analysis Software

Five software systems have been used by U.S. investigators to analyze GPS observations for high-precision applications:

Bernese 3.0	developed at the University of Berne and used at Colorado, Lamont, and USGS
GAMIT	developed at MIT and used at Scripps
GPS22	developed at NGS and used at Caltech
GIPSY	developed at JPL and used at Scripps, Univ. So. Carolina, and Univ. Puerto Rico, Caltech, Delft, U. Colo.
MSODP	developed and used at the Univ. of Texas

All of these software systems incorporate the three essential elements necessary to obtain baseline estimates with an accuracy of better than a part in 10<sup>-7</sup>:

1. accurate models of the satellites' motions and the relative positions of the satellites and receiver antennas;
2. algorithms for estimating baseline coordinates and satellite positions from phase observations that are free of clock errors;
3. capability to detect and repair cycle slips in the phase observations (though some systems are more highly automated in this than others).

A fourth feature which is implemented in varying degrees of sophistication in most of the packages is the ability to resolve the integer-cycle ambiguities in phase observa-



tions. With the present constellation for western North America, ambiguity resolution generally improves the accuracy of the east component of the baseline by a factor of two [Blewitt, 1989; Dong and Bock, 1989]. The GIPSY, Bernese, and GAMIT software have the ability to estimate stochastic atmospheric delay parameters, a feature that generally improves baseline accuracies, depending on the amount of water vapor present during the observations [Lichten and Border, 1987; Tralli et al, 1988].

At present, a time-consuming part of data processing is the detection and repair of cycle slips. The effort has been driven by the large number of slips present in phase data recorded by the TI 4100, and by the fact that it has proven difficult to devise simple algorithms which work for all receivers under all ionospheric conditions. Several software systems now incorporate automatic data editing capable of achieving better than 99% cycle slip correction. The TurboEdit program in the GIPSY package [Blewitt, 1989], however, requires both carrier phase and pseudorange data.

Although results of similar accuracy (2-5 parts in 10<sup>8</sup>) have been obtained for the western U.S. with several different software packages, there has not yet been a detailed intercomparison of baseline estimates using common data. A limited comparison of the Bernese and GAMIT software was performed at the University of Colorado in 1988 (C. Rocken, personal communication), and this work is being continued at the USGS and MIT. K. Hurst at Lamont is performing a comparison of the Bernese and GIPSY software, eventually to be extended to include GAMIT.

### 2.3.2.3. Data Information Systems

GPS observations are collected daily by stations of the Cooperative International GPS Network (CIGNET) and are archived and distributed by NGS. High-precision field observations are collected by JPL, NGS, USGS, and a number of university groups under the auspices of the University Navstar Consortium (UNAVCO). During the past year, with a very limited pool of receivers, the number of observations collected has exceeded by at least an order of magnitude that collected by SLR and VLBI. The number is likely to double in 1989 and again in 1990 as more receivers become available for scientific studies.

There is at present no standard procedure for archiving high-precision GPS data, nor any government facility for maintaining the archives. This situation is a natural result of the development of GPS hardware by a number of private firms, and support for research and development by several different government agencies.

For its own internal needs, the NASA Geodynamics Program presently has a GPS data archiving system at JPL. Using this system, analysts can retrieve files containing raw observations (in the standard FICA international exchange format) from high-precision GPS experiments conducted under the Geodynamics Program. Files are quickly referenced by date and station name, and can be saved to, retrieved from, or deleted from the archiving database. Other information is also archived, such as nominal station locations, data edited by the JPL's GIPSY software, meteorological and WVR data, nominal orbit files, and geodetic solutions.

Such an archiving/database system could be improved and expanded to include all high-precision GPS data taken which may be useful to NASA and the geodetic com-

munity at large. A major input to such a system would be data recorded by an international, global tracking network. GPS data from future NASA flight missions should also be archived with the geodetic data, since it has been shown [Melbourne *et al.*, 1988] that the two types of data sets can be combined synergistically to improve both tracking control and geodetic solutions. There are many issues, such as formats, quality control, and data distribution privileges which need to be resolved. Since it is in NASA's interest to have access to high precision GPS data, the initiative should be taken as soon as possible to move towards establishing a GPS archiving facility under guidelines established by a committee representing the interested parties.

### 2.3.3. Current Limitations in Performance

Many of the present limitations to GPS accuracy are shared by VLBI and/or SLR and are being addressed with the same techniques by many of the same analysts. The corrupting effects of unmodeled variations of tropospheric water vapor on vertical measurements are essentially the same for mobile VLBI and GPS. Non-gravitational perturbations on the GPS satellites are more severe than for LAGEOS but are not a limiting source of error for short-arc baseline analyses. Millimeter-level precision is impaired with all three techniques in mobile campaigns by the difficulty of relating the measuring point of the instruments to a monument on the ground. A common solution is improved calibration against external standards and the use of permanently mounted instruments.

Performance is also limited by the sparseness of GPS satellites currently in orbit, and the lack of a permanent global tracking network. The announced DoD schedule for launch of the Block II satellites promises to remove the first constraint by 1993. There are 4 launches planned in 1989, and 5 each year from 1990 through 1993. The number and quality of CIGNET stations has increased each year since 1986. NASA is developing an international co-operative GPS tracking network to support TOPEX. The possibility of augmenting the CIGNET and TOPEX networks with additional worldwide sites to form a more extended global tracking system is now under study by a special working group of the CSTG Subcommittee on GPS.

The accuracy of current receiver systems, while adequate to yield cm regional baseline results, is below that required for mm accuracies or for autonomous functions such as phase re-connection or self-diagnosis. Aside from media delay calibration errors, the current instrumental factors that limit accuracy for the best receivers, in both the carrier phase and pseudorange measurements, are multipath and antenna "phase center" variation. For current receivers, multipath is near the centimeter level for carrier phase and usually at least several decimeters and often higher in pseudorange. Phase center variations with azimuth and elevation can amount to several cms, but these variations tend to be nearly identical for two antenna/backplane systems of identical design and installation. Also, most of this effect can be calibrated. It will be important to test the effects of multipath and phase center variations on carrier phase measurements at the 1 mm level, to be assured of the reproducibility of the antennas from a given manufacturer, and to determine the effective phase centers of all the relevant antennas from empirical measurements. Some controlled experiments have been carried out [e.g., Meertens and Rocken, 1989; Gurtner *et al.*, 1989], but this work is far from complete. Multipath and thermal data noise, typically at the meter level on pseudorange measurements in past experiments, has been reduced by an order of

magnitude in recent field tests of the Rogue receiver and antenna/backplanes (*Young et al, 1988; Rocken and Meertens, 1989*).

#### 2.3.4. Support Measurements

The GPS data can provide strong determination of tropospheric delays. However, the availability of sub-cm troposphere delay calibrations from WVR's, or other means, would strengthen baseline estimation and improve system temporal resolution. Accurate (mm) ground surveys tying the GPS reference points to local benchmarks are also required.

Another potentially useful set of support measurements could be obtained from the proposed ACRE experimental satellite [*Beard, 1989*]. The ACRE satellite, carrying a GPS transmitter as well as a laser retroreflector in a 12 hour orbit, could provide an independent verification of GPS ranging accuracies at sites with colocated GPS and SLR receivers.

#### 2.3.5 Future Prospects

*Receiver Costs.* The progress of both design and manufacturing technology in the field of very large scale circuit integration (VLSI) continues to be rapid. This has allowed the development of GPS receivers that use digital baseband signal processing techniques, removing the phase and delay variation errors that are present in analog circuits. It has also led to major reductions in cost, weight and power. Next generation receivers will use VLSI advances to digitize the incoming GPS signals directly at L Band frequencies, as well as to further reduce size and cost (*Thomas et al. 1988*). A factor of 3-5 reduction in equipment costs appears likely within the next five years, suggesting eventual unit costs for dual band P-code receivers of 10 thousand dollars or less. More powerful onboard microprocessors, together with special purpose hardware, will give new receivers greater capability for autonomous operation. These "smart receivers" will allow some data analysis to be performed in real-time. Advanced receiver processing combined with more expert post-processing algorithms will reduce the cost of GPS baseline determination by as much as an order of magnitude. Moreover, if cycle ambiguities can be quickly removed with combined pseudorange and carrier phase data, the resulting "carrier range" will provide near instantaneous geometric differential positioning. This would significantly reduce production costs by reducing the dwell time at each measurement site. These and other advanced concepts will be incorporated into a continuously operating GPS array being developed jointly by the Scripps Institution of Oceanography and JPL for initial deployment in Southern California in late 1989.

*Measurement Accuracy.* A number of approaches to refining the design and composition of antennas and backplanes promise major future improvements in phase center and multipath errors. These advances coupled with the high instrumental accuracies provided by all-digital systems, are expected to yield advanced GPS receivers and antenna systems capable of carrier phase accuracies below a mm and smoothed pseudorange accuracies with 30 minute averaging, near a cm. A digital front end located at the antenna, with a long fiber optic link to the baseband processor, will allow the antenna site to be optimized for low multipath. The design architecture of next generation receivers, using combined carrier phase and pseudorange measure-

ments under a wide range of dynamic conditions, will be adaptable to specialized applications such as positioning ocean platforms for sea floor geodesy, or satellite based applications. Most of these capabilities should be commercially available by late 1991.

Recent short baseline tests with high performance laboratory receivers, and experience in cycle ambiguity resolution with actual field data, suggest that errors due to instrumental effects can be reduced to the mm level. However, tropospheric delay and GPS ephemeris errors will limit the realization of this accuracy depending on the region and its scale. In relatively benign environments such as the Western U.S., (with vertical wet troposphere delays of 0-20 cm and a few cms of spatial and temporal variability), the current baseline errors due to the troposphere are in the range of 0.5-1 cm for the horizontal components and 1-3 cm for the vertical. These figures tend to be somewhat worse for regions with wetter climates that also have higher variability. For benign environments stochastic modeling without WVR calibration has proven as effective as WVR calibration alone - at the current level of GPS and WVR system accuracies. For tropical regions a combination of WVR calibration and stochastic modeling of residual WVR errors has proven the most effective [Tralli *et al*, 1988]. Substantial progress can be made in more sophisticated stochastic tropospheric modeling including azimuthal variability, in water vapor radiometer instrumentation, in region-dependent recovery algorithms, and in the use of synoptic data.

The prospects for improved modeling of the troposphere will be greatly enhanced by the increasing use of high performance receivers capable of tracking up to 8 satellites simultaneously. The preponderance of GPS field campaigns to date have provided limited sky coverage, with only 3 or 4 satellites tracked simultaneously for 7 hours or less per day. The future abundance of quality GPS data will allow for more robust estimation of tropospheric delay, and a concomitant improvement in the estimation of vertical baseline components. In addition, the tropospheric mapping function could itself be parameterized and refined through constrained estimation techniques. For example, azimuthal tropospheric asymmetry could be accommodated at those sites which require it, thus improving the horizontal baseline components as well as the vertical. In addition to improving spatial resolution, more satellites imply better temporal resolution, since tropospheric fluctuations are believed to be a leading error source for the estimation of baseline parameters with short spans of data. This point is particularly pertinent to kinematic surveys for rapid pre-seismic spatial densification and post-seismic spatial and temporal densification.

The use of sophisticated modeling of and direct solution for tropospheric delay in conjunction with insitu WVR measurements, possibly aided with synoptic observations, to reach the mm horizontal accuracy level, particularly in the more humid and meteorologically unstable regions, is a challenge requiring thorough investigation over the next few years. Additional improvement in performance could be realized with receivers that simultaneously track GPS and the Global Navigation Satellite System (GLONASS) under development in the U.S.S.R. Joint reception of GPS and GLONASS signals would help protect against satellite outages, improve overall data strength, and, by effectively doubling the sky sampling density, improve our ability to recover spatially variable tropospheric delay with the satellite observations themselves.

For baselines longer than roughly 1000 km, GPS ephemeris errors tend to dominate. With the advent of global tracking and high precision pseudorange with good multipath control, the optimal data arc length for simultaneous estimation of orbits and geodetic baselines is expected to be less than 24 hours. Presently, the optimal arc length is 1-5 days and careful attention must be given to satellite force models. With the shorter time spans, sensitivity to force mismodeling will be greatly reduced. Orbits can be further improved using day-to-day connection of carrier phase data differenced between the global tracking sites. This technique [Meehan *et al.*, 1988] uses the diurnal nature of pseudorange multipath to resolve the integer discontinuity in carrier phase data sampled on consecutive days. After several days, this effectively converts the carrier phase data into an ultra-precise pseudorange data type with an order of magnitude improvement in observable precision. At this point, orbital errors due to measurement precision will be negligible relative to systematic modeling errors.

Another potentially troublesome source of error is antenna phase center variation on the GPS satellites. Bounds on the size of this effect on pseudorange have been placed at 15 cm over a several hour pass [Neilan, 1986 and Young *et al.*, 1985]. Recent unpublished results suggest that this bound may be so low as 5 cm [Young, 1989]. The differential effect is baseline length dependent and is negligible for regional baselines. With high performance receivers and ground multipath control one can discern this effect as a function of tracking geometry. It is anticipated that with a wealth of sufficiently precise data this source of error can be modeled and removed.

Millimeter geodesy will place demands on a number of other currently used models in GPS systems. The dry troposphere zenith delay, for example, can be in error by several mms due to atmospheric departures from hydrostatic equilibrium [Bender, 1987] and [Treuhaft and Lanyi, 1987]. To reach 1 mm accuracy it may be necessary in some situations to use synoptic meteorological data. Improved algorithms may be required for mapping the delays from zenith to the GPS directions.

Current dual frequency calibration schemes typically reduce ionospheric delay errors to the subcm level. Higher order ( $\geq$  third) terms in the ionosphere may contribute several mms of delay at low elevations during high ionospheric activity [Melbourne, 1989]. Another error remaining after dual frequency calibration of the ionosphere is the effect due to the residual left circular polarization (LCP) component of the GPS signal. The propagation velocities of the RCP and LCP waves differ slightly due to the presence of the geomagnetic field. At the minus 10-20 db level, errors remaining after dual frequency calibration can reach several mms [Bassiri, *private communication*, 1989]. Additional modeling of these effects may be required to achieve mm system performance.

Improved modeling will also be needed for Earth platform processes such as ocean loading, Earth tides, Earth orientation, etc. Environmental factors, such as ground water table variability and freeze/thaw effects, may cause noticeable changes in monument location and will also require further modeling.

### 2.3.6. Future Applications

*Permanent Geodetic Networks.* A new generation of smart receivers and automated post processing software systems will be introduced in stages over the next several years. These elements will be assembled into continuously operating regional geodetic networks capable of determining baselines with mm precision at time resolutions as short as 1 hour. Data will be edited and compressed within the receivers and sent at low rates to a central site where an automated system will continuously monitor network geometry looking for signals of geophysical significance. Mobile receivers will complement the permanent arrays to provide rapid network densification by kinematic surveying. The combined use of carrier phase and high precision, low multipath pseudorange will enable rapid cycle ambiguity resolution between any two receivers, permitting non-continuous mobile receiver operation and short dwells at each site. Some networks may be equipped to sense seismic activity and respond by automatically reducing the data compression interval to capture the detailed course of high rate events. (Routine data compression will be delayed by several hours in order to preserve high resolution data surrounding an event.)

Land and ocean based continuously operating networks will be used for observing intermediate term crustal deformation, volcanic uplift, seafloor spreading, sea level change and ocean circulation, and the detailed 3-dimensional crustal motion occurring both during an earthquake and in the crucial intervals immediately preceding and following. Operation of the first pilot network in southern California will begin in late 1989 under a cooperative program led by the JPL and the Scripps Institution of Oceanography, with investigators from several other institutions participating. Full operation, including automated geophysical signal analysis and seismic event detection, will require 2-3 years to realize. Regional networks of this kind will eventually be linked to serve as vital elements of a unified GPS-based global observatory, combining ocean, solid Earth, atmospheric, and ionospheric science. This is described in more detail below.

*Sea Floor Geodesy.* A combined GPS/underwater acoustic ranging system is under development for precise measurement of sea floor baselines. The acoustic system will consist of benchmark triplets permanently installed on the sea floor, each equipped during the surveying campaign with precision underwater acoustic transponders. A surface platform or buoy will be located over the center of the array and will range to the transponders. The platform will also carry GPS receivers for determining platform attitude and its position relative to a reference site on shore [Spiess, 1985]. The combined acoustic/GPS measurements are expected to provide cm-level baseline accuracies over 100 km in water depths of 6 km within the next decade. This technique would enable precise tracking of sea floor sites in regions where no convenient islands are available (e.g., convergence across major trenches, Pacific plate reference points for Pacific/North America motion and seafloor spreading).

*Synthetic Aperture Radar Platform Positioning.* There are at least two applications of GPS to Synthetic Aperture Radar (SAR) that should be developed. The first is the use of dual satellite based SAR systems operating in a differenced mode to make direct global maps of ocean currents. GPS data are required to provide the orientation and velocity of the satellite as a calibration to the differenced SAR data.

A second application of high accuracy GPS to SAR would be the combining of images from a single SAR element. These images, taken during different orbits, are combined after the use of GPS tracking to determine the relative SAR antenna trajectories to much better than a wavelength. If target coherency is preserved between the successive images, this technique would allow synthesis of SAR apertures the size of the orbit separation.

*Ocean Tide Gauges.* Another future application will involve the development of free floating high performance GPS receivers, deployed in the oceans, to serve as floating tide gauges. Measurement from arrays of floating receivers can be tied with centimeter accuracies or better to land-based fiducial points over great distances, enabling precise monitoring of ocean tides far from the complicating influence of land masses. It would also enable highly dense monitoring near land masses.

*Earth Orientation Monitoring.* When the full Block II constellation is deployed and a global network of GPS reference stations is operating, the tracking data from this system will provide a valuable addition to monitoring Earth orientation variability currently conducted using VLBI and SLR through the International Earth Rotation Service (IERS). GPS tracking will provide complementary and accurate short period information and longer period information of comparable accuracy. Although the GPS (and the SLR) requires VLBI for maintaining the inertial reference system, its introduction into Earth orientation monitoring will fundamentally change the mix in the use of these three techniques for this application.

*Precise Low Earth Orbiter Positioning.* Differential GPS techniques analogous to those used for measuring Earth baselines will soon provide precise orbit determination for lower orbiting Earth satellites, achieving accuracies of a few cms. This will be possible even at the lowest satellite altitudes and for platforms as dynamically complex as the Space Shuttle and the manned space station. GPS-based precise tracking will require a globally distributed network of 6 to 10 reference sites and a top-quality receiver aboard the orbiter providing continuous carrier phase and pseudorange data on many parallel channels. Several distinct orbit determination strategies are possible with this arrangement, including a conventional dynamic approach, a purely kinematic (geometric) approach, and a robust synthesis of the two known as reduced dynamic tracking.

The accuracy of dynamic orbit determination is typically limited by deficiencies in the mathematical models needed to describe the forces acting on the satellite—forces which include gravity, atmospheric drag, solar radiation pressure, outgassing, and unbalanced thermal radiation. The continuous 3-dimensional coverage provided by GPS, together with the combined pseudorange and carrier phase data types, enable the fundamentally different kinematic approach. Kinematic tracking requires no satellite force models and thus offers performance that is virtually independent of satellite altitude and dynamics; it is, however, sensitive to changing observing geometry and is thus vulnerable to ground site or GPS satellite outages. The complementary strengths of dynamic and kinematic tracking are neatly combined in the reduced dynamic technique, which can be tuned to give better performance than either the dynamic or kinematic technique alone while being far more tolerant of model errors and outages. Detailed

studies have shown that with the proper system configuration, continuous 1-3 cm orbit accuracy is possible for virtually any low orbiter.

The first demonstration of GPS-based precise orbit determination will be carried out with the TOPEX/Poseidon satellite, a NASA/CNES oceanographic mission set for launch in 1992. Because of the limited satellite tracking capacity and somewhat restricted field of view of the demonstration receiver on TOPEX, the accuracy goal for the TOPEX Demo has been set at 10 cm. This will be tightened to 1-3 cm for the polar orbiting platforms of the Earth Observing System (Eos) and the low inclination manned space station, now expected to fly in the late 1990's. To achieve such performance it will be necessary to develop space qualified versions of the highest performance GPS ground receivers now in operation. Other satellites expected to carry precise GPS receivers include Gravity Probe B, ARISTOTELES, and the European and Japanese platforms for EOS and the space station. By the end of this century we can expect to see a fleet of at least a half dozen high performance GPS receivers in Earth orbit.

*GPS Science from Earth Orbit.* Orbiting GPS receivers will play a much larger role than simply providing accurate orbits for the host platforms. Placed on suitably stable low orbiters, they will help to refine models of the Earth's gravitational field and to quantify its seasonal and secular variations. They will also contribute materially to ground based GPS geodesy. Computer studies show that when GPS data collected in Earth orbit are combined with ground data they can improve both the accuracy and time resolution of regional and global baseline measurements. This appears to be the result of several distinct effects. The rapid orbiter motion substantially improves GPS satellite orbit determination over short time periods and provides many intermediate observing points between widely separated ground points having little or no GPS common visibility. In addition, the orbiters introduce a vertical dimension to GPS satellite observations that improves determination of vertical baseline components. Finally, careful filter tuning, taking into account the absence of troposphere in the orbiter observations, can help reduce the effect of tropospheric delay uncertainty on baseline solutions. The net improvement in baseline accuracy may be up to a factor of 2 for observing periods of a few hours.

For a wholly different set of science objectives, orbiting GPS receivers will precisely track variations in GPS carrier phase as the signals are occulted by the Earth's atmosphere and ionosphere. The changing Doppler shift during signal occultation will reveal atmospheric refractivity, which in turn can be used to recover profiles of atmospheric density, pressure, and temperature. Temperature accuracies of 1 K or better can be achieved throughout much of the stratosphere and the upper troposphere. Dual frequency carrier and pseudorange data will permit precise global measurement of ionospheric electron content along many raypaths, enabling 3-D tomographic reconstruction of transient structures such as equatorial bubbles and the mid-latitude trough. They will also allow detection and tracking of acoustic gravity waves propagating in the ionosphere, the result of a variety of events taking place in the atmosphere and solid Earth. This will contribute to monitoring the flow of energy through and across different Earth systems.

*The GPS Earth Observatory.* Looking further ahead, we can see these apparently disparate thrusts in GPS science and systems gradually merging into a common enter-



prise: By approximately the year 2000 a fleet of orbiting geodetic receivers will operate in concert with a global reference network and a profusion of specialized regional arrays, both land and ocean based. These will be linked through an international data information system supporting regional science centers to form a permanent observatory for monitoring global change. This will be an extended, unified network providing raw data and higher science products to a diverse Earth science community. Its scope will be vast, embracing the ionosphere to its outer reaches, the atmosphere and climate, the many forms of ocean variability, and the evolving solid Earth. It will become a central resource in the growing multidisciplinary study of the Earth as a dynamic union of interdependent systems.

Though this vision is far from reality, it will be reached. Already the first regional networks, a full global reference network, a central data information system, and at least a half dozen space-based receivers designed to support all of these applications are being developed under various NASA, NOAA, NSF and international programs. The broad multinational initiatives connected with the Earth observing system, the international space station, and NASA's Mission to Planet Earth can provide the impetus and resources to bring these critical elements together to effectively serve Earth science.

*Super GPS.* The Global Positioning System was designed for real time positioning with 10-20 m accuracy. No consideration whatever was given to the precise science applications described here, a fact that has considerably complicated science user equipment and procedures and inhibited performance. A future system of satellites specifically designed to support geodesy could be implemented which would allow the use of much simpler receivers. Choice of more favorable signal frequencies would allow carrier cycle ambiguities to be determined with only 1 second of data, and multiple tones would allow the more accurate calibration of ionospheric delays. In addition, the design of a dedicated satellite for geodesy would provide the opportunity to reduce satellite associated errors, such as mismodeled accelerations due to drag, radiation and outgassing, and the multipath originating from the satellite antenna. Moreover, removal of DoD-mandated features like selective availability, anti-spoof, nuclear event detection, satellite-satellite links, and other military-specific requirements would greatly reduce system cost. One possibility for a dedicated satellite system is the GEOBEACON concept [Cangahuala, 1989]. This system would differ significantly from the GPS system design in that signal transmissions would originate at the ground sites and be received on-board the satellites. Although a newly designed satellite system for Earth science would be an ambitious undertaking, with broad international sponsorship it could become a realistic prospect by the end of the century.

### 2.3.7 GPS System Development Plan

Because GPS is just emerging as an effective tool in Earth science, current GPS science initiatives—on land, in the oceans, and in space—call for an aggressive program of technology development. Attention focuses on a short list of driving requirements taken from the broad range of science objectives:

- 1) 1 mm accuracy in determining the horizontal components of baselines up to 200 km in length, and  $5 \times 10^9$  accuracy thereafter, with a time resolution of 1 hr or less;

- 2) fully automatic data reduction and analysis, beginning with in-receiver data editing and compression, all the way through offline parameter estimation;
- 3) compact receivers that can track a dozen or more satellites at a cost enabling permanent high density coverage over extensive regions (e.g., 10 km centers over 100x100 km<sup>2</sup>).

These requirements, which we may summarize as accuracy, autonomy, and density, lead to a cascade of specific technical challenges that the development program must address. We can collect these into three general categories: Receivers, Data Analysis, and Calibration & Modeling. An additional category, which we call Systems, deals with application-specific and general support systems needed for the diverse science investigations.

#### *2.3.7.1 Receivers*

Field receivers must deliver exacting performance under a great range of operating conditions and be rugged, compact, and affordable. We distinguish three receiver subsystems that require improvement:

*Front End Assembly.* The development plan calls for a portable assembly comprising a dual frequency antenna/backplane with integral low noise pre-amplifier and digital RF sampler. In reasonably benign reflecting environments, the antenna/backplane should limit multipath peaks to a few cms on pseudorange and a few mms on carrier phase, to enable rapid model-independent carrier ambiguity resolution and to keep carrier multipath error below a mm after 1 hour of data averaging. The electronics should effectively eliminate instrumental variations and support 10 cm pseudorange and submm phase precision with 1 second observations. At present only the amplifier stage is clearly adequate. The plan thus calls for implementation of the digital RF sampler currently under development, and further refinement of the antenna/backplane unit.

*Processor Hardware.* Building on the technical heritage from the Rogue receiver, development will proceed toward a field processor approximately the size of a laptop computer, able to track at least 8 satellites and store up to a year of 10-minute observations. For more effective troposphere calibration, future versions will provide dual GPS/GLONASS capability with 24 parallel channels. The immaturity of current technology is most evident in receiver costs, which are typically \$40-80K. This plan seeks a processor cost of \$10K or less by 1995, approaching \$1K by 2000.

*Processor Software.* Upgraded in-receiver signal processing and executive software will be developed for continuous unattended operation, providing real time data editing, cycle break detection and correction, data compression to specified time intervals, and a variety of data management, communications, and executive tasks.

#### *2.3.7.2 Data Analysis*

Although many offline data analysis requirements are application dependent, here we identify three areas of needed development having broad utility:

*Advanced Kinematic Surveying.* The next generation of receivers will enable rapid kinematic surveying without the need for continuous carrier phase tracking during receiver relocation. While the techniques are understood in principle, no development activity is yet underway. The plan covers the development, testing, and refinement of the needed algorithms and delivery of operational kinematic surveying software.

*Efficient Solution Partitioning.* The sparse matrices and natural groupings of parameters that arise in GPS applications are particularly well suited to efficient computer manipulation. A massive solution comprising weeks of data, dozens of receivers, and thousands of parameters can be partitioned into smaller elements to be treated independently and combined in a final step equivalent to processing all data at once. This can result in enormous efficiencies, enabling large scale processing on PC's, fast parallel implementations, and ready combining of results from separate experiments—features that will be invaluable when large scale GPS operations are commonplace. Although some theoretical work has been done, no formal development is in progress. The plan calls for an initial period of theoretical development followed by implementation and validation.

*Automated Processing.* The more exacting forms of GPS processing today tend to demand unflinching vigilance and frequent intervention by the analyst. Future round-the-clock operations will dwarf today's campaigns, forcing a transition to fully automatic processing, starting with the first steps of data conditioning through delivery of final products. Some applications will require expert systems to aid in interpreting results and identifying important signals. The development plan therefore includes a directed program of process automation.

### *2.3.7.3 Calibration and Models*

Millimeter baseline accuracy will require reduction of a host of errors now typically at the 1-5 mm level. The instrumental precision of the carrier phase measurement itself is not a concern; modern receivers achieve better than a mm precision in 1 second, and this is smoothed to insignificance with a few minutes of data. Systematic errors attaching to the measurements and models used in the solution are the key limiters. Some of these will average down significantly over an hour data span, permitting the instantaneous error to be well above a mm. Six error categories to be addressed are summarized here.

*Troposphere.* Estimating both wet and dry tropospheric delay corrections directly from GPS data has been effective at the subcm level in North America and some other regions and will improve with completion of the GPS constellation, introduction of asymmetrical delay models, and the advent of many-channel GPS/GLONASS receivers. Consistent mm performance under less favorable conditions, however, will demand a combination of improvements in radiometry, dry tropospheric refraction models, synoptic calibrations, and GPS solution techniques. The plan thus calls for continued development in all these areas. It should be noted, however, that much of this work is also required by other measurement techniques. Hence, there would be shared funding for such items as radiometry.

*High Order Ionosphere.* Third and fourth order ionospheric effects, which are typically several mms but potentially more than a cm, and which are currently ignored, will be reduced by an order of magnitude through use of dual frequency TEC measurements in combination with geomagnetic field and electron distribution models. The development plan concentrates on the formulation, implementation, and refinement of those complex models and validation of the resulting calibrations.

*GPS Satellite Dynamic Models.* GPS orbit accuracy must be improved from the 40-80 cm achieved with today's best solutions to about a decimeter. This will entail refinement of the solar radiation pressure model and the stochastic techniques used to accommodate unpredictable satellite dynamics. More detailed investigations will be undertaken to better understand the underlying causes of currently unpredictable satellite motion. The addition of a laser retroreflector on a GPS satellite could be very helpful.

*GPS Satellite Multipath.* The effect of signal reflections off the GPS satellites themselves, though it is believed to be significant over baselines longer than 100 km, is not yet well documented. A systematic campaign of field observations covering baselines from 50 to 1000 km, and using both directional antennas and double differencing techniques with omnidirectional antennas, will be mounted to evaluate the effect and calibrate it at the required level.

*Antenna Phase Center.* Techniques will be refined for pinpointing the location and variation of the receiving antenna phase center, and experiments will be conducted to determine, firstly, the degree to which precise tolerances on antenna manufacture and mounting can lead to common mode error cancellation, and, secondly, how that cancellation varies with baseline length. We expect that errors below a mm will be achievable over baselines of a few hundred km.

*Ocean Loading, Earth Tides, & Monument Stability.* As these concerns are not unique to GPS, a more broadly based development program is called for and no GPS-specific development activity is proposed here.

#### 2.3.7.4 Systems

A number of distinct configurations of equipment, communication links, and processing techniques must be assembled and deployed in order to carry out the variety of GPS science initiatives now proposed. The following application-specific systems are included in this development plan:

*Permanent Geodetic Arrays.* The plan calls for immediate deployment of a pilot continuously operating network in southern California, and covers the purchase of six receivers (others are already available), site preparation, system deployment, and round-the-clock operations beginning in 1990. The initial network will consist of 12 sites. The plan also includes a program of technology development to improve system performance, increase automation, reduce operations costs, and enlarge the scope of science applications.

*Free-Floating Ocean Arrays.* Analogous to the Permanent Geodetic Arrays, these will consist of arrays of free-floating buoys equipped with GPS antennas and receivers, power sources, and telemetry systems deployed in the oceans to monitor tides, sea level, ocean circulation, and various forms of ocean variability. Other types of instrumentation for monitoring the oceans will likely be included. The development plan focuses on the design and testing of durable, self-contained GPS receiver-buoys.

The two general purpose support systems described below are essential to the long term development of GPS technology for Earth science. Because they are not associated with a particular application, and because their development appears to be covered by programs already underway, they are listed here for completeness only and are not part of this development plan.

*Global GPS Tracking Network.* A permanent worldwide network of GPS tracking stations meeting the strictest standards established for mm geodesy, serving as global fiducial points, and providing continuous decimeter quality GPS orbits is central to the long term GPS development plan. By the mid-1990's the network should comprise at least a dozen sites, and by 2000 will extend into space to include perhaps a half dozen high performance GPS receivers in low Earth orbit. Initial deployment of a 6-site global network in the early 1990's will be supported in part by NASA for the TOPEX/Poseidon mission. Augmentation of CIGNET and the TOPEX network will be achieved through increasing participation by other national governments.

*Global GPS Data Information System.* Investigators worldwide in an assortment of disciplines will require ready access not only to the products of the global GPS tracking network but to data and results from the full range of ongoing GPS science investigations. This should be facilitated by establishment of a global GPS Data Information System (DIS), an objective that could be achieved either by developing a new system from the ground up or by exploiting the vastly more ambitious DIS planned as a central feature of the Earth Observing System Program. Though it is not yet apparent which approach would be preferable from a GPS science standpoint, for the purpose of this plan we assume that the EosDIS will serve the GPS science community.

## 2.4 Very long baseline interferometry (VLBI)

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### 2.4.1. Present Measurement Capability

Very long baseline interferometry uses observations, in the microwave frequency band, of extragalactic radio sources. From these observations, the difference in the arrival times of signals from the radio sources can be determined, which in turn, can be used to determine the positions of the radio telescopes and the radio sources along with other parameters related to the synchronization of the clocks at the radio telescopes, the delays induced by the signal's propagation through the Earth's atmosphere, and various parameters associated with the rotation of the Earth. The average long term repeatability of VLBI estimates of position, for measurements of 24 hours duration, can be characterized by baseline length uncertainties of  $5 \text{ mm} + 2.4 \times 10^{-9}l$ , where  $l$  is the intersite distance (See figure 2.4.1). The repeatability of horizontal position estimates has a similar characteristic except that the dependence on intersite distance is about 50% larger due to the uncertainty of about 0.5 mas in the terrestrial reference frame. The estimates of height have an average uncertainty of about 30 mm for 24 hour measurements. These values represent the average performance for the ensemble of VLBI stations in use today. There are some station combi-

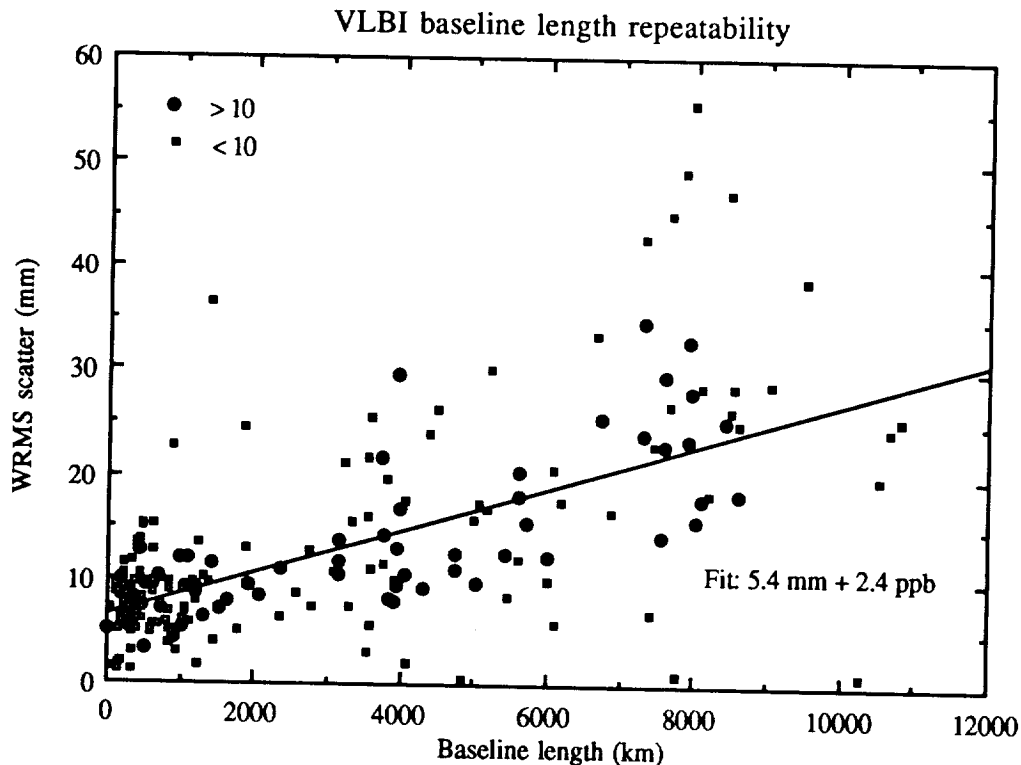


Fig 2.4.1 Plot of weighted-root-mean-square (WRMS) scatter of VLBI baseline length estimates about 'best-fit' slope for 24 hour observing sessions. The different plot symbols (see legend) denote if more or less than 10 measurements were used in computing the WRMS scatter. Results from 200 different baselines, using data obtained in 799 experiments between July, 1980 and February, 1989 are shown.

nations which do not perform this well, and more importantly, there are some combinations which have much better repeatability. For example, the repeatability of the baseline length between Westford, MA and Mojave, CA is 6.5 mm compared to the 11 mm which would be predicted based on the average performance of the VLBI system. Similarly, there are a number of sites whose height repeatability is 20 mm compared to the average of 30 mm. Earth rotation parameters are also determined with VLBI. These parameters are divided into two types: those which are long period compared to the rotation rate of the Earth (when viewed from the Earth), and those with nearly diurnal periods (when viewed from the Earth). Both of these types can be determined with an uncertainty of about 0.5 mas (equivalent distance 15 mm at one Earth radius) from 24 hours of data. The highest temporal resolution has been obtained from 2 hour measurements of the rotation angle about the polar axis (UT1). The uncertainty of these measurements is about 1.5 mas (4.5 cm).

#### 2.4.2. Systems Presently in Operation

There is currently a network of 10 VLBI sites dedicated to geodetic VLBI measurement programs:

Westford, MA	(18m)	Kashima, Japan	(26m)
Fairbanks, AK	(26m)	Ft. Davis, TX	(26m)
Mojave, CA	(12m)	Vandenberg AFB, CA	(9m)
Richmond, FL	(18m)	Maryland Point, MD	(26m)
Wetzell, FRG	(20m)	Shanghai, China	(25m)

where the value in parentheses is the diameter of the radio telescope. In addition, NASA and NGS operate two mobile VLBI systems (3 m and 5 m in diameter) in measurement programs in California, the western United States, Alaska, Canada, and other places in the world. A number of radio telescopes and tracking stations around the world are part time participants in geodetic measurements:

Haystack, MA	(37m)	Goldstone, CA	(26, 34 m)
Medicina, Italy	(32m)	Onsala, Sweden	(20m)
Owens Valley, CA	(40m)	Hat Creek, CA	(26m)
Hartebeesthoek, S.Africa	(26m)	Kauai, Hawaii	(9m)
Tidbinbilla, Australia	(34m)	Rio Namor, Kwajalein	(26m)
Madrid, Spain	(34m)	Pie Town, NM	(25m)

New VLBI facilities which should be operating in 1989 and which will contribute to geodetic programs include two Italian telescopes: Matera (20 m) and Noto (32 m). The U.S. Naval Observatory plans to reactivate a 26 m telescope at Greenbank, WV. The Pie Town antenna is the first of a series of ten antennas being constructed by the U.S. National Radio Astronomy Observatory as a dedicated Very Long Baseline Array (VLBA). When completed in the early 1990's, this facility should provide much useful geodetic data from antennas located in New Mexico (2 antennas), Arizona, California, Iowa, Texas, Washington, New Hampshire, Hawaii, and the Virgin Islands. The Canadians have plans to reactivate the Algonquin Park (46 m) telescope. The Japanese are planning several new facilities on the islands near Japan and

in the Antarctic. The Chinese have plans for two additional antennas. Groups in Brazil, Saudi Arabia, and India all hope to have operational facilities in the 1990's.

An examination of those VLBI systems which are generating the highest quality results (in terms of repeatability), reveals several common features. A "good" radio telescope for VLBI is characterized by:

1. Rapid slew rate ( $\geq 1^\circ/\text{sec}$ ) so that many parts of the sky can be reached quickly;
2. Good sky coverage ( $\leq 5^\circ$  elevation angle cutoff, full azimuth coverage) so that the complete sky can be seen;
3. High sensitivity so that group delays (at X band) can be determined with  $\leq 10$  mm uncertainty from  $\leq 200$  seconds integration on a radio source. The sensitivity of the S band system can be about one order of magnitude lower.
4. Hydrogen maser frequency standard with an Allan standard of between  $3 \times 10^{-15}$  and  $10^{-14}$  so the effects of variations in the clock time can be easily estimated;
5. Uncalibrated system delays which depend on the orientation of the telescope of  $\leq 1$  mm, and orientation independent temporal variations no worse than the hydrogen maser;
6. Dual frequency bands so that the ionospheric delay can be calibrated;
7. Locations which are not likely to have anomalous atmospheric delays,
8. Sufficient quality meteorological sensors so that atmospheric delays and elevation angle dependence can be computed. If a water vapor radiometer is available then the pressure sensor should have an absolute calibration error of  $\leq 1$  mbar (equivalent zenith delay error 2.3 mm). Temperature should be known to 2 C (effective error at  $10^\circ$  elevation angle 3 mm [Davis *et al.*, 1985], see discussion below).

#### 2.4.3. Present Limitations in Performance

The major source of error in VLBI estimates of position and Earth orientation is due to the errors in modeling the delays induced by the propagation of the radio signals through the Earth's atmosphere. This delay is composed of two parts: that due to the constituents in the atmosphere which are in hydrostatic equilibrium, the so called "hydrostatic" or "dry" delay; and that due to water vapor, the "wet" delay. The hydrostatic delay is the larger, but is better modeled from surface meteorological conditions. Its value, in the zenith direction, is directly related to surface pressure and is typically 2300 mm. The wet delay is typically less than 100 mm, but can reach values of over 300 mm in tropical regions, and can not be determined well from surface conditions because of the variable mixing ratio of water vapor to the other constituents in the atmosphere. In nearly all VLBI analyses the wet delay is estimated along with the geodetic parameters of interest. How well these delays can be estimated determines how well the other geodetic parameters can be estimated.

There are a number of limitations to the current VLBI system which affect the accuracy with which the wet delays can be estimated. Some of these limitations are directly related to the VLBI system itself, while others are related to our uncertain knowledge of the state of the atmosphere. Currently, the major limitations from the VLBI system are due to the slew rate, sky coverage, and the sensitivity of the radio telescopes. Each of these limitations affect how well the variations in the atmospheric delays can be separated from the estimates of the geodetic parameters. The



limitations associated with the state of the atmosphere are due to: (1) the effects of changes in the temperature profile above the site which affects the relationship between the zenith value of the hydrostatic delay and its value at non-zenith elevation angles; and (2) the spatial variations of the distribution of water vapor and the atmospheric state variables (pressure and temperature). These latter limitations are thought to affect estimates of position by less than 10 mm in all components much of the time, but at specific times and locations the effects could be larger by a factor of 3 or so, although this latter value is very uncertain.

Other limiting errors at the moment are related to the effects of undiagnosed equipment failures and errors in the calibration system. The latter errors are thought to be less than 10 mm typically in the group delay measurements, but in certain circumstances can be larger. The most serious type of errors here are those which are affected by the orientation of the radio telescope (particularly elevation angle) since these will affect the estimates of the atmospheric delay variations and thus the estimates of position. Antenna deformation is also thought to be a minor limitation at the moment (<10 mm in all position components), but one which will be addressed in the future. A finite element study carried out recently by GSFC indicated that for the Fairbanks radio telescope (26 m diameter) the effects on the delay measurements of gravitation deformations are <5 mm, and the effects of temperature variations are <10 mm for a temperature range of -20 20 C. Both the thermal and gravitational deformations should be repeatable and the model for the Fairbanks antenna structure will be included in future analyses. Models for other antennas need to be developed. The effects of radio source structure are also thought to be less than 10 mm for the estimates of positions, although for individual delay measurements the effects can be as large as a few hundred mm on some of the stronger quasars which have large structure (these sources have now been eliminated from most geodetic observing schedules). For those sources whose structure could still affect position estimates at the millimeter level corrections can be made from maps of these sources obtained from the geodetic data itself, augmented with data from the VLBA.

#### 2.4.4. Required Support Measurements

In addition to the VLBI delay and rate measurements, other measurements are needed to allow the data to be analyzed. The most critical of these are the values of pressure, temperature, and, somewhat less importantly, relative humidity. These values are used to compute the hydrostatic delay and the partial derivatives for estimating the variations of the wet delay. In the future, many different type of atmospheric parameters will be needed (see below). In addition, measurements of the delay through the cables from the hydrogen maser to the pulse generator for the phase calibration are also needed. These measurements are made by a special cable calibration system, and are used during the analysis of the VLBI delay measurements. They are added directly to delay measurements. Finally, since the VLBI estimates of position refer to the intersection of the axes of the telescope, or to the position of the projection of the secondary axis onto the primary axis for non-intersecting axes telescopes, this geometric position should be related to ground marks in the region around the VLBI site.

#### 2.4.5. Developments Required to Improve Performance

The area in which the most improvement needs to be made is atmospheric delay calibration. There are two approaches which can be taken for achieving these improvements: direct calibration or estimation, with probably some combination of these two being the approach which will ultimately be used. Because of VLBI's sensitivity to errors in calibrating the atmospheric delay, the former approach dictates that the direct calibration must be very accurate, and even our current requirements require state of the art remote sensing techniques. With the estimation approach, there is a loss of precision in the estimates of the geodetic parameters because of the need to estimate additional parameters for the atmospheric delay. In addition, the partial derivatives which are related to the change in the atmospheric delay with elevation angle and azimuth are also needed. The various aspects of direct calibration of the wet component of the atmospheric delay are discussed in the NASA WVR panel report, and will not be discussed further. We will also be able to utilize atmospheric field data for better sensing of atmospheric conditions.

To support complex atmospheric parameterizations, we need to obtain data which covers as much of the sky as possible. Thus we need higher sensitivity so that observations can be made as short as possible, and we need to minimize slew time between sources which implies we need rapid slewing radio telescopes. Differences between observing schedules can affect the uncertainties of estimated parameters by factors of two, and thus is a very important consideration. To achieve higher accuracy delay measurements wider bandwidths should be used. Doubling of the current bandwidth is possible, and the technology for achieving this doubling has just been tested in an experiment using Westford, Fairbanks, and Mojave. There will also need to be improvements in the data analysis techniques. The current quality of results is partly due to improved parameterizations of the VLBI theoretical models, particularly those parameters associated with the atmospheric delay modeling.

Currently, the repeatability of VLBI baseline length measurements is about twice that which would be expected from the formal standard deviations obtained either by the Kalman filter or autoconstrained SOLVE. This difference must be related to errors in modeling the VLBI observables. In addition to errors in modeling the atmospheric delays, other areas of deficient modeling at the moment are: (1) Short period UT1 variations, which can not be accurately captured with 0.1 mts precision IRIS Intensive UT1 measurements, and cannot be interpolated from the IRIS 5 day measurements; and (2) antenna deformations and thermal expansion modeling; plus other items discussed in the limitations section. Many of these limitations are amenable to modeling.

#### 2.4.6. Projected Performance Over the Next Decade

With the improvements discussed above incorporated into the VLBI system, it is currently felt that the accuracies of estimates of position should improve to a few mm in all components with a temporal resolution of 24 hours. Horizontal components will probably be still better determined than height, but we expect that height should be determined with a standard deviation of 5 mm with 24 hours of data. This sigma is four times better than current performance, and about twice as good as we should be

obtaining now if not for deficiencies in our models of the elevation angle and azimuth dependence of the atmospheric delays. By use of three dimensional atmospheric field data, we expect to gain most of this factor almost immediately. The other factor of two we should be able to gain through improvements to the sensitivity, bandwidth, and phase calibration system improvements. The improvement we would expect in the estimates of horizontal position are not so clear because we are not sure of all of the errors affecting these components. However, since the current uncertainties in the estimates of horizontal positions are below 5 mm, we expect that these should be improved to a few mm with the improvements in the VLBI system discussed above.

To progress to a 1 mm uncertainty for a 24 hour VLBI experiment will, we believe, be difficult. However, 1 mm accuracy should be obtainable by data averaging. Of course, 1 mm accuracy will then come at the expense of temporal resolution. In fact, baseline length repeatability of 2 mm has already been demonstrated for the intercontinental (5,600 km) Westford Wettzell baseline when 90 day averages of the 5 day separated IRIS data are analyzed. Data of this quality would allow mm/yr uncertainties for baseline length rate of change to be determined with only a couple of years of data. Some of the questions which will need to be addressed before we can be confident of achieving high accuracy by averaging data are the correlation time of errors in modeling the atmospheric delay, and the effects of changes in the brightness distribution of the radio sources.

As the accuracy of VLBI estimates of position improve we will need to start monitoring the stability of the radio telescopes with respect to the ground around them. This activity will involve some measurements of the radio telescopes themselves so that the position of the intersection of axis can be determined directly with respect to ground marks, and some measurements of the position of these ground marks relative to a surrounding network. These latter measurements will need to be of the same accuracy and frequency as the VLBI position estimates.

#### 2.4.7. Present and Projected Level of Data Flow

Currently a typical 24 hr, 5 station VLBI experiment generates about 1000 delay observations. When these observations are incorporated into the VLBI data base which includes theoretically computed delays, calibration information, partial derivatives, and correlator summary information, the data base reaches a size of about 2 Mbytes. The operational Earth orientation service (IRIS) generates about 75 data bases of this size each year, bringing the total data set size to about 150 Mbytes per year. The CDP generates a similar amount of data each year in mobile, Pacific plate motion, North American plate stability, Eurasian plate motion, and research and development experiments. Thus the total VLBI data base grows at a rate of about 300 Mbytes per year. About half of the data volume is computed quantities (*e.g.*, partial derivatives) with the remaining half being directly related to the observations (*e.g.*, calibration and quality information). In the future, it should be possible for this data acquisition rate to reach about 1 Gbyte per year (equivalent to 4–5 stations running continuously). While some additional correlator facilities will be needed to process data collected at this rate, with double speed correlation (which is now possible, although not routinely used), and additional correlators which are already being planned for the early 1990's, it should be possible to at least approach the above rate.

Currently available VLBI analysis programs such as the CALC/SOLVE/SOLVK/SOLV3 should be able to handle the higher rate of data acquisition, although some automation may need to be added to these programs. Already, CALC, SOLVE (the least squares analysis program) and SOLVK (the Kalman filter analysis program) are fully automated, at least for processing experiments which have no major equipment failures. (This quality of experiments represents about 90% of the data obtained.) There will also need to be additional automated software which is capable of obtaining estimates of atmospheric parameters such as mean atmospheric temperature, lapse rate, and height of tropopause from three dimensional atmospheric field data.

#### 2.4.8. Modes of Data Storage and User Access

The Mark III VLBI system has its own database and catalog system (which is also incorporated into the CDDIS). Each institution which processes VLBI delay and rate data, maintains its own catalog of VLBI experiments. These catalogs contain information about the number of versions of each database and the locations of these databases, be it either on disk or archive magnetic tapes. Once a database has been entered into a catalog, all future changes and locations of the database are tracked by the catalog system. Transfer of databases between institutions is by 800/1600/6250 BPI 9" tape but in the future could be by CD ROM disk or other high density medium.

Although the current VLBI database/catalog system has been extremely successful in maintaining the integrity of the VLBI data set, there are some improvements which could be made such as notifying user catalogs of errors in the original data (*e.g.*, phase calibrator problems, poor quality data which originally passed quality checks). Currently these problems either have to be fixed within the user data set, or a new catalog entry created for the corrected databases. There could also be some improved status checking of experiments and reporting of problems within data sets.

The geodetic results obtained from VLBI data are obtainable from a number of sources. The results obtained from the CDP experiments can be obtained from the CDDIS system about one year after the data was taken. These results include estimates of position and Earth orientation information from both CDP and IRIS experiments. Earth orientation values obtained from the IRIS observing sessions are available from the IRIS bulletin and online from the NGS computers in Rockville, MD. Informal requests directly to NASA/GSFC, NGS, or the Harvard Smithsonian Center for Astrophysics provide a means for obtaining the most recent results.

#### 2.4.9 System Development Plan

##### *Current Activities.*

Current activities to improve the accuracy of VLBI measurements have focused in two main areas: (1) improving the intrinsic accuracy of the VLBI group-delay measurements; and (2) improving the accuracy of the atmospheric delay calibrations. The activities associated with item (1) have included developing new hardware for the phase calibration system, improvements to the cable system, modifications to the feed-horns to reduce ohmic losses and improve polarization purity, and doubling the spanned bandwidths at both X and S band. The hardware needed to implement these

improvements will be tested at four stations in October 1989. The costs of replicating this hardware for about a dozen other sites is included in the VLBI section of the implementation plan. These hardware improvements should improve the group delay measurement accuracy to about 5 mm equivalent path length.

Improvements to atmospheric delay calibration have centered on improved estimation strategies for extracting the atmospheric delay contributions along with the geodetic parameters of interest. In this area, most of the studies have concentrated on making observations at low elevation angles (as low as  $4^\circ$ ) to better separate atmospheric delays from the estimates of height. Two series of experiments conducted over the last few years have been very successful in this regard. The "LOWEL" experiments using radio telescopes in Mojave, CA, and Westford, MA, produced 22 estimates, each obtained from 24 hours of data, of the 3900 km chord distance between these two sites with an weighted-root-mean-square scatter of 7 mm—about twice as good as typical results for this baseline at that time. These experiments were followed by a larger set of experiments named "Advanced Technology Development (ATD)" experiments which added the site in Fairbanks, AK. For the Westford to Mojave baseline, the ongoing ATD experiments have produced even better results than the LOWEL experiments.

Other recent R&D activities have included the development of finite element models of some radio telescopes (Fairbanks, AK, and Ft. Davis, TX) so that the effects of antenna deformation can be studied. These effects have been shown to be less than a centimeter, but not ignorable at the millimeter level. The utility of water vapor radiometers (WVR's) for calibrating the delays due to the dipole component of water vapor refractivity has also been studied. The most accurate of these instruments currently improve the repeatability of VLBI estimates of position. However, as the VLBI instrumentation and observing scenarios improve, even greater accuracy requirements will be placed on these instruments.

### *Future Activities*

Although there are current activities aimed at improving the accuracy of the VLBI delay observables, further work needs to be done. Over the next five years a series of incremental improvements to the VLBI system and data analysis will be investigated. As these improvements are made they will be tested on a three to four station network (nominally Fairbanks, AK; Kauai, HI; Westford, MA; and possibly Mojave, CA) during intensive, continuous experiments lasting for one to two weeks. These types of experiments are expected to be carried about once a year. The first such experiment is scheduled for October, 1989. Those modifications which seem warranted will then be installed at other sites in the VLBI network.

The areas of improvement that will be investigated in the future are:

1. improvements to atmospheric delay modeling and estimation;
2. improvements to the feed horn design;
3. improvements to modeling antenna deformation;
4. improvements to hydrogen masers;
5. incorporation of the effects of time varying source structure; and
6. the use of the VLBI phase delay observable.

In addition, tasks which are not solely related to VLBI include the comparison of the results from independent techniques, and locating VLBI/SLR/LLR stations in local reference frames. There should also be investigations of new measurements systems which will set the framework for geodetic systems in the year 2000.

The strategy for calibrating the effects of atmospheric delays is multifaceted involving improvements to both the models of the atmospheric delays and the VLBI instrumentation so that more elaborate estimation techniques may be used. At this time it is clear we need more meteorological data input to the estimation systems. These data are needed to, in effect, compute partial derivatives for the estimation. The likely source of these data at the moment is the National Meteorological Center (NMC) three-dimensional field data. Software needs to be developed to extract the needed information from this very large data set (about four 6250 BPI tapes in compressed form per year). It is expected that the development of such software, and its incorporation into the VLBI data system, will be about 2 my per years for the next few years. In addition to these activities, further studies of WVR's should be carried out, at a level of about 2 my per year for the next few years. The success of the estimation techniques will depend on having high quality, accurate VLBI data, and thus research must be continued in this area.

One of the largest remaining instrumental sources of error probably arises from the feed horns. The two problems which need to be addressed here are: (1) ohmic losses in the feeds; and (2) polarization purity. The first introduces noise into the system, and thus increases the uncertainty of the delay measurements. The second causes baseline dependent delay errors because of leakage of the left circularly polarized signal into the output of the nominally right circular port. These delay errors depend on the relative orientation of the feed horns, and will introduce delay-closure errors, i.e., the sum of the delays around triplets of baselines will be non-zero even in the absence of source structure effects. Redesign of the feed horns will probably take about 2 years at an effort level of 1 my per year. Hardware costs for this task are expected to be about 50K per feed.

Studies of antenna deformation have already been carried out at GSFC, and these should be continued. These studies use finite element, mechanical engineering techniques, and lead to testable hypotheses about the deformation of the antennas. These models can be evaluated during the intensive experiments. About 1 my per should be allocated to these studies with 50 K per year for engineering evaluation.

The hydrogen maser clocks at the VLBI sites provide the time reference relative to which the VLBI delay measurements are made. Most of the masers in use have performances of between  $5 \times 10^{-15}$  and  $10^{-14}$  Allan standard deviations. Even with these performances, hydrogen masers show variations relative to each other of up to 1 ns (30 cm equivalent path length), even after the removal of quadratic terms, during a 24 hour VLBI experiment. Studies should be carried out investigating newer generation hydrogen masers, and improving the performance of the existing ones. This task will involve 1 my per year for a couple years with hardware costs of order 100 K to improve existing masers, and 250 K for the purchase of each new maser.

The effects of source structure on VLBI delays have been studied now for nearly two

decades, and yet models for these effects are still not routinely included in the analysis of geodetic VLBI data because the net effect of geodetic position estimates appears to be at most a few mm. However, such effects will soon be no longer ignorable. With the system improvements discussed above, more compact radio sources can be used (which tend to be weaker) and thus the effects of source, without explicit incorporation into the data processing, may remain small. However, some studies do need to be carried out to ensure that this is the case. About 1 my per year would seem appropriate.

With many of the improvements mentioned above incorporated into the VLBI system, it should be possible to resolve the phase delay ambiguities using the VLBI group delay measurements. The use of the phase delays will result in about a twenty fold improvement in the precision of the VLBI delay measurements reducing their uncertainty to below 1 mm. The realization of improved geodetic position estimates using the phase delays will depend on the improvements to the atmospheric models. However, these studies are worthwhile carrying out because they provide a very sensitive probe of systematic errors in the VLBI system. Effort here should be at the 1 my per year level.

There should be an ongoing effort to incorporate newly developed technologies, such as new receiver hardware, into the VLBI system. This effort will involve the monitoring of development of systems in other areas, and evaluating their potential applications to VLBI. Some funds will be required to purchase some of this new hardware at an expected cost of about 100 K per year. The level of effort here will be about 1 my per year. Funds should also be allocated to upgrading computer hardware and storage media to allow for the processing of the accumulated VLBI data set along with data from other space geodetic system. These items are expected to cost about 100 K per year. The evaluation of new geodetic systems (DORIS, PRARE, PRAREE, GeoBeacons) should also be encouraged at an R and D level initially. Later on in the program a decision point will be reached when we will need to decide if any of these new technologies should be implemented. The costs of such implementations could be several million dollars per year spread over several years.

In general, all of the improvements to the VLBI system are incremental with each contribution being a few mm. Thus, we will probably not see a dramatic onetime improvement but rather a slow progression towards geodetic position estimates with millimeter accuracy.

## Cost Schedule

FY	90	91	92	93	94	95	96	97	98	99
Atm modeling*	.20	.20	.20	.20	.20	.20	.20	.20	.20	.20
Atm RS	.20	.20	.20	.20	.20	.20	.20	.20	.20	.20
WVR purchases	.20	.40	.20							
Analysis Tech	.20	.20	.20	.20	.20	.20	.20	.20	.20	.20
Feed horn study	.10	.10								
hardware		.15	.15	.20	.15					
Antenna Def*	.15	.15	.15	.15	.15	.15	.15	.15	.15	.15
Hydrogen masers study	.10	.10	.10	.10						
hardware		.10	.25	.25	.25	.25	.25	.25	.25	.25
Source struc- ture*	.10	.10	.10	.10						
Phase delays*			.20	.20	.20	.20	.20	.20		
R&D for upgrades study	.10	.10	.10	.10	.10	.10	.10	.10	.10	.10
hardware		.10	.10	.10	.10	.10	.10	.10	.10	.10
Computer up- grades	.20	.20	.20	.20	.20	.20	.20	.20	.20	.20
New technology	.40	.40	.40	.40	.40	.40	.40	.40	.40	.40
"Mk IV" study	.20	.20	.20	.20	.20	.20	.20	.20	.20	.20
VLBA upgrades	.20	.20	.20	.20	.20	.20	.20	.20	.20	.20
<b>Total</b>	<b>2.35</b>	<b>2.90</b>	<b>2.95</b>	<b>2.80</b>	<b>2.55</b>	<b>2.40</b>	<b>2.40</b>	<b>2.40</b>	<b>2.20</b>	<b>2.20</b>

\* Once the algorithms for these items have been developed, it is assumed that the routine use of these will be incorporated into the cost of carrying out the VLBI measurement program. For some of the study costs it is assumed that costs in later years will cover the cost of implementing the hardware and/or algorithms from the earlier studies.



## 2.5 Other microwave techniques

T.Herring, T. Clark

### 2.5.1. DORIS

The French DORIS measurement system involves one way Doppler measurements designed for precise orbit determination for altimeter missions with a goal of 5–10 cm radial accuracy. The design stresses an accuracy goal of 0.3 mm/sec in the determination of range rate. The system involves one way transmissions from ground based transmitters, with the receiver on the satellite. Both the transmitter and the receiver have high stability crystal oscillators ( $5 \times 10^{-13}$  over 10 minutes). The transmitter radiates about two watts at UHF (400 MHz) and S band (2.1 GHz) to support dual frequency ionospheric calibration. Uplink signals involve brief transmissions from each participating terrestrial beacon as scheduled by a timer in the transmitter. The uplink signals also transmit digitally encoded meteorological and calibration data.

The first DORIS package will be launched on the SPOT 2 satellite in mid 1989 or when SPOT 1 is replaced. The goal is for the early deployment of some 60 ground based transmitter packages to work with the SPOT 2 DORIS receiver; about 15 of these will be located at VLBI and SLR stations and at world wide tide gauge sites. It is also planned to carry DORIS hardware on the TOPEX/POSEIDON and SPOT 3 missions.

### 2.5.2. PRARE

The West German PRARE system is a spaceborne two way, two frequency (S/X band) range and range rate measuring system, which will be flown for the first time on ERS 1 in late 1990.

PRARE is a self contained system, being able to up- and downlink all relevant data from and to the ground stations on its tracking loop. Included in its space segment is sufficient data memory to store the onboard regenerated tracking data and transmitted corrective data from the global station network for transmission to the master ground station during overflight times. Through the master station, commands and broadcast data are transmitted into the onboard memory and are disseminated from there to the ground stations.

The ground stations operate as regenerative coherent transponders. They are of low weight, highly mobile and can be operated unattended. The equipment consists of an antenna unit (0.6 m diameter steerable parabolic dish), an electronics box and a weather unit. The PRARE system will operate:

1. at X band (in the 7.19 7.235 GHz region) with 10 MHz bandwidth in the up link,
2. at X band (in the 8.45 8.50 GHz region) with 10 MHz in the down and up link respectively, and
3. at S band (in the 2.20 2.29 GHz region) with 1 MHz bandwidth in the down link.

The procedure to perform range and range rate measurements is as follows: Two signals are sent to the Earth from the satellite, one of which is in S band, the other in X band (8.5 GHz). Both signals are modulated with a PN code (pseudo random noise) for the distance measurement containing data signals ("broadcast information") for the ground operation. The time delay in the reception of the two simultaneously emitted signals is measured in the ground station and retransmitted to the onboard memory for later ionospheric correction of the data. In the ground station the received X band signal is transposed to 7.2 GHz, coherently modulated with the regenerated PN code (or with one of three orthogonal copies for code multiplexing) and retransmitted to the space segment where the PN code is fed into a correlator to determine, on board, the two signal delay, which is a measure of the two way slant range between the satellite and ground station. In addition, the received carrier frequency is evaluated in a Doppler counter to derive the relative velocity of the spacecraft to the ground station. Four independent ground correlators and four Doppler counters allow the simultaneous measurements with four ground stations in code multiplex. Geometric position and orbit determination approaches are applicable in this case.

The PRARE measurement accuracy is estimated to be 0.1 mm/s for X band Doppler (integration interval 30 seconds) and 3 to 7 cm for X band ranging (one measurement per second); the main error source is the tropospheric refraction (2 to 5 cm). A future addition of two optical up links to the PRARE system may overcome this tropospheric refraction limitation. With this upgraded equipment it will be possible to determine the tropospheric correction to better than 5 mm, so the resulting range accuracy will be better than 1 cm. The PRAREE (=PRARE Extended version) is planned for post-ERS 1 missions.

### 2.5.3. GeoBeacons

Recently, before the National Academy of Sciences, and at the NASA GPS workshop in Pasadena (April, 1989), Prof. Counselmann of MIT, presented a "straw man" design of a geodetic measurement system which could provide many of the measurement types needed in the 1990's. This system uses inexpensive ground transmitters (similar to garage door openers in the current model), inexpensive satellites, which effectively just relay signals from all of the ground transmitters (there would be some signal rejection onboard to stop abuse of the system), and "expensive" ground stations where all of the signals from the ground transmitters would be separated. The basic observables of this system would be doubly differenced carrier phase, and therefore none of the components in the system would require accurate clocks. The satellite transponders could be either free flyers or attached to some other satellite. It is currently felt that the transponder package would weigh less than 50 kg. Probably between 4 and 10 satellites would be required by this system. (Larger numbers of satellites assure that at least two satellites would always be visible. The satellite orbits could be selected to provide optimum coverage over specific regions of the world.)

The GeoBeacon is still in the concept phase, but it offers many of the features needed for a geodetic system of the 1990's. In particular, with inexpensive transmitters (expected cost  $\leq$ \$1000 each), many—perhaps thousands—of them could be placed in

the field. Since all of the signal analysis is carried out at ground facilities, where size and power limits are minimal, this system could support thousands (possibly even millions) of ground transmitters, thus allowing a region such as California to be covered with transmitters separated by 10 km on average. With sufficient numbers of satellites, the positions of these transmitters could be monitored continuously, and subcentimeter positions could be determined with only a few minutes of data. With frequency bands near the water vapor and oxygen lines, the system may be able to calibrate the atmospheric delays either through radiometric techniques or through very accurate differential dispersion measurements. The addition of these higher frequency bands could considerably increase the cost of each of the segments of this system. Without the higher frequency channels, atmospheric delays would be accounted for by a combination of estimation and ancillary data such as NMC 3 dimensional field data.

This system seems to offer enough incentive for its further study that some resources should be allocated to evaluate the feasibility of the system. These resources are expected to be 1 to 2 man/years per year for the next few years. Without the detailed design studies, it is difficult to assess the cost of the system at this time, but it is expected that the satellites will be of the "explorer" class, and thus less than 30M each. With the option of piggy backing them on other vehicles, their cost could be considerably less; using the ARIANE Small Attached Payloads (ASAP), the commercial Pegasus, or AmRock Corporation launch, the cost of launch plus vehicle could be less than two million dollars with launch cost sharing with other users. The large cost in this system will be the development of the ground receiving system. The closest model we have is probably that of the Mark III or VLBA correlator development, and thus component costs will likely be several million dollars, and development cost considerably more.

## 2.6 Radar Altimetry for Marine Gravity

D. Sandwell, B. Tapley

### 2.6.1. Background

High resolution mapping of the marine gravity field with satellite altimeters is the most successful application of NASA spaceborne technology to marine geology and geophysics. Indeed, radar altimeter profiles collected by the GEOS-3 and Seasat missions have revolutionized our understanding of the seafloor and oceanic lithosphere, especially in the remote Southern Ocean. While these missions have been very successful, the premature failure of the Seasat spacecraft has led to an incomplete mapping of the marine gravity field. Moreover, improvements in altimeter design and implementation promise additional major scientific advances.

### 2.6.2. Requirements

The solid Earth requirements for marine gravity and pseudo-bathymetry derived from marine gravity are:

1. Complete coverage of the oceans
2. Spatial resolution, 10 to 3000 km
3. Accuracy < 2 mgal

These coverage, resolution and accuracy requirements can be met with a Geosat or TOPEX-class satellite altimeter placed in an orbit with a ~180-day repeat cycle for 4.5 years or longer. At the present time planned missions (Geosat/ERM, Spinsat, ERS-1, TOPEX/Poseidon) do not have the long repeat cycle and the long duration necessary to meet the above requirements. It is recommended that such a long lifetime altimeter mission be given a high priority in the SES program for the 1990's decade.

### 2.6.3. Method

Satellite altimeters use pulse-limited radars along with global tracking to measure the topography of the ocean surface. To a good approximation, the topography of the sea surface corresponds to the marine geoid (i.e. the equipotential ocean surface). Thus satellite altimeters directly measure variations in the marine gravity field at the ocean surface. For marine geology and geophysics applications, it is desirable to compute gravity anomaly  $g_z = g_0 \partial N / \partial z$  or vertical deflection  $\eta = \partial N / \partial x$  from geoid height  $N$  where  $g_0$  is the average acceleration of gravity. Measurement accuracies are most easily evaluated in terms of vertical deflection along individual satellite altimeter profiles. It is convenient that 1 microradian ( $\mu\text{rad}$ ) of vertical deflection error translates into 0.98 mgal of gravity anomaly error.

#### 2.6.4. Present Measurement Capabilities

Present measurement capabilities (Table 2.6-1) for the completed satellite altimeter missions are briefly expressed in terms of altimeter precision, along-track resolution, cross-track resolution, orbit accuracy and accuracy of 2-dimensional gravity that can be recovered. Altimeter precision depends primarily on short wavelength (<100 km) altimeter "noise" and intermediate wavelength (100-1000 km) ocean variability due to eddies. An example of the precision that can be achieved with Geosat/Exact Repeat Mission (Geosat/ERM) data is shown in Figure 2.6-1. Individual profiles have an rms repeatability of about 6  $\mu$ rad (~6 mgal) while the uncertainty is substantially reduced to less than 1  $\mu$ rad by averaging many repeat cycles.

The along-track resolution of the satellite altimeter profiles depends on the ratio of gravity signal to altimeter noise. Figure 2.6-2 shows the along-track resolution that has been achieved by the best vertical deflection profiles from Geosat/ERM.

**TABLE 2.6-1 Present Capabilities**

Mission	Altimeter Precision	Along-Track Resolution	Equatorial Cross-Track Resolution	Radial Orbit Accuracy	2-Dimensional Gravity Acc..
GEOS-3	30 mgal	35 km	10 - 400 km	1.00 m	15 - 30 mgal
Seasat	10 mgal	25 km	80 km	0.50 m	10 mgal
Geosat Primary <sup>1</sup>	6 mgal	15 km	4 km	0.50 m	3 mgal
Geosat/ERM <sup>2</sup>	1 mgal	10 km	160 km	0.40 m	10 - 30 mgal

<sup>1</sup> Data are classified by Department of Defense

<sup>2</sup> Enhanced accuracy and along-track resolution is achieved by averaging 44 repeat profiles.

Averaging many repeat profiles reduces the altimeter noise and improves the resolution from 15 km to 10 km. Additional improvements will be increasingly difficult to achieve because shorter wavelength anomalies are strongly attenuated by upward continuation from the seafloor to the sea surface.

The cross-track resolution of the gravity field that can be recovered from satellite altimetry depends on the ground-track spacing which depends on the length of a repeat cycle. Short repeat cycles, such as the Geosat/ERM result in poor cross-track resolution while long repeat cycles, such as Geosat Primary, result in maximum potential cross-track resolution.

Orbit accuracy depends on a number of factors such as the accuracy of the low degree and order gravity field, tracking coverage/accuracy and spacecraft drag characteristics. It should be noted that radial orbit error is primarily a long wavelength (> 10,000 km) phenomenon. Thus vertical deflection and gravity errors introduced by 1-2 m orbit errors are less than  $2 \times 10^{-7} = 0.2 \mu$ rad ~ 0.2 mgal. Since recent orbit dynamic analyses have reduced Seasat and Geosat orbit errors to the 0.5 m level, it is clear that orbit

accuracies do not influence the accuracy of the gravity field that can be recovered from vertical deflection profiles.

Finally the last column of the table shows the accuracy of 2-dimensional gravity anomalies that can be recovered from each satellite altimeter data set. This 2-dimensional accuracy depends on both the cross-track spacing of the profiles and the along-track accuracy of the profiles. The Geosat Primary mission is close to satisfying the required accuracy, resolution and coverage although the data are classified.

#### 2.6.5. Planned Missions

The expected accuracy, along-track resolution, cross-track resolution and orbit accuracy for 3 missions having firm launch schedules are given in Table 2.6-2. Spinsat will be launched by the US Navy in early 1990 as a replacement to the current Geosat/ERM. It is primarily an oceanographic mission since its ground track will repeat every 17 days along the Geosat/ERM ground track. ERS-1 will be launched by the European Space Agency in early 1991. Its primary mission is a synthetic aperture radar (SAR) mapping of the Earth in either a 17 or a 35-day repeat orbit. If the spacecraft survives beyond its primary mission then there is a possibility that it will be placed in a long-repeat cycle orbit (176 days) which would nearly achieve the above cross-track sampling requirement. However, the mission lifetime is not likely to allow multiple 176-day repeats so the accuracy requirement will not be achieved.

TOPEX/Poseidon will be launched by NASA in mid-1992. While TOPEX/Poseidon has an orbit accuracy and altimeter accuracy that greatly exceeds the above requirements, the cross-track resolution (310 km) of the 10-day repeat cycle is not even close to meeting the coverage requirement.

**TABLE 2.6-2 Under Development**

Mission	Altimeter Precision	Along-Track Resolution	Equatorial Cross-Track Resolution	Radial Orbit Accuracy
Spinsat	1 mgal	10 km	160 km	0.20 m
ERS-1	1 mgal	10 km	80 km	0.40 m
TOPEX/Poseidon	<1 mgal	10 km	310 km	0.13 m

For all missions it is assumed that enhanced accuracy is achieved by averaging many repeat profiles.

#### 2.6.6. Limitations

The primary limitation of the completed and scheduled missions is poor coverage of the ocean surface. Along widely spaced ground tracks the accuracy and resolution requirements have been (or will be) achieved by Geosat/ERM, Spinsat, ERS-1 and TOPEX/Poseidon. Averaging many repeat cycles is needed to reduce altimeter noise and mesoscale variability. However, none of these missions have (or will) attain the required cross-track resolution. Best cross-track coverage will be acquired by ERS-1 but even for this best case the cross-track resolution 80 km is much greater than the required along-track resolution of 10 km. The Geosat Primary mission did obtain complete ocean coverage but these data are classified by the US Navy. Furthermore,

our calculations indicate that the 2-dimensional primary missions gravity field is accurate to only 3.5 mgal; At least one 180-day repeat cycles is needed to achieve 10 mgal accuracy.

#### 2.6.7. Support Measurements

Supporting measurements include:

- Precise laser, Doppler and GPS tracking
- Precise long-wavelength gravity field to allow improved orbit accuracy
- Ionospheric and tropospheric measurements to correct for atmospheric propagation effects

#### 2.6.8. Hardware Developments

Existing hardware such as a two-frequency, TOPEX-class altimeter can achieve or surpass the accuracy and along-track resolution requirements. Hardware improvements in the TOPEX altimeter may reduce short-wavelength altimeter noise and thus reduce the number of repeat cycles needed to achieve 1 mgal accuracy.

#### 2.6.9. Software Development

Areas of ongoing software development include:

- Calculations of precise orbits using state-of-the-art gravity/tide models along with a variety of tracking data types.
- Methods for constructing high/accuracy gravity anomalies by integrating satellite altimeter data variety of spacecraft having different accuracies, resolutions and orbit errors. This includes estimating the errors in the derived gravity fields.

#### 2.6.10. Performance

Projected performances are given in table 2.6–2. Performance improvements are not needed to achieve requirements.

#### 2.6.11. Data Flow

Data flow from each altimeter is approximately 200 Mbytes/day. A ground facility is needed to receive data from the satellite on a daily basis.

#### 2.6.12. Data Storage

Data can be stored and retrieved from the NODS data facility at JPL.

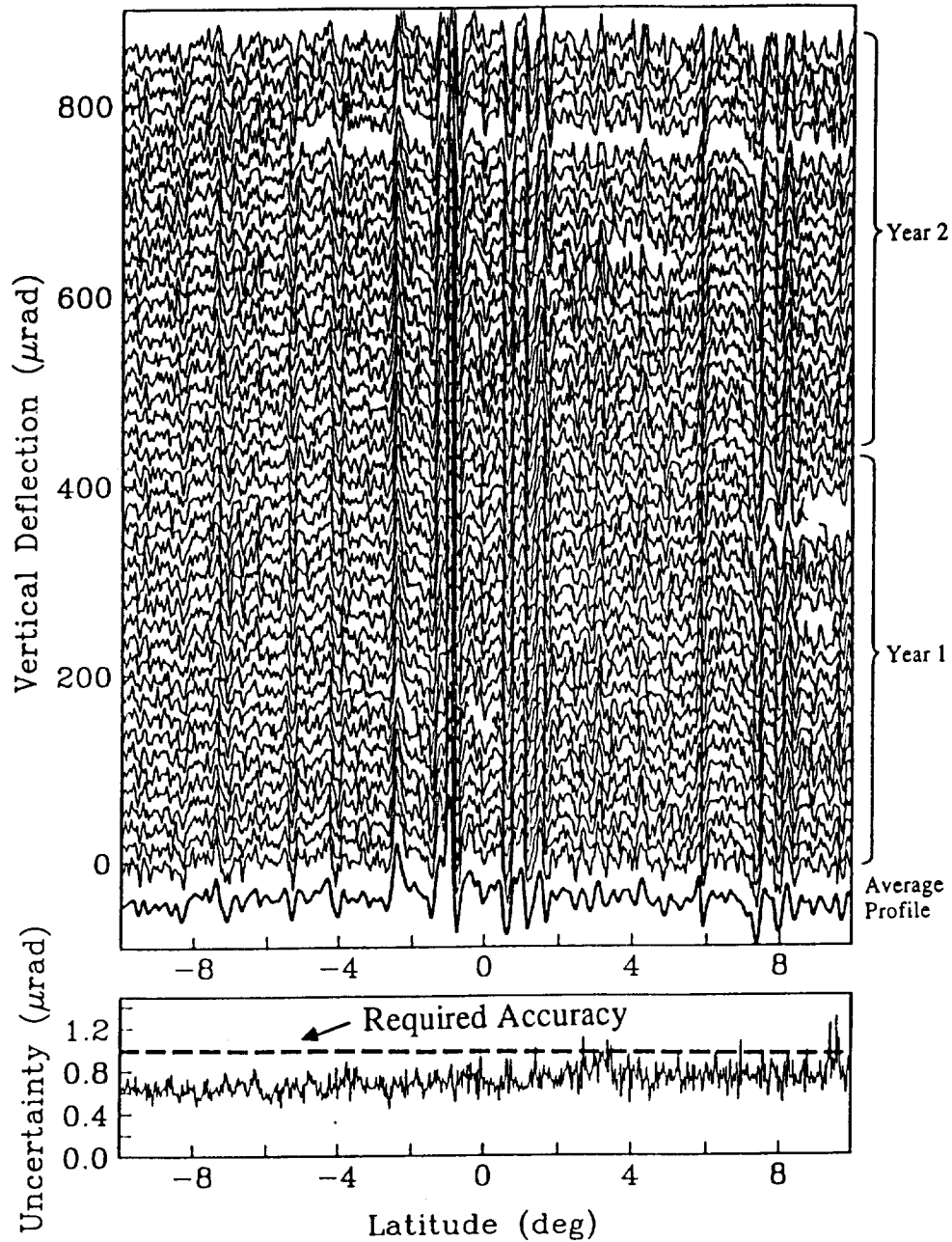


Figure 2.6-1 Along-track vertical deflection for a Geosat/ERM track crossing the Equatorial Atlantic. Each of the 44 individual repeat profiles (22 cycles per year) has an rms precision of  $\sim 6 \mu\text{rad}$ . The average of the 44 profiles has an estimated accuracy of  $< 1 \mu\text{rad}$  (lower plot). This demonstrated accuracy meets the 1 mgal requirement.



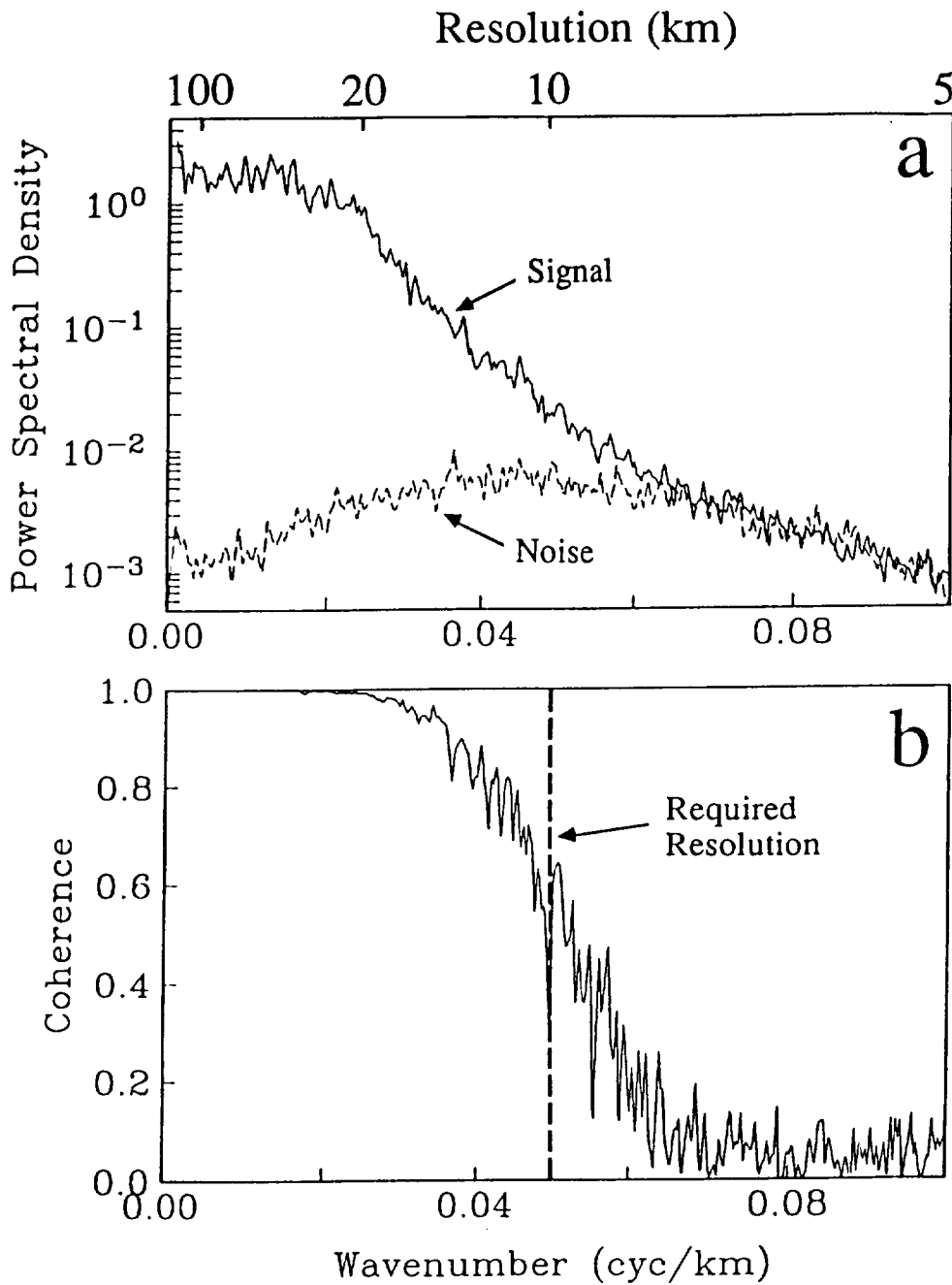


Figure 2.6-2 Power spectral density (upper plot) of vertical deflection profiles consisting of a 1-year average (~15 repeat profiles). This 1-year average represents the vertical deflection "signal". The "noise" PSD is the difference between the first year average and the second year average. The signal to noise ratio is high for resolutions greater than 10 km and low for resolutions less than 10 km. The spectral coherence (lower plot) between the year-1 average and the year-2 average demonstrates a resolution capability of 10 km of satellite altimetry.

## 2.7 GPS/Acoustic ocean geodetic techniques

F. Spiess

### 2.7.1 Requirements.

Space-based geodetic measurement techniques at present have no capability to contribute answers to geodetic measurement questions except where land stations can be established. Most of the science questions addressed in this study have aspects that require understanding of the motions of points on the deep seafloor, since that zone includes two-thirds of the Earth's surface and very nearly all of the active plate margins. In order to make contributions to these answers it is necessary that seafloor locations be established repeatedly with accuracies at least as good as a few centimeters. While this represents an appropriate initial goal one would anticipate that, as with other techniques, once a barely useful operational capability exists, developments would be formulated leading to further improvements in accuracy. The essential environmental performance requirement is to be able to achieve this cm level performance in water depths of at least six km and over baselines of hundreds of km (i.e. accuracies of at least a part in  $10^7$ ).

### 2.7.2 Approaches.

In order to carry out seafloor geodetic measurement programs, there must be some sort of communication with or among benchmarks. In space-based systems used at the Earth's surface, electromagnetic approaches (radio, optical, etc.) play this role. Within the ocean, these forms of radiation are attenuated rapidly, or (because of very long wavelength) lack the necessary resolution and thus acoustic energy provides the transmission mechanism of choice. Unfortunately, the natural variation of propagation velocity with time and space limit our ability to convert underwater acoustic travel times into distances beyond an accuracy of about a part in  $10^5$ . Since cm are the initial goal, it is clear that, for distances of greater than a few km, one must use a hybrid system -- acoustic in the water and electromagnetic in the atmosphere and above it, with some sort of vehicle at the sea surface to make the transformation.

For each of these three system components there are various approaches that can be used, and thus an initial system will involve making design choices based on the level of contributing technology and compatibility of the various elements.

On the acoustic side, one must range on at least three well-separated points on the seafloor, since the alternative of using a single seafloor unit and measuring angle (given the fact that the acoustic wavelengths involved are of the order of ten cm) cannot achieve cm accuracy ( $5 \times 10^{-5}$  radians) at reasonable signal to noise ratios [Committee on Geodesy, 1983]. Ranging must involve a two-way path in order that any component of water flow along the acoustic path will not have to be measured. Given the present state of development of precision transponders, the necessary travel-time accuracy for an initial system is achievable. The principal problem is that the sound velocity structure near the sea surface can vary enough to produce unmodeled changes in the integrated sound speed over the entire path of the order of a part

in  $10^4$ . This uncertainty translates into cm level errors in horizontal position provided one operates the interface platform within about 100 m of the sea-surface point above the center of the seafloor transponder array.

The surface platform could be an ordinary ship or a special buoy or barge. The principal difficulties with a conventional ship are radio receiver multi-paths due to superstructure complexities and acoustic problems due to background noise and turbulence in the vicinity of the hull. By mounting the antennas and acoustic transducer on a modest sized buoy, coupled to the ship with an electromechanical cable 100-200 m. long, both of these problem types are avoided.

In selecting the electromagnetic system, there are two requirements. First, the system must not be significantly degraded by antenna motion. Second, it must be able to produce position estimates on demand with better than 1/10 second temporal resolution to track the wave-induced motion of the surface platform. GPS is the only currently operating system that can meet these requirements, as well as achieving the desired part in  $10^7$  accuracy (or better). GPS can also provide the information on platform attitude necessary to relate the position of the acoustic transducer to the positions of the GPS antennas, in the same coordinates as those in which the GPS satellites are located.

### 2.7.3 System Configuration And Development Status.

Given the considerations outlined above, a particular integrated GPS/acoustic system development has been initiated [Spiess, 1985]. The approach uses a configuration of three long-lived precision transponders (plus a fourth to assure system reliability) to define each seafloor reference point. Successive determinations of the location of each point require deploying a float close to the sea-surface point immediately above the center of the transponder array. The float provides a rigid structure supporting the underwater acoustic transducer at an adequate depth and an array of GPS receiving antennae. Signals from these elements are transmitted over a 100-200 m cable to the tending ship on which initial data processing and recording will take place. At the same time a number of land stations would be occupied in order to provide the necessary simultaneous comparison data. Conceptually, the combination of GPS determination of the horizontal and vertical time-varying coordinates of the top of the float, and its attitude, are matched against successive acoustically determined local x, y, and z coordinates of the sonar transducer with the eventual output being the location of the origin of the transducer coordinate system in relation to the positions of the land-based GPS reference stations.

At the present time, prototype precision acoustic transponders with 8 cm one-shot uncertainties measured over km paths in the sea exist. A sound velocity meter with part in  $10^5$  accuracy has also been demonstrated at sea. GPS capabilities appropriate to this problem also exist. Integration of the acoustic and GPS measurement systems and buoy design are currently in process.

#### 2.7.4 Required Support Measurements.

In addition to the support measurements relevant to precise GPS baseline determination, this system requires in-water information relevant to acoustic system performance. Two types of variables must be measured during the few days that one would be on station. These are seafloor pressure as a function of time (determination of tidal effects) and vertical profiles of sound velocity (or temperature and salinity from which sound velocity can be derived with accuracy adequate for operation of this system). The required accuracies for measuring both pressure and sound velocity are well within present state of the art.

Pressure measurements made on the rigid subsurface structure of the float are desirable in order to determine the position of the antenna array and the sonar transducer relative to the level of the sea surface. While these measurements are not essential as constraints on measurement of horizontal coordinates of the float, they do produce, after averaging, the vertical distance between the sea surface and the antenna, and thus the vertical coordinate of local sea level in relation to GPS, to whatever accuracy the GPS system can deliver. Such data may be of use in other contexts (e.g. altimeter ground truth over the open sea).

#### 2.7.5 Projected Performance Over The Next Decade.

It is anticipated that initial operational versions of this system should achieve baseline length measurement accuracies of a few cm. Once the first generation system has been in operation, there will surely be areas for hardware improvement. More important, however, will be the fact that effort can then be put into modelling the oceanographic effects that will constitute the ultimate limiting factors. These should lead to achievement of subcentimeter performance by the end of the decade.

A major area in which improvement can probably be achieved is that of cost of revisit. One would clearly look toward the possibility of using a satellite relay link to send data from the buoy to shore. This would initially make it feasible for buoys to be installed and recovered as ancillary research ship operations at times convenient for economical ship scheduling, leaving the buoys to be put into an active data collection mode at some subsequent time conveniently related to other GPS observation campaigns ashore. This approach would also make it possible to monitor several sites simultaneously without having a ship standing by each one.

#### 2.7.6 Implementation Plan-Development Phase.

During the 1990-1992 time frame, effort will concentrate on:

1. Conversion of prototype components (particularly acoustic transponders and the acoustic/GPS surface float) into operational units. Emphasis will be on reliability over at least a 5-year lifetime.
2. Integration of acoustic and GPS hardware, particularly in the surface float.
3. Development of software for integration of the data from both acoustic and GPS (including attitude information) data.

4. Modifications to GPS receivers to optimize them for this particular system application.
5. At-sea tests to validate performance of individual components and for full system integration.

Subsequent to initiation of the operational phase, development will continue: (1) to refine initial hardware and software elements; (2) to improve modelling of environmental error sources; and (3) to develop in-buoy partial processing of received signals and data storage or telemetry via satellite in order that several sites can be monitored simultaneously without need for a ship to be standing by each surface float.

#### 2.7.7 Implementation Plan—Operational Phase.

In some sense the operational phase will start in 1990 or 1991 with installation of an initial station in the deep ocean on the Pacific plate off Southern California in support of development activity. Starting in 1992, one expedition per year for the subsequent 5 years should be devoted to establishment and initial occupation of 3 or 4 sites in some region of interest. In 1993, this should be augmented by a second expedition to revisit the sites established in 1992. By 1994, the program should build to a rate of 3 expeditions per year, one instrumenting a new region and the other two being revisits. In 1997, the program should be reviewed to decide whether further regions should be added. Although site selection would be integrated to complement measurement campaigns planned for land operations, there are several that can be identified as logical targets:

1. Pacific Ocean off the California coast, tying into ongoing investigations of transform fault motion between the North American and Pacific plates on the continent and in the continental borderland islands off Southern California.
2. Pacific Ocean south and west of the coast off Baja California and the Mexican mainland to contribute to studies of the margins of the Pacific, North American and Cocos plates, particularly in relation to the Gulf of California and the East Pacific Rise at 21° north.
3. Cocos plate stations to provide seaward control of motion across the Middle America Trench and to relate to East Pacific Rise studies in well mapped areas at 9° and 12° N.
4. Juan de Fuca plate area to contribute to understanding of motion of a small plate (with no islands) captured between two larger ones, as well as understanding of convergent motion off the southwest coast of Canada.
5. Seaward side of the Aleutian Trench to establish, in conjunction with observations on the Alaskan mainland and the Aleutian Islands, the nature of convergence in relation to inferences from and about earthquake characteristics.

## 2.8 Measurement validation and system integration

W. Strange, R. Allenby, T. Herring, M. Pearlman

### 2.8.1 Reference Mark Stability and Acquisition

At the mm and submm level questions of local stability of the reference monument and referencing of the instrument measurement point to a specific point on the reference mark become important. The locating of the instrument measurement point to a specific point on the reference mark has two aspects. First, there must be a point on the reference mark which can be located at the required accuracy. In principle, this is not difficult to achieve, but it is unlikely that the current punch marks on brass disks are compatible with submm reference. Submm accuracy reference marks will require care in placing the indentation on the mark. Also, retaining this accuracy will require protection from the elements and use where instruments are placed directly on the indentation. Possibly harder metals than brass may be required.

In most cases, the horizontal positioning of instrument antennas over the measurement point on reference marks is accomplished with optical plummets. If submm accuracy is to be attained, it will be necessary that horizontal positioning of the antenna over the reference point on the mark be accomplished using rotating optical plummets. Current vertical positioning of GPS antennas is commonly done using steel tapes with slant distances measured and then converted to vertical distances. The National Geodetic Survey uses graduated rigid steel rods, which are even more accurate. However, the measurement must be done prior to placing the antenna on the tribrach which opens the possibility of movement of the tripod in mounting the antenna.

To assure submm positioning of GPS antennas relative to the reference mark, some type of forced centering device will probably be required. This will require construction of new marks with the forced centering system as an integral part of the mark. Experimentation with forced centering is already being undertaken in applications where horizontal movements of a few mm can be important, such as monitoring of dam deformation.

Local stability of a mark to the mm level will be very difficult to achieve; in some sedimentary areas, it may be almost impossible at reasonable cost. It is unlikely that the same type of reference mark will be applicable to all areas since hard rock and sedimentary rock present quite different situations. Past practice has been to use different types of marks for hard rock (igneous and metamorphic) and soft rock (sedimentary) areas and in soft rock areas to use different types of monuments for horizontal and vertical. In hard rock areas, a disk with a shaft is used, with a hole drilled into the rock and the shaft inserted and cemented in. In soft rock areas, the mark used for high accuracy horizontal control has been a concrete monument such as shown in Figure 2.8-1. Repeated high accuracy EDM measurements show this type of monument is stable to better than 3 mm much of the time, although movements of up to 1 cm or more can occur. For high accuracy vertical control, a hole is drilled and a pipe inserted to some depth. A stainless steel rod is then driven through the pipe to "refusal," i.e., to some depth where additional driving of the rod reaches some prescribed level of difficulty. The area between the pipe and rod is then filled with some type of heavy oil.

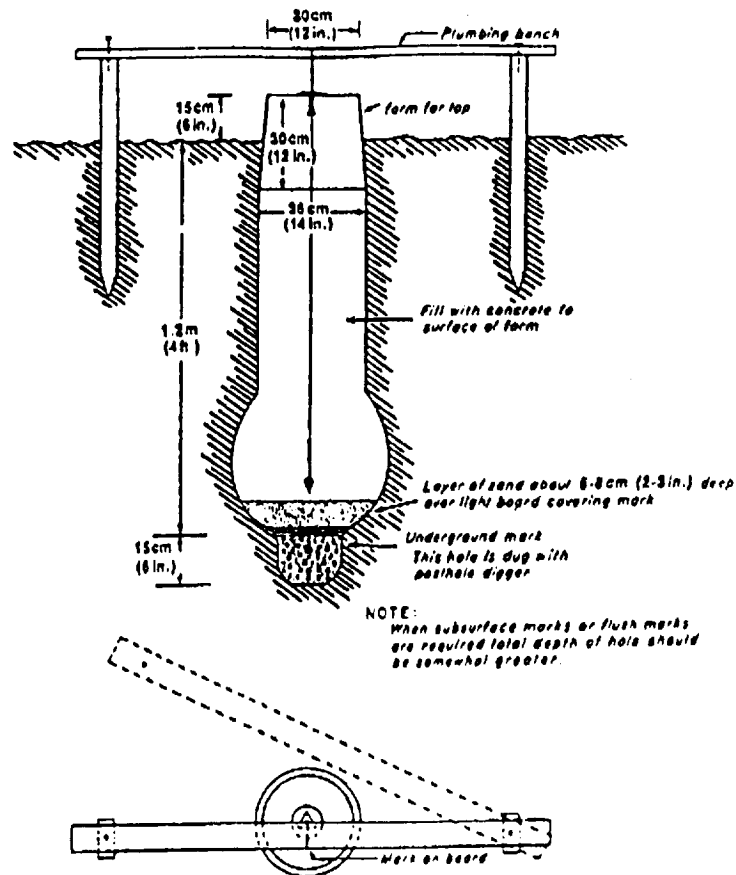


Figure 2.8-1. A typical calibration baseline monument with optional underground monument.

The purpose of this approach with vertical marks is to separate the rod from the near surface sediments which deform during wetting and drying and freezing and thawing. There have been attempts to make the central steel rod stiff enough to have this type of mark serve as a three-dimensional mark, but it is questionable if there is enough stiffness to maintain horizontal stability at the 1 mm or better level.

Two primary approaches exist to improving the integrity of horizontal mark stability. One is to connect the surface mark to a mark at depth such is done for the strain meter at Pinyon Flats using, perhaps, optical fibers to measure the surface mark to subsurface mark offset. A second alternative is to use a set of monuments. There is reason to believe, based on repeat measurements, that a set of five marks similar to that illustrated in Figure 2.8-1 set in the form of a central mark and four marks in cardinal directions might be adequate to maintain horizontal integrity at about the 1 mm accuracy under many conditions. Repeat measurements between the five monuments, set 50 to 100 km apart, would serve to identify excessive local movements of one or two of the monuments over the intervening time period since the previous measurement. This approach could prove to be less expensive and easier to implement than the use of surface mark/deep mark and optical connections. It would also provide redundancy.

In the case of vertical control, it is not clear that realistic alternatives to the type of mark discussed above will be found in the 1990's. For this reason, serious consideration must be given to establishment of independent horizontal and vertical reference marks.

*Requirement for tectonic "footprint" sites.*

For the correct analyses and interpretation of larger scale plate tectonic motions utilizing data generated by space geodetic techniques, it is necessary that the individual, separate displacements contributing to the total motion vector be identified and understood. The correct, large scale motion vector, can only be obtained after localized motions have been removed.

Disturbances of a single monument are protected by having the central observing monument ringed by at least three reference monuments, located at distances of roughly 25 or 50 meters. Most sites also include an azimuth monument and several laser calibration piers (corner cube reflectors). These monuments are carefully tied together with a least squares solution, thus, any significant individual monument disturbance is easily detectable.

It is also likely that localized motion on a slightly larger scale may move the observing and reference monuments as a unit. Such dislocations must be understood and accounted for in analysis to prevent them from complicating the results due to large scale tectonism. Such localized motions usually involve:

1. Primarily vertical motions caused by ground water withdrawal and recharging, magma injection, or frost heave.
2. Complex motions caused by land slides or localized tectonism along minor faults.

Intermediate monumentation, which is designed to detect and correct for these effects, involves placing a network of very stabilized monuments at distances of 10 to 15 km from an observing site. These monuments are carefully tied into the observing site and are designed to show subcm motions between the observing site and the reference monuments. These intermediate monuments are popularly referred to as tectonic "footprint" sites. Before the advent of GPS, the establishment of footprint sites was inordinately expensive and time consuming. Now (mid 1989), utilizing GPS, footprints have already been established around the Palos Verdes, Santa Paula and Vandenberg, California sites, and additional footprints around at least Mojave, California, Pinyon Flats, California, and McDonald, Texas, are planned for 1990. Hopefully, as soon as feasible, all our major sites will be protected by tectonic footprints.

Salient features of the footprint sites are as follows:

1. Surveying will be done and maintained by GPS systems.
2. Existing, well constructed, monuments will be used whenever possible. Where this is not possible, special monuments designed for maximum stability will be installed.
3. The footprint network will consist of at least 3, and preferably 4, monuments.



4. Monuments will be 10 to 30 km from observing site and will be located to form a strong geometric configuration around the site.
5. Footprint monuments, where possible, will be located on stable geologic formations, preferably on the same formation as the observing site.
6. No known active faults should separate the footprints from the observing site.
7. Top implementation priority should go to:
  - a. Sites with a long history of occupation.
  - b. Frequently occupied sites.
  - c. Focal sites in baseline networks.
  - d. Sites in complex geological terrains.
  - e. Sites with suspected localized motion.

### 2.8.2 Measurement Validation and System Integration

Measurement validation must take into account effects of hardware, software, data processing, modelling, and data acquisition strategy. System performance and measurement quality are routinely examined through calibration procedures carefully designed to isolate and characterize specific systematic error components that would otherwise corrupt geophysical measurements, but these procedures do not view the entire measurement process through independent paths or through an overall standard.

Since the accuracy of space geodetic techniques has now surpassed that of ground-based survey methods for all but the shortest baselines (<10 km), the best means of measuring system performance over long baselines is through comparison with other space geodetic instruments.

#### *Collocation*

Collocation tests, in which similar types of instruments are operated side-by-side, are a fundamental tool which provides considerable insight into the presence and nature of machine-dependent range biases that might otherwise go unnoticed. The simultaneity of operations and the close proximity of the two instruments reduces uncertainties due to geodetic modelling and refraction, and permit rapid and regular comparison of critical supporting data, such as timing and barometric pressure readings. Collocation tests have been used almost entirely by SLR, and are an integral part of the SLR performance validation program. However, it is relevant to the other techniques, and in particular could be a very important tool for GPS.

Collocation tests have the disadvantage of considerable commonality between instruments, leading to the possibility of common and hence unnoticed errors. It has the benefit, however, of common observables at many steps along the measurement and processing path at which direct comparisons can be made for diagnostic purposes.

Collocation is not a direct measure of accuracy, but rather a measure of how two machines differ in their performance. It does not identify which, if either, of the two machines is working correctly, nor does it directly identify errors that the two machines have in common. A more complete evaluation is made through the combination of collocation, ground testing, and careful analysis of data and results. However, if two machines in collocation agree to within the measurement accuracy estimated

through ground-based characterization measurements, then there is considerable confidence that the instruments are operating within that degree of accuracy.

### *Intercomparison*

In intercomparison tests, machines of different types are operated side-by-side, measuring the same baseline or other geophysical quantity. The measurements may be fundamentally different (such as SLR and VLBI) relying on different observables and even different reference systems. In principle, intercomparison tests give us two independent views of the same quantity which should highlight not only machine specific biases, but also error signatures that may be technique dependent. Once again, the close proximity of the instruments reduces uncertainties due to geodetic modelling and, to some extent refraction and facilitates comparison of supporting data.

As with collocation tests, intercomparison tells us how two machines differ, not which is more accurate or which is working correctly. However, the combination of intercomparison tests with ground tests, coupled with careful analysis of data and geodetic results, provides very strong insight into the performance of each machine.

Intercomparison tests have the advantage that measurements are independent, and comparisons are being made at the full system level. On the other hand, there may be few if any intermediate parameters for comparison to use for intermediate diagnostics. Intercomparisons are being used now among SLR, VLBI, and GPS, and will certainly encompass GLRS once it is available. The demand for subcentimeter, and eventually mm accuracies, will require an even greater role for intercomparisons on a routine basis.

### *System*

Any measurement network system that we envision encompasses a combination of techniques, with VLBI and SLR providing long baseline measurements and Earth rotation monitoring, and GPS and GLRS providing intermediate and shorter baseline measurements. Any duplication of capability between techniques, such as baseline determination, is far offset by: (1) the need for intercomparisons to develop and validate performance; and (2) the unique capabilities that each provides to the program.

Analysis then, will require combinations of data from not only different space geodetic techniques, but also supporting groundbased and geological data. It is anticipated that considerable effort will be required to develop approaches to properly combine data from the separate sources.

### 3. REMOTE SENSING TECHNIQUES

This section of the Measurement Techniques and Technology Panel report deals with remote sensing instrumentation. Inputs and requirements from the scientific panels were analyzed; based on those needs, a combined set of recommendations was developed, summarizing the most urgent requirement needs of all the geology panels. Succeeding sections cover several areas of remote sensing for geologic applications. Section 3.1 details capabilities and requirements for instruments and missions in the reflected visible, near-infrared, and short wavelength infrared wavelength regions. Section 3.2 has the same format and covers needs and capabilities in the emitted thermal infrared wavelength region, both for compositional information and direct temperature measurements. Section 3.3 covers airborne and satellite-borne synthetic aperture radar imaging systems. Present capabilities and future planned missions are described. Section 4 covers a number of instruments and techniques, all dealing with derivation or acquisition of digital topographic data. Section 5 describes needs for measurement of gases and aerosols associated with volcanic activity.

The individual contributors for each section are identified after the titles. The entire section was assembled and edited by Michael Abrams and Anne Kahle of the Jet Propulsion Laboratory.

#### *RECOMMENDATIONS*

The consensus recommendations from the geological science panels for instrument development and new missions are:

1. A global topography mission: requirements are for global digital topographic data with 30 m horizontal resolution and 3–4 m vertical resolution; this will require a new mission or systematic conversion of SPOT stereo imagery.
2. High resolution panchromatic data, global coverage of the land areas; 1–5 m spatial resolution; this requires a new mission.
3. Multispectral thermal infrared, global coverage of the land areas on a one-time basis; this can be met by an upgrade to the Eos ITIR instrument proposed by the Japanese.
4. Synthetic aperture imaging radar: multi-channel, multi-polarization global coverage; accommodated by the Eos SAR instrument.
5. Visible-near infrared imaging spectrometer providing global coverage; this will be satisfied by the Eos HIRIS instrument.
6. Continue strong support for NASA's aircraft instrument program.

#### *Recommendations concerning remote sensing issues:*

1. Complete and low cost access to all historic and current remote sensing data.
2. Return of the Landsat system to systematic data acquisition.

#### *Recommendations supported by several panels:*

1. High resolution global panchromatic stereo imagery; 1–5 m spatial resolution.
2. Imaging in the ultraviolet wavelength region.

## 3.1 Orbital and airborne sensors for the visible–near infrared.

M. Abrams, A. Kahle

### 3.1.1. Requirements

1. Global cloud–free high sun–angle imagery
2. Spectral range: 0.4–2.45  $\mu\text{m}$
3. Spatial resolution < 30 m
4. Spectral resolution : 10–100 nm (20–200 bands)
5. Temporal:
  - a. 100% of land area 1 time for 2–4 seasons
  - b. 40% land area annually
6. One time each. AM/PM panchromatic data (0.6–1.0  $\mu\text{m}$ ) at <5 m  
⇒ Requirements are driven by Land Surface Panel; other panels requirements are satisfied by these requirements.

### 3.1.2. Description of Technique

#### 3.1.2.1 *Multispectral data*

The concept is called imaging spectrometry, which consists of simultaneous acquisition of images in several hundred contiguous spectral bands. There are two instrumental approaches to accomplish this task: using line arrays, or area arrays. The former method has a dedicated detector element for each cross–track pixel, which increases the residence, or integration time to the interval required to move one IFOV along the track. There are limitations to using multiple line arrays, each with its own spectral band pass filter; the most severe is that having more than about 10 bands increases instrument complexity beyond the point of usability. A second line–array approach is to pass the light from every pixel through a spectrometer where it is dispersed and focussed onto a line array. Thus each pixel is simultaneously sensed in as many spectral bands as there are detector elements in the array. This approach is suited to an airborne sensor that flies slowly enough that the readout time of the detector array is a small fraction of the integration time. Because of high orbital velocities, spacecraft–borne sensors require the use of two–dimensional area array detectors at the focal plane of the spectrometer, thereby obviating the need for the optical scanning mechanism. In this configuration, there is a dedicated column of spectral detector elements for each cross–track pixel.

#### 3.1.2.2. *Panchromatic data*

Satellite–borne panchromatic data can be acquired using line array detector instruments, described above. The requirement for 5 m spatial resolution can be easily met from a technical stand–point with existing technology.

### 3.1.3. Present Measurement Capability and Systems

#### 3.1.3.1. *Multispectral data*

There are no existing operational satellite systems providing the required high spectral resolution data. The Landsat Thematic Mapper Scanners on Landsats-4 and 5 have 6 channels in the desired wavelength region, with global coverage capabilities, and the necessary 30 m spatial resolution. They lack sufficient spectral bands to meet the need of mineralogical identification. Several aircraft instruments do operate with the needed performance characteristics. These are owned by: NASA/JPL (the AVIRIS scanner), GER instruments, New York; Carr-Boyd, Australia. These instruments have proved the concept of imaging spectrometry, and are beginning to deliver data with up to 200 spectral bands in the VNIR.

The only satellite instrument under development is the High Resolution Imaging Spectrometer (HIRIS) for the Eos polar platform-1, under the control of JPL. This instrument will acquire 210 spectral bands, 10 nm wide, with a spatial resolution of 30 m and a 30 km swath width. HIRIS is envisioned as an experimenter-driven instrument, rather than as a global surveying mission. It will acquire limited data for individual researchers, due to constraints on data rate transmission.

#### 3.1.3.2. *Panchromatic data*

Existing panchromatic satellite instruments currently operating are the French SPOT scanner, and Soviet photographic satellites. SPOT provides 60 km swath width digital data, with stereo capability, with 10 m IFOV on a global basis. The Soviet photographic systems provide 5 m data on a request basis, but not in digital format. In theory, either system could provide a portion of the requirements for panchromatic data, but not meet all of the requirements.

Systems under development to acquire 5 m digital panchromatic data include plans by the Japanese for ITIR scanner on Eos platform-2, which will include a stereo capability, single channel in addition to other VNIR and TIR bands. This instrument is still in the Phase-A stages of development, and could change before Phase-B arrives. The future SPOT satellites may also be upgraded to provide 5 m digital panchromatic data.

### 3.1.4. Present Limitations

For both required measurement systems, there are problems with existing and planned instruments to meet stated requirements. For multispectral measurements, temporal desires to obtain global coverage are not currently being considered, due to the enormity of the data storage, archiving, and processing problems. A single HIRIS scene (30×30 km) has 2,000 Mbits, acquired at a raw rate of 512 Mbits/sec. The TDRSS relay satellite imposes a limit of 300 Mbits/sec on transmission rate; this requires already almost a two-fold factor in data compression/editing/reduction. To obtain complete one time global coverage would involve collecting 300,000 HIRIS scenes, or  $6 \times 10^8$  Mbits of data, a daunting task.

For acquisition of panchromatic data, no systems are currently planned to obtain both AM and PM coverage. Eos platforms are all sun-synchronous orbits in the late morning; no instruments are envisioned for late afternoon coverage.

#### 3.1.5. Required Support Measurements

Both the Volcanology and Land Surface panels require global digital topographic data sets, coregistered to the VNIR data, for accomplishment of scientific goals. Resolution requirements are 30 m spatial for the multispectral data, and 5 m for panchromatic data. Vertical resolutions are .5 m and .1 m respectively. Both panels require certain kinds of ground truth information: absolute age dates for 10 anchor sites for the landforms panel; age dates and calibration data for the Volcanology panel. Other satellite measurements (SAR, atmospheric gases, GPS) are covered in other sections of this report.

#### 3.1.6. Developments Required to Improve Performance

The only improvements required for planned instruments are in the panchromatic data. Spatial resolution must be increased to 5 m, and the orbit should be asynchronous to allow PM data acquisition. Both items are currently feasible, and require no major technological advances.

#### 3.1.7. Projected Performance Over the Next Decade

Given the current plans for future instruments, performance requirements can be partially met. Some modifications in satellite orbits, instrumentation, and data collection strategy can satisfy the needs as expressed by the Volcanology and Land Surface panels. This assumes that 5 m spatial resolution in the panchromatic data will be realized, and, of necessity, flown on a free-flier satellite, not part of Eos. HIRIS data collection strategy will have to be changed to operate the instrument in a mapping mode to obtain systematic data coverage of the land surfaces on a global basis.

## 3.2 Orbital and airborne sensors for the thermal infrared.

A. Kahle, M. Abrams

### 3.2.1. Introduction

In the passive mode, both broad-band and multispectral thermal measurements are made of the thermal radiance emitted by the Earth's surface. In general, this radiance is a function of both surface temperature and surface spectral emissivity. Both are important variables for geology. The temperature is a key variable in volcanological and geothermal studies. Thermal inertia, a physical property derived from measurements of the diurnal variation of the surface temperature, allows inferences about surface density and thermal conductivity. The multispectral measurements lead to lithologic discrimination and, with sufficient spectral resolution and sensitivity, lithologic identification. These data are particularly sensitive to silicate mineralogy and hence complement the VNIR data which are mostly insensitive to silicates.

Active measurements, using CO<sub>2</sub> lasers, are being developed by the Australians, providing very high spectral resolution reflectivity measurements for identification of surface spectral features.

Imaging, profiling and point measurements are required.

#### 3.2.1.1. Requirements—Multispectral TIR

1. Global cloud-free images, coregistered with VNIR
2. Spectral range 8–13  $\mu\text{m}$
3. Spatial resolution  $\leq 30$  m
4. Spectral resolution 0.5  $\mu\text{m}$
5.  $NE\Delta T$  0.1K
6. Temporal: 100% of land area 1 time for 2–4 seasons; 40% of land surface annually
7. Research instrument (aircraft?) providing 0.1  $\mu\text{m}$  spectral resolution
8. Research instrument (aircraft?) operating in the 3–5  $\mu\text{m}$  range

#### 3.2.1.2. Requirements—Temperature (Thermal properties)

1. Day–night pairs of radiance data over selected sites
2. Spectral range: 8–12  $\mu\text{m}$
3. Spatial resolution  $\leq 30$  m
4. Spectral resolution: N/A
5.  $NE\Delta T$  0.1K
6. Temporal: day–night pair acquired about 12 hours apart.

Selected research targets only—not global coverage

### 3.2.1.3. Requirements–Temperature Measurements (Volcanic processes)

1. Repeated coverage of selected volcanic targets
2. Spectral range: 1–5, 8–12  $\mu\text{m}$
3. Spatial resolution 10–30 m
4. Spectral resolution: 0.5  $\mu\text{m}$
5. Temporal: Preeruption baseline coverage of about 20 selected active volcanoes. Monitoring precursor, eruptive, and post-eruptive activity in real or near-real-time, as eruptions occur

### 3.2.2. Description of Technique

#### 3.2.2.1. Temperature data

Radiance emitted by the surface is measured by either multispectral or broadband radiometers. In general images are required, which are achieved by optical/mechanical scanning or by pushbroom linear or area array scanning. High instrument sensitivity and frequent (preferably every line) calibration is required. The measured radiance  $R$ , as function of wavelength can be expressed as

$$R_{\lambda} = [\epsilon_{\lambda} B_{\lambda}(T_g) + (1 - \epsilon_{\lambda}) R_{atm \uparrow}(\lambda)] \tau_{\lambda} + R_{atm \downarrow}(\lambda) \quad (3.2.1)$$

where  $T_g$  = ground temperature

$\epsilon_{\lambda}$  = ground emissivity

$B_{\lambda}(T_g)$  = emitted ground radiance, which from Planck's Law

$$= \frac{\epsilon_{\lambda} C_1}{\lambda^5 [\exp(C_2/\lambda T_g)]}$$

$R_{atm \downarrow}$  = downward atmospheric radiance

$\tau_{\lambda}$  = atmospheric transmissivity

$R_{atm \uparrow}$  = upward atmospheric path radiance

Thus, to solve for temperature one needs a priori knowledge of the surface emissivity, and must measure or model atmospheric parameters (temperature and water vapor profiles).

The maximum radiance from the surface at normal terrestrial temperatures will be between 9 and 10  $\mu\text{m}$ , so measurements in the 8–12 atmospheric window are most appropriate. However, at volcanic temperatures (1000–1200K) the maximum radiance will be between 1–2  $\mu\text{m}$ , so sensing between 1–2.5  $\mu\text{m}$  and also in the 3–5  $\mu\text{m}$  window is desirable. Multispectral rather than broadband measurements allows one to make inferences about surface emissivity and/or the areal extent and temperature of hot spots which are significantly smaller than a pixel—the normal situation in most volcanic features.

In order to determine surface thermal inertia one needs to measure temperature at or near the times of maximum and minimum temperature during a diurnal cycle. The temperature difference, combined with albedo images can be used to calculate “apparent” thermal inertia. Alternatively, models involving knowledge of net fluxes of radiation,



sensible and latent heat can be convolved with the temperature and albedo data to provide more quantitative values of thermal inertia.

#### 3.2.2.2. Spectral Data

The same multispectral radiance measurements which allow temperature determination also provide surface spectral emissivity. Again one uses equation 1, but solving for  $\epsilon_\lambda$ , rather than  $T$ . Because the system of  $n$  equations (one for each wavelength band) is underdetermined, with  $n+1$  unknowns ( $T$ , plus  $n$  values of emissivity) one must again use a priori knowledge or multitemporal measurements for a solution.

#### 3.2.3. Present Measurement Capability and Systems

There are no orbiting systems which provide multispectral thermal infrared data at either the required spectral or spatial resolution. AVHRR provides three channels of thermal radiance measurements, but has only 1 km spatial resolution, of very limited use for geologic applications. The Landsat-5 has a single broadband thermal channel (10–12  $\mu\text{m}$ ) with 120 m resolution which has found very little use in geologic applications due to low dynamic range and poor spatial resolution. The near-infrared Landsat bands at 0.73–0.90, 1.55–1.75, and 2.08–2.35  $\mu\text{m}$  have proven quite useful for determining temperatures of a few isolated volcanic targets, but the 16-day repeat cycle and slow data availability do not allow monitoring NASA's airborne Thermal Infrared Multispectral Scanner (TIMS) has proven to be an excellent instrument for multispectral remote sensing for geologic applications. TIMS has 6 channels between 8 and 12  $\mu\text{m}$ , a swath width of 78°, and IFOV of 2 1/2 milliradians providing a pixel size of from 5 to 50 m depending on aircraft altitude, and an excellent  $NE\Delta T$  of 0.1 K. The primary problems, as with any aircraft scanner, are lack of coverage, long delays between data request and data acquisition, and general inaccessibility by the global community. There are only three other such scanners in the world, one in Italy, one in Australia, and one operated commercially by GER, New York.

Currently under development is an experimental airborne Thermal Infrared Imaging Spectrometer (TIIS) which will provide much higher spectral resolution TIR data between 8 and 12  $\mu\text{m}$ , but which will have only limited areal coverage. The Australians are currently nearing completion of an airborne (active) CO<sub>2</sub> laser reflection spectrometer which will operate between 9 and 11  $\mu\text{m}$ . Both these instruments will provide a demonstration of the utility of high spectral resolution thermal infrared data for lithologic mapping. The TIIS will be used in conjunction with the TIMS, to provide improved geologic mapping capability to NASA-sponsored investigators.

Daedalus is currently building an aircraft scanner, Wildfire, for NASA Ames which will have about 50 channels, including 24 between 1 and 2.3  $\mu\text{m}$ , 16 between 3 and 5  $\mu\text{m}$ , and 10 between 8 and 12  $\mu\text{m}$ . The instrument has been designed for remote sensing of wild fires, but its applications to volcanic studies is obvious.

The first opportunity to have a multispectral thermal IR instrument in orbit currently lies with Eos. The Japanese facility instrument ITIR (Intermediate Thermal Infrared Radiometer), as currently configured, will have 3–5 bands in the TIR, with 60–90 m resolution and an  $NE\Delta T$  of 0.3K. Efforts are underway by the TIGER (Thermal Infrared Ground Emission Radiometer) Team to influence the Japanese to upgrade ITIR

to be closer to the proposed TIGER instrument (an imager with 4 bands between 3–5  $\mu\text{m}$ ; 10 bands between 8–13  $\mu\text{m}$ ; 90 m resolution;  $NE\Delta T$  about 0.1K plus 3 profilers with 0.1  $\mu\text{m}$  bands in the same wavelength region,  $NE\Delta T$  about 0.1K). (TIGER is not presently scheduled to be built.)

#### 3.2.4. Present Limitations in Performance

The current limitations in the acquisition of thermal infrared data are severe, owing to lack of sensors.

There is no adequate orbiting multispectral thermal infrared scanner system.

There is no multispectral imager or profiler operating in the 3–5  $\mu\text{m}$  wavelength range, either orbital or airborne.

There is no high spectral resolution instrument (imager or profiler, airborne or orbital).

There is no orbital system which allows real-time or near real-time monitoring of volcanic targets.

#### 3.2.5. Required Support Measurements

##### 3.2.5.1. Meteorological Data

Vertical profiles of atmospheric temperatures and water vapor profiles need to be acquired at the time of overflight to allow for atmospheric corrections. Also desirable are aerosol content and atmospheric ozone (total or profile). These data could be provided by radiosonde data acquired by a ground truth team. Preferable would be simultaneously acquired profiles from other instruments on the same platform, such as may be provided by Eos.

##### 3.2.5.2. Field Measurements/Requirements

1. Portable thermal IR field spectrometers
2. Calibrated thermal IR video or other imaging system—multispectral capability:  
(1) low temperature (2) high temperature imager for mapping lava flows, fire fountains, plumes, and lava lakes
3. Polarization measurements

##### 3.2.5.3. Laboratory Studies

1. Spectral libraries: minerals, rocks, soils
2. Ground truth: spectral analysis, sample composition, dating of eruptive material

##### 3.2.5.4. Ground Stations

1. Automatic volcanological ground stations with satellite readout, to produce daily readouts of seismicity, tilt, temperature, released gases. Need approximately 1–5 per volcano, 5–10 volcanoes.

### 3.2.6. Development Required to Improve Performance

#### 3.2.6.1. Current Systems

TIMS should be incorporated into the NASA aircraft program as a facility instrument. Opportunities for data acquisition by TIMS (and later, by Wildfire) should be made more readily available to the scientific community. For volcanic studies, priorities need to be given for aircraft quick response to impending or occurring eruptions.

#### 3.2.6.2. Future Systems

##### 3.2.6.2.1. Orbital

###### *TIGER/Enhanced ITIR (or better)*

An orbiting multispectral thermal infrared imager operating between 8 and 13  $\mu\text{m}$ , with 30 m spatial resolution, 0.5  $\mu\text{m}$  spectral resolution and 0.1K  $NE\Delta T$  is required to provide improved lithologic mapping on a global basis. If the Eos/ITIR/TIGER does not provide these data, then consideration should be given to an Eos Earth Probe TIGER.

###### *Geostationary Volcano Observatory*

Geostationary satellite to provide synoptic monitoring capability of the rate of gas release and dispersal of volcanic gas species ( $\text{SO}_2$ ,  $\text{CO}_2$ ,  $\text{HCl}$ ,  $\text{H}_2\text{O}$ ), and provide high temporal resolution (once per hour) of the thermal history of volcanic craters and flows. Such a satellite should provide the capability to detect geothermal activity (about 5°C) hotter than ambient, and permit the determination of lava temperatures to an accuracy of about 20°C over temperature range 500–1150°C. temperature measurements should be obtained once per hour, including at night.

###### *Orbital Volcano Observatory*

A low-altitude (330–500 km) volcanological “Earth Probe” mission to study, at high spatial resolution, the distribution and rate of eruption volcanic gases ( $\text{SO}_2$ ,  $\text{CO}_2$ ,  $\text{HCl}$ ,  $\text{H}_2\text{O}$ ) and the thermal characteristics (about 20°C temperature resolution, 10–30 m spatial, 10–20  $\text{km}^2$  areal coverage) of lava flows and volcanic craters at least once per week. Spatial resolution to be matched either with the capability of SPOT-1/2 panchromatic capability or HIRIS from Eos, depending upon the frequency of site revisits from Eos at this resolution.

##### 3.2.6.2.2. Aircraft

Required instruments include:

1. High spectral resolution (0.1  $\mu\text{m}$ ) imagers (TIIS)
2. A 3–5  $\mu\text{m}$  imager
3. Laser reflectance spectrometers
4. Polarization imagers

### 3.2.7. Projected performance over the next decade

The ITIR on Eos will provide some orbital multispectral thermal IR capability. At this time, the configuration and design parameters are not finalized. If 5 thermal bands, an  $NE\Delta T < 0.3$  K, and spatial resolution of about 90 m are achieved, then this will provide only a limited subset of the required data—*i.e.*, 20–50 spectral bands,  $NE\Delta T$  about 0.1 K, 30 m resolution. If the ITIR is not, therefore, substantially upgraded from the current projections, consideration should be given to an Eos or Earth Probe TIGER.

### 3.2.8. Data Flow and Flow Limitations

No quick turn around of data.

### 3.2.9. Mode of Data Storage and User Access

#### 3.2.9.1. Current

EROS data center; EOSAT; JPL/Ames archives; PLDS

#### 3.2.9.2. Projected

##### 3.2.9.2.1. EosDIS

##### 3.2.9.2.2. A volcano archive is required consisting of:

1. Synoptic satellite data; archived sets of data (TOMS, AVHRR, TM, SPOT and GOES) for areas of explosive and effusive volcanism. Synoptic data to include temporal coverage sufficient to track dispersal of eruption plumes around the globe. Provide mechanism wherein new orbital data (ERS-1, JERS-1, SIR-C, Eos, etc.) can be added to this archive.
2. Supplemental data: Supplementary aircraft, field and climate data for the observed eruptions. These data to include geophysical measurements of volcanic constructs, digital terrain models of volcanoes and their surroundings, airborne thermal measurements of activity, and ground observations of eruption rates and dimensions.
3. Real time data for new eruptions: Ensure data availability for new eruptions in close to real time. These data to include TOMS, AVHRR, TM, SPOT, and GOES, but should also include future space missions such as ERS-1, JERS-1, SIR-C, and MOS-1/2. An interface between the volcanological community and EosDIS must also be deployed.

### 3.2.10. Plan for system development

Enhanced ITIR or TIGER on Eos or Earth Probe; OVO (Orbiting Volcano Observatory); Geostationary Volcanological Observatory.

## 3.3 Orbital and airborne imaging radar

T. Farr

### 3.3.1. Introduction

Synthetic Aperture Radars (SAR) are used for geologic investigations mainly because of their sensitivity to topography, surface roughness, and material dielectric properties which are all related to lithology, structure, geologic age, geobotanic phenomena, and geomorphology. Radar's independence from weather and illumination allows geologists to study many remote and inaccessible regions. Seasat, and the first two Shuttle Imaging Radars, SIR-A and SIR-B have already demonstrated the utility of SAR data for investigating previously unmapped regions or humid areas that are obscured by cloud cover. In addition, an aircraft radar has been operated for several years by the JPL as a testbed for advanced radar techniques and to acquire new data for ongoing geologic and other studies. In the future, SIR-C will explore the utility of multifrequency, multipolarization radar, and the EoSAR will provide global coverage for solving larger scale problems. Other countries will contribute substantially to radar studies during this time, as well.

### 3.3.2. Requirements

#### 3.3.2.1. *Surface Roughness*

The roughness of geologic surfaces at cm-m scales is a characteristic used by field geologists to recognize and map at the outcrop scale rock type, the effects of surficial processes, and volcanic deposits. Many rock types can be distinguished and even identified on the basis of their physical weathering characteristics. In arid climates, jointed resistant rocks like quartzite can be immediately recognized by outcrops of large angular blocks, while granitic rocks weather to sandy lumps.

The ability to map geomorphic surfaces over large areas on the basis of surface roughness is valuable for paleoclimatic, tectonic, volcanic, and arid zone erosion studies. With age, most geologic surfaces in arid areas exhibit a decrease in cm-m scale roughness, caused by physical weathering processes that break down small-scale rock projections and depositional processes that fill in low areas.

One of the main characteristics of volcanic surfaces used to classify them and deduce the conditions of their origin is cm-m scale surface roughness. This scale of surface texture is important for an understanding of the thermal history and composition of lava flows and can yield information about block sizes and hence eruption rate and volatile content in the case of explosive volcanism.

#### 3.3.2.2. *Dielectric Constant*

The dielectric constant of natural surfaces is determined mainly by moisture content, density, and composition. The real part of the dielectric constant of rocks and soils at microwave frequencies generally lies between 3 and 9. Water has a dielectric constant of 80, so the effects of moisture variations greatly overshadow compositional

effects. Moisture variations in agricultural fields have been mapped using Seasat data. In general, surface roughness variations cause much larger changes in radar backscatter than moisture variations, so that dielectric constant has been difficult to determine from radar data. The development of accurate scattering models may eventually make it possible to untangle dielectric constant from surface roughness effects.

#### *3.3.2.3. Topography and Topographic Change*

For much of the Earth, topography is only poorly known, so that reconstructions of continental evolution, gravity modeling, and the response of geomorphic processes and landscapes to recent climatic change can at best only be estimated. Topography at local- ( $\sim 100 \text{ km}^2$ ), regional- ( $\sim 10^3\text{--}10^6 \text{ km}^2$ ) or continental-sized scales could permit many such geologic investigations. Resolutions required for these different scales range from 1 m or better, horizontal and vertical for local studies; 30 m or better for regional studies; and about 100 m on a global basis. In addition, extremely high resolution (few m horizontal, few cm vertical) measurements of topographic change would be useful for monitoring active geomorphic, volcanic, and tectonic processes.

Radar techniques that can attain these resolutions have been demonstrated (*e.g.*, stereo-radargrammetry, interferometry) or designed (*e.g.*, scanning radar altimetry). See the chapter on these radar techniques for more detail.

#### *3.3.2.4. Subsurface Properties and Mapping*

In studies of hyperarid regions of the Eastern Sahara and Arabia, SIR-A and SIR-B demonstrated the capability of SAR to penetrate through a meter or more of dry sand and alluvium to reveal previously unmapped bedrock features as well as regionally extensive but buried fluvial topography. Detailed surface and subsurface investigations revealed that different subsurface characteristics such as caliche (subsurface layers of calcium carbonate) development and distribution of subsurface rocks could be mapped on the images. These characteristics are directly related to past climatic history of the areas.

#### *3.3.2.5. Mapping and Monitoring in Adverse Conditions*

Many of the world's least-known places are perennially covered in clouds or are dark for long periods of the year. Imaging radar, by supplying its own illumination, offers the unique capability to allow mapping and monitoring of active geologic processes, including volcanic eruptions, in these areas.

#### *3.3.2.6. Vegetation*

Geologic surfaces are seldom completely free of vegetation. Both type and density of vegetation provide clues to the rock type and soil on which it grows as well as on climate in the present and recent past. Vegetation patterns need to be mapped on a regional basis for integration into geologic and climatic models.

Radar analyses of heavily vegetated areas have emphasized the discrimination of geologic units on the basis of their topographic and structural associations. In these analyses, the morphology of the vegetation canopy, particularly in tropical areas, has been

employed to infer bedrock geology. In general, radar responds more strongly to morphology than sensors operating in the visible to infrared.

#### *3.3.2.7. Hydrology*

Requirements in hydrology involve determination of the sources and sinks of water, and the links between them. Radar sensors can provide information on soil moisture, as noted above, and can aid in mapping drainage networks, both modern ones on the surface and ancient buried ones.

#### *3.3.2.8. Structure*

The mapping of geologic structure is as important as rock type in the first-order understanding of Earth's surface and the processes that shape it. Radar's sensitivity to morphology allows subtle structural features to be recognized, much as low sun-angle photography is preferred for the same purpose. Fault scarps are also easy to map in radar images, provided the illumination direction is nearly normal to the scarp. Scarps of even a few 10's of cm may be recognized in this way.

### 3.3.3. Description of Technique

#### *3.3.3.1. General*

Radars produce images of the strength of microwaves transmitted, scattered, and received by a single radar antenna looking to the side of the platform. Smooth flat surfaces, such as calm water, reflect radar waves specularly away from the antenna and appear dark. Surfaces that are rough at scales near the radar wavelength (typically cm–m) will scatter the radar energy diffusely in all directions, some of which will end up at the antenna, creating a bright image area. Smooth surfaces tilted toward the illumination direction will also appear bright.

The Synthetic Aperture Radar technique is used in most imaging radars to produce high resolution from a small antenna. The technique makes use of a large number of pulses emitted during a pass which are collected, then added together coherently (*i.e.*, preserving the phase of the waves) to synthesize a large antenna, thus attaining high resolution. A result of this technique is that resolution is independent of altitude of the sensor.

#### *3.3.3.2. Multifrequency*

Most imaging radars operate in a few bands: X-band (about 3 cm wavelength), C-band (5 cm), S-band (12 cm), L-band (25 cm), and P-band (70 cm). It has been shown in theory and practice that the response of radars to surface roughness and the amount of subsurface penetration is dependent on wavelength. Scattering theories have shown that radar waves interact most strongly with surface roughness elements that are near the wavelength in size. Thus X-band images show strong returns (bright areas) for pebble-sized material, C-band images are bright for cobble-sized material, and so on. Penetration is also proportional to wavelength: in dry, well-sorted material, radar waves typically penetrate several wavelengths.

### 3.3.3.3. *Multipolarization*

Because imaging radars are active systems, their polarization can be controlled, both in transmit and receive. Up until recently, only linear combinations were used for terrestrial remote sensing: Horizontal pulses were alternated with vertical in transmit and receive to create four, usually, simultaneous images: HH (horizontal send, horizontal receive), VV, HV, and VH. Earth-based radar images of other planets are usually made using circular polarizations, since Earth's ionosphere rotates linear polarizations. Theory and practice have shown that HH polarization is most sensitive to surfaces, VV couples better with the subsurface, and HV and VH, which are equivalent, are sensitive to very rough surfaces.

Experiments on the NASA/JPL aircraft SAR in 1985 were the first to show that by keeping track of the relative phases between HH, VV, HV, and VH returns, any polarization could be synthesized, including circular, elliptical, etc. This allowed a full scattering-matrix representation of each radar-image pixel for input into scattering models. Additional possibilities were soon exploited including polarization filtering to maximize contrast between similar surfaces and scattering mechanism classification.

### 3.3.3.4. *Multi-incidence angle*

Control is also possible over the radar illumination angle measured from nadir (look angle) or from the normal to a flat surface (incidence angle). For smooth, flat surfaces, radar returns are at a maximum near 0° look angle and fall off rapidly with increasing angle. Rough surfaces, because they scatter over many directions, have a flatter response.

Because they operate closer to the ground, aircraft radars produce images in which look angle varies significantly across the image. Typical values for the NASA/JPL SAR are from 15° to 60°. Thus, it is difficult to compare signatures across a single aircraft image. Orbital radar images suffer very little from this problem; the typical range is only a few degrees. This allows multiple passes of the sensor to compile radar-brightness vs. incidence-angle signatures for surfaces that allow their roughness to be more accurately estimated.

Similarly, orbital radar images acquired at different look angles can be viewed in stereo, much like ordinary airphotographs.

### 3.3.3.5. *Processing*

Synthetic aperture radars record phase and amplitude data that, in their raw holographic form, are not useful to geologists. The process of image correlation is necessary to produce images from these raw data. Digital correlators have been developed that produce images in near real-time, *i.e.*, for 1 hour of data collected, 1 hour is required to convert the data to image form. At present however, most precision correlators require approximately 4 to 10 times real-time to process raw SAR data. This slows image distribution considerably when large amounts of data need to be processed.



Calibration, both radiometric and geometric, is an important post-processing task. Radiometric calibration is at present a research issue, being approached from both system and external perspectives. Internally, radar hardware is being improved in stability and calibration tones added to assess system performance.

Externally, both active and passive point and extended targets are being used to estimate correction factors. Significant resources are being expended in the aircraft and SIR-C areas on calibration of those sensors.

The geometric rectification of radar images has been demonstrated using topographic data supplied independently. Since radars produce an image in the cross-track direction based on time-delay from the platform, the tops of topographic highs such as mountains are displaced toward the near-range part of the image. This effect, called foreshortening, is more pronounced in images obtained at smaller look angles. Knowledge of the topography allows correction for this effect.

### 3.3.4. Present Measurement Capabilities and Systems

#### 3.3.4.1. *Systems*

Imaging radars that have been flown by NASA include Seasat, SIR-A, SIR-B, and the NASA/JPL aircraft SAR. Seasat was orbited in 1978 and obtained L-band (25 cm) HH polarization images of virtually all of north America and Europe with swaths that were 100 km wide. As its name implies, it was meant to observe the oceans and so had a small look angle ( $23^\circ$ ) to enhance small differences in ocean-surface roughness. Unfortunately, Seasat suffered a major failure of its electrical system after only 3 months in orbit, so its oceanographic mission was never fully realized. Geologists soon recognized the usefulness of Seasat's land images, leading to proposals for the Shuttle Imaging Radar (SIR) series.

SIR-A (1981) and SIR-B (1984) also operated at L-band, HH, but at different look angles. SIR-A had a fixed antenna aimed at  $45^\circ$  and SIR-B had a movable antenna that could obtain images from  $15$ – $55^\circ$ . Because of the shorter orbital stay of the Space Shuttle (about 1 week), narrower swaths, and lower data rates, SIR-A and SIR-B obtained much less coverage of the Earth than Seasat. Much of the coverage was selected, however, with geologic objectives and in areas that Seasat could not reach.

One of the best known examples of SIR-A and SIR-B data was the discovery and mapping of buried river valleys in the Saharan and Arabian Deserts. The relatively long wavelength of the radars enabled penetration of several meters of extremely dry sand, allowing reflection of the radar waves off the buried river banks.

Currently, NASA/JPL is flying a three-wavelength SAR on the NASA DC-8. This system is a prototype of the C and L-band channels of SIR-C and has an additional experimental channel at P-band. All three frequencies operate in a polarimeter mode, allowing full scattering-matrix measurement of each radar-image pixel.

### 3.3.4.2. Calibration

Radiometric calibration of radar systems is still a research issue, but significant progress has been made over the last few years. Seasat data were calibrated using calibration tone that was injected into the receiver during data takes. This turned out to be a very labor-intensive effort, so only a small amount of data were calibrated. Currently, for the aircraft SAR, either passive or active point targets are placed in the site to be imaged so that their known cross-section can be used for calibration. If the aircraft system can be shown to be stable over long periods, it may only be necessary to fly a set of known targets occasionally, easing logistical problems.

Geometric calibration has been demonstrated and geocoding is performed routinely on Seasat and SIR-B images. Rectification of foreshortening distortion is also done on a more-or-less routine basis, but requires ancillary topographic data, the accuracy and resolution of which limit the SAR product.

### 3.3.4.3. Data Systems

NASA radar data are processed at , archived by, and distributed from JPL. Currently all aircraft, SIR-A, and SIR-B data and most Seasat data have been correlated and archived. A sophisticated catalog, the SAR Data Catalog System, is maintained for on-line access of coverage and processing information. Radar data in the form of photographic or digital data are distributed through the JPL Radar Data Center. NSSDC also maintains some NASA radar data, including Seasat and SIR.

## 3.3.5. Present Limitations

### 3.3.5.1. Calibration

The main limitation in calibration is in radiometric calibration, since a logistically efficient method has not yet been determined for calibrating large amounts of aircraft or spacecraft data. Progress is being made on this point, though.

### 3.3.5.2. Scattering models, especially subsurface

In order to extract geophysical quantities from radar data, accurate scattering models are needed that invert radar backscatter at multiple frequencies, polarizations, and angles to estimates of surface roughness, dielectric constant, and subsurface properties. Significant progress has been made on the first two quantities, but subsurface scattering is a harder problem.

### 3.3.5.3. Interferometry

The present limitation to the development and use of radar interferometry is the lack of an instrument. Some data were collected by Seasat in 1978 that were processed 10 years later to show changes, the causes of which were difficult to document. Some data were also collected by the NASA/JPL aircraft SAR when it was mounted on the NASA CV-990. This aircraft was fitted with two wing-tip antennas for interferome-

try. The current DC-8 does not have these extra antennas, nor have they been funded for future addition.

#### *3.3.5.4. Lack of Regional and Global Data Sets*

A critical need exists for regional and global radar image data. Seasat produced regional coverage at a single frequency, polarization, and look angle of north America and Europe. Digital, geocoded mosaics of the western U.S. are now being used in regional geomorphic mapping projects. No other radar data at a similar scale exists. The EosSAR will eventually provide the first global radar data set for use by geologists, in combination with other sensors, for mapping geomorphic surfaces, geologic structures, and subsurface features.

#### *3.3.5.5. Lack of Topography at Sufficient Resolution for Geometric Rectification*

Geometric rectification, while a routine process, requires digital topographic data at a resolution comparable with the pixel size of the radar image. These data exist for only small parts of the U.S. For work in areas of moderate to high relief, rectification is necessary in order to extract the most information from the radar data.

#### *3.3.5.6. No P-band data from orbit*

Recent experiments with the NASA/JPL aircraft SAR have shown the utility of P-band (70 cm) images. This system has been shown to be sensitive to large-scale (1–10 m) surface roughness, and should penetrate more into geologic volumes. More work needs to be done with this system, but the limitations of airborne systems make it desirable to fly it as a Shuttle or Space Station payload.

### 3.3.6. Required Supporting Measurements

#### *3.3.6.1. Surface Roughness, Moisture, Subsurface Properties*

Field measurements are required to calibrate and validate models that seek to extract surface roughness, moisture content and subsurface properties from radar data. A helicopter system has been found to work well for surface roughness measurements at cm resolution over 10's of m. This system needs to be used in more environments. Soil moisture content is measured by well-known techniques, but measurements need to be coordinated with radar acquisitions. Similarly, subsurface properties such as rock size distributions and depths of hard layers are straightforward to measure, but must be made intelligently, preferably in conjunction with soil scientists accustomed to working in trenches.

#### *3.3.6.2. Coregistered Topography*

The case for digital topography at a resolution comparable to the radar pixel size was made above.

### *3.3.6.3. Calibration*

If current and future radar systems prove stable enough, it may only be necessary to have a few "calibration sites" where images can be acquired over a field of calibration targets. At present, several targets are required in each aircraft radar scene to guarantee calibration.

### *3.3.6.4. Scatterometers: Airborne, Truck, Backpack*

Another method, similar to that used for visible–near infrared and thermal infrared sensors, is to find an homogeneous patch of ground that is then characterized with a field device. Images of this patch of ground, an extended target, could then be calibrated by forcing the image to agree with the field device. Airborne (fixed–wing or helicopter), truck–mounted, or potentially backpackable units could be used. At present, NASA has no adequate scatterometer facilities for this type of work, although several are available commercially.

## 3.3.7. Developments Required to Improve Performance

### *3.3.7.1. Wider Swaths*

A critical development that is needed is a return to wide swaths. As complexity and number of modes went up, limitations in data rate caused the resulting swaths to decrease from 100 km in 1978 (Seasat) to less than 10 km for some modes of SIR–C. Clearly, a global data set will be nearly impossible to acquire with 10 km swaths. An effort needs to be made to identify key radar variables that are most useful for different objectives, similar to the choices in bandpass location that were required for Landsat TM. It is possible that two frequencies at two polarizations could satisfy most of the objectives of the SES program. This would allow much wider swaths. These tradeoffs must be made intelligently, though, with sufficient data both from aircraft and space.

### *3.3.7.2 Scattering Models*

Scattering models are a key to the quantitative use of radar data. While rapid progress is being made, much still needs to be done, particularly in the subsurface scattering area, use of polarimetry, and the evaluation of models that use only a few parameters.

### *3.3.7.3. Calibration*

Fully internal calibration of future radar sensors would render field targets unnecessary.

### *3.3.7.4. Space–based P–band Imaging Radar*

An orbital P–band imaging radar would probably be of use in both surface subsurface mapping. Additional studies with the current aircraft P–band system and potentially a Shuttle system would help establish the usefulness of P–band imaging radar for geology.

### 3.3.8. Projected Performance over Next Decade

#### 3.3.8.1. Systems

SIR-C is designed to be versatile enough to meet a variety of observational requirements. The sensor will operate at both L-band (25 cm wavelength) and C-band (5.6 cm wavelength) and will provide images of the relative phase difference between HH, VV, VH and HV returns that will allow derivation of the complete scattering matrix of the scene on a pixel-by-pixel basis. From the scattering matrix, every polarization configuration (linear, circular or elliptical) can be generated by ground processing. NASA, the Bundesministerium fur Forschung und Technologie (BMFT) of the Federal Republic of Germany and the Italian Space Agency (ASI) are currently planning to fly an X-band (3.0 cm) system (X-SAR) in conjunction with the SIR-C mission. Comparison of SIR-C and X-SAR images will provide new insight into the back-scatter response of the Earth's surface at different radar frequencies. The first SIR-C/X-SAR flight is planned for 1992, with a second flight in 1993 and a third flight in 1994 to enable data acquisition during at least two different seasons.

The EosSAR will be the first orbital imaging radar to provide multifrequency, multipolarization, multiple incidence-angle observations of the entire Earth. This instrument will be derived from the SIR-C design and is planned for a 1998 launch. The EosSAR mission will also take advantage of experience gained from Seasat, SIR-A, SIR-B, as well as other international SAR missions expected over the next several years. These include the ERS-1, a polar orbiting 3-day repeat cycle platform with a C-band radar; Radarsat, a Canadian platform also with a C-band radar; and JERS-1, which includes an L-band radar. These different missions, taken together, will provide continuous radar observation capability spanning the whole decade of the 1990's with the EosSAR continuing into the next century. NASA has signed Memorandum of Understanding (MOU) with the ESA and the Science and Technology Agency of Japan (NASDA) to acquire ERS-1 and JERS-1 data at the Alaska SAR Facility (ASF) at the University of Alaska, Fairbanks; a similar MOU is under negotiation with the Canadian Centre for Remote Sensing for Radarsat data. SAR data from these missions will be processed and archived for distribution to scientists involved in a broad range of investigations of the oceans, ice cover and land.

#### 3.3.8.2. Data Systems

Data systems are planned that will keep up with the increasing volume of radar data over the next decade. JPL will process, catalog, and archive SIR-C data; the Alaska SAR Facility will process and archive ERS-1 and JERS-1 data for Alaska. ESA will handle ERS-1 data for the rest of the world at several sites.

### 3.3.9 Data Flow and Limitations

#### 3.3.9.1. NASA

NASA/JPL aircraft SAR, Seasat, and SIR data are all on a JPL catalog (Sar Data Catalog System). This system works very well and is remotely accessible. Data dis-

tribution efficiency, however, could be improved. The role of NASA's Pilot Land Data System in radar data archiving or cataloging is unknown.

### 3.3.9.2. *ERS-1*

Plans for ERS-1 data distribution by ASF look promising. The accessibility of non-ASF ERS-1 data by U.S. investigators is not known. There were only a few geologically oriented U.S. investigations chosen by ESA for ERS-1.

### 3.3.9.3. *Other Systems*

Plans for EosSAR, JERS-1, Radarsat data distribution are unknown.

### 3.3.10. Mode of Data Storage and User Access

1. JPL has most data, catalog good, distribution needs work.
2. NSSDC has some data
3. ASF looks good for future
4. Eos, JERS-1, Radarsat unknown

### 3.3.11. Plans for System Development

1. Interferometry
2. Space-based P-band Imaging Radar
3. Scanning Radar Altimeter

## 3.4 Digital topography

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### 3.4.1. Requirements

The requirements for digital topographic data are driven by the Land Surface Panel, the Lithosphere Structure and Evolution Panel, and the Volcanology Panel. The Volcanology Panel requires topography at a scale of 3–5 m vertical and a spatial resolution of 10 m to study relief of individual lava flows. This can only be accomplished with airborne instruments, and will not be further described here.

The Land Surface and Lithosphere Structure and Evolution Panels have similar requirements: The Lithosphere Structure and Evolution Panel indicates that mapping of neotectonic features may require 1 m vertical and 10 m horizontal data. To support interpretation of satellite derived gravitational and magnetic data, 10 m vertical and 1 km horizontal resolution are needed. Land Surface panel recommends building a system to obtain global data at a horizontal scale of 100 m and vertical resolution of 10 m. For optimal use, the scales should match existing remote sensing data: 30 m horizontal, and 3 m vertical.

The bulk of this section is abstracted from the *Topographic Science Working Group (1988) Topographic Science Working Group Report to the Land Processes Branch, Earth Science and Applications Division, NASA Headquarters*, Lunar and Planetary Institute, Houston, 64 pp.

### 3.4.2. Existing Topographic Data

Topographic data are available in two main forms: (1) maps consisting of contours of equal heights interpolated from spot elevation measurements; and (2) digital data, usually digitized from contour maps. Outside Europe and North America, detailed map coverage (better than 1:100,000 scale) is limited, and ranges from 100% in the USSR to 20% for Asia and South America at scales better than 1:250,000. The availability of digital data is far worse; the best available worldwide digital database has a spatial resolution of about 10 km (map scale of about 1:50,000,000). In addition to limitations of areal coverage and scale, the database has shortcomings in both accuracy and usability. Relative accuracy (precision) is required between adjacent or nearby maps for comparison purposes in local and regional studies. A high degree of absolute accuracy is a prerequisite if repeat coverage is to be used to monitor change. Currency is required in order to update information with respect to both man-made changes and natural phenomena such as volcanic effects, earthquake deformation, and shoreline changes.

### 3.4.3. Techniques and Constraints for Acquisition of Topographic Data

#### 3.4.3.1. Mapping techniques

The techniques currently available for elevation measurement fall into three categories:

1. High resolution techniques for local studies: stereophotogrammetry from high resolution photographs or imaging systems, laser profiling systems; usually operate from aircraft platforms, but can employ space-borne platforms;
2. Intermediate resolution techniques: stereophotogrammetry from space imagery, for example, suitable for regional scale coverage;
3. Intermediate to low resolution techniques suitable for global mapping from a space-based platform.

#### *3.4.3.2. Photographic Stereo*

Stereo techniques utilizing either film or digital images are at present the most widely used method for recovery of elevation data over continents. With such techniques advantage can be taken of many years of development and use of hardware technology.

Spacebased techniques are required for global coverage. The main disadvantage of spacebased optical stereo methods are that some sort of sun-synchronous orbit is required, data cannot be acquired at night, and coverage is weather dependent. Although the horizontal resolution of these systems is high ( of the order of the pixel size), the vertical accuracy is limited by the geometry of the observing system, and is typically equal to the horizontal accuracy. Table 3.4.1 lists space-based stereoscopic missions and their parameters.

A primary advantage of stereo is that the required hardware already exists. For example, the Large Format Camera is a metric device that has already flown successfully on the Space Shuttle. Performance was on the order of 10 m both horizontally and vertically. Another operational system is the French SPOT satellite and instrument, providing stereoscopic panchromatic imagery capable of producing digital topographic data with a horizontal resolution of 10 m and vertical of perhaps 5 m. It is difficult to quantify rigorously all the costs and problems associated with cloud cover, degraded vertical resolution, and lack of statistical surface information inherent in a stereo-based global topography program relative to a direct spacebased altimetric measurement. A plausible figure for obtaining global coverage is perhaps in the \$100–200 M range.

#### *3.4.3.3. Synthetic aperture radar stereo*

Synthetic aperture radar (SAR) techniques are attractive because they do not suffer from the cloud problems that plague optical systems. SAR stereo is similar in principle to photographic stereo and can be used for systematic mapping in the multiple-look (off-nadir) angle mode, where an antenna is articulated or electronically steered to image the same path as that surveyed in the previous orbit. The mathematical foundation for radar stereo is also well established.

The disadvantages are poorer resolution (25–50 m) and the extra processing required to obtain the original images before stereo correlation can be performed. The main advantage is independence of solar illumination and penetration of clouds.



**Table 3.4.1 Space-based stereoscopic missions**

Instrument/ mission	agency/ year	resolution	base/ height	RMS accuracy(m)		Total ground cover	
				Height	plan	swath M-km <sup>2</sup>	width km
Metric camera/ Spacelab-1	ESA DFVLR/ 1983	13	1:3-1:1.6	15	15	12	190
Large Format Camera	NASA/ 1984	8	1:1.6-1:1.8	10	10	80	190
HRV/ SPOT-1	CNES/ 1986	10	1:2-1:1	10	5	-	60
MEOSS/ SROSS-II	DFVLR ISRO/ 1988	80	1:1	50	30	-	255
Metric Camera/ Atlas-1	DFVLR NASA/ 1991	5	1:3-1:6	10	10	10	190
Stereo- MOMS	DFVLR/ NASA 1991/92	5-10	1:1	10	10	.25	32
SPOT3	CNES	10	1:2-1:1	10	10	-	60
Landsat-7	EOSAT 1992	10	TBD	TBD	TBD	-	41

#### 3.4.3.4. Laser Altimetry

Laser altimetry is the only way to obtain elevation data with centimeter-level vertical precision and high horizontal resolution. Today, several high-precision aircraft laser altimeter systems are in operation. The scanning systems are used for precise terrain mapping of relatively small areas. Although limited by cloud cover and instrument lifetime, laser altimetry from aircraft offers an attractive near-term capability for very high resolution topographic characterization. Spaceborne laser altimeters are not an immediate prospect for global topographic data acquisition. However, a proposed Eos laser altimeter offers the prospect of obtaining high resolution topography for selected local areas by operating in a profiling mode.

#### 3.4.3.5. Radar Altimetry

Radar altimetry provides an alternative to optical techniques for acquisition of topographic data, because data acquisition is independent of cloud and weather. All space-borne systems flown to date have been wide-beam systems limited in accuracy by their pulse duration. The fundamental obstacle to narrow-beam space-borne radar altimetry is the physical constraint on antenna size. Large antennas are required for small radar footprints, making deployment of narrow-beam altimeters difficult.

#### 3.4.3.6. Scanning Synthetic Aperture Radar Altimeter

Nadir-pointing radar altimeters have the ability to provide high-precision vertical resolution altimetric data, as demonstrated by the Seasat altimeter. On the other hand, SAR has in many instances provided horizontal resolutions much better than can be provided by nadir-pointing space-borne altimeters. There is no instrument at present that combines the features of global coverage combined with high vertical and horizontal resolutions. All three can be combined in a scanning, SAR altimeter.

To achieve moderate to high horizontal resolutions (500 m or better), the radar beamwidth must be narrow. This also implies that a high radar frequency is used: Ka-band at 37 GHz, for example. To obtain the desired horizontal resolution, one must use a real-aperture, mechanically stable antenna; studies have shown that horizontal resolution of 300 m and 1–3 m vertical resolution is achievable.

#### 3.4.3.7. Synthetic Aperture Radar Interferometry

The use of SAR in an interferometric mode is a relatively new concept that holds great promise. A SAR with two antennas separated by meters to several tens of meters images an off-nadir swath. The two images obtained are geometrically identical, and constitute a stereo pair with a baseline too small to generate measurable parallax. However, because SAR uses coherent illumination and the phase of the echoes is maintained in standard processing, the phase difference in distance from each pixel can be measured. This phase difference is proportional to the difference in distance from each antenna to the target. When effects due to the curvature of the Earth are removed, the residual is the effect due to terrain elevation. In effect, a digital elevation map that is perfectly registered to the radar image is created. Tests with an airborne SAR with antennas mounted under each wing have provided very encouraging results. The concept has also been tested from space by using adjacent Seasat-SAR images acquired several days apart and processing the data to recover the phase information. In principal, data with 50 m horizontal and 1–2 m vertical resolutions are achievable.

#### 3.4.4 Technology summary

The results of the survey of technologies are summarized in Table 3.4.2 Topographic mapping from space for the next decade is subject to the following physical and technical constraints:

1. Photographic stereo, particularly with the LFC and SPOT, provides high horizontal resolution data, and acceptable vertical resolution. Technology and data

reduction techniques are well developed; all necessary hardware exists and is flight-proven. A serious problem with applying such technology globally would be cloud cover and the cost of data reduction; some important areas would never be covered. Also vertical accuracy is not sufficient for certain scientific applications.

2. SAR stereo provides cloud penetration and day/night capability, but has high data reduction costs and low accuracy.
3. A scanning radar altimeter can generate global, moderate resolution topographic data.
4. SAR interferometry which can provide high resolution without the problems inherent in stereo Eos deployment in mid-to-late 1990s is feasible for global coverage.
5. Laser altimetry has the potential for generating high resolution topographic data and would be characterized by relatively straightforward technology and data reduction. However, advances in technology would be required to provide a scanning laser capability for global coverage. Cloud cover problems also apply. Laser altimetry from aircraft is attractive for local, high resolution coverage.
6. GPS tracking of the altimeter platform will be required in order to fully recover accurate elevation data.

**Table 3.4.2 Survey of technologies**

Technique	State of Technology	All-weather capability	Sun-synchronous orbit required	Amount of processing	Problems/drawbacks
Photographic stereo	mature	no	yes	medium	accuracy, stereo
SAR stereo	mature	yes	no	high	accuracy, cost
SAR interferometry.	new	yes	no	high	new technique
Scanning radar altimetry	new	yes	no	medium	new technique
Airborne laser	mature	no	no	low	local
Space laser	develop.	no	no	low	not global

## 3.5 Spectrometry for gas and aerosol measurements.

W. Rose

### 3.5.1. Requirements

The Volcanology Panel has identified a need for satellite-based remote sensing of volcanic emissions of volcanic gases, including H<sub>2</sub>O, CO<sub>2</sub>, SO<sub>2</sub>, HCl, HF, CO, H<sub>2</sub>S, S<sub>2</sub>, SiF<sub>4</sub>; and aerosol particles, especially sulfates. The desire is to provide daily coverage of volcanoes to determine changes in gas composition and concentrations, particularly for active eruptions.

### 3.5.2. Present Measurement Capabilities

Most present methods to measure and sample volcanic emissions are made from the ground. Many methods are required because sampling is difficult and subject to many environmental difficulties (reactions, contaminations, danger). Usually best results are obtained when many methods are used. Current techniques include: direct gas sampling, restricted by atmospheric contamination and reactions; correlation (ultraviolet) spectrometry to measure SO<sub>2</sub> flux, requires transparent plume; infrared spectrometry, a CO<sub>2</sub> detection method that works like the last; condensed gases, collects trace elements; sublimate and incrustation sampling, samples later analyzed; particles in fume, plume, and eruption cloud, allow for temporal and spatial sampling; treated filters, samples plume to estimate elemental fluxes to the atmosphere; melt inclusions and trapped volatiles, measures degassing and original gas composition.

Present remote methods are few. Ultraviolet spectrometry from the ground for SO<sub>2</sub> is the only currently used remote sensing technique for volcanic gas studies. The TOMS UV imager was used to detect the SO<sub>2</sub> eruption plume from the El Chichon eruption in Mexico. There are also plans for cooperative observations of volcanoes with the DoD Delta Star UV imaging mission. Particle remote sensing has been done with weather satellites, where thermal channels allow quantification of eruption rates.

### 3.5.3. Present Limitations in Performance and Developments Needed

Volcanoes release a bewildering variety of gas species. A partial list includes over 400 species of major and trace gases measured from volcanic eruptions, such as Augustine volcano in Alaska. When the hot gases enter the atmosphere, they are quickly diluted and cooled. The degree of this dilution is often a factor of 10,000 or more, so the plumes of volcanoes are mostly atmospheric gases. In order for a volcanic plume to be detected by a remote sensing instrument, it must induce a detectable anomaly from the surrounding atmosphere. Components such as SO<sub>2</sub>, HCl, H<sub>2</sub>S are so much more abundant in volcanic gases than the ambient atmosphere that volcanic plumes still have anomalous concentrations after high dilutions.

It seems desirable to attempt remote sensing measurements of several species, because it would seem to allow a better prospect of forecasting activity. Experience with ground-based sensing is almost restricted to SO<sub>2</sub>, but experts are agreed in

desiring a multi-species capability. It is particularly desirable to have direct data on CO<sub>2</sub>, given its low solubility. SO<sub>2</sub>, HCl, H<sub>2</sub>S, and HF are also of great interest and value. H<sub>2</sub>O may be very difficult to accomplish because of atmospheric background problems.

#### 3.5.4. Future Missions

The only candidate volcanological mission presently being discussed is the Orbiting Volcano Observatory (OVO), proposed as an Earth Probe mission with the Italian Space Agency. This mission will be in sun-synchronous, polar orbit and have several sensors aboard, each with 20–40 m pixels:

1. UV imager, 2 bands at .28 and .31  $\mu\text{m}$
2. UV spectrometer 2 angstroms/pixel resolution from .21 to .36  $\mu\text{m}$
3. Visible imager, 1 broad band in visible
4. SWIR imager, 5–10 bands between .7 and 5  $\mu\text{m}$ .

## 4. GEOPOTENTIAL FIELD MEASUREMENT TECHNIQUES

This section deals with measurements of the gravity and magnetic fields from space platforms and aircraft. There are two fundamental techniques for high resolution gravity mapping - satellite to satellite tracking and gradiometry. Accurate, but lower resolution tracking of satellites from ground stations is covered above. The section will discuss the current status of both techniques, followed by a review of drag free systems, common to both. Next is a review of spaceborne vector and scalar magnetometers, along with a discussion of possible future missions. Finally, there is a discussion of the methods for analyzing the performance of satellite field measurement missions, a relatively new area.

For gravity, the most demanding requirements come from the continental evolution and deformation objectives. These need to achieve a surface field accuracy of 1 mgal, with a resolution of 50 km, probably the best that can be achieved from space, in the foreseeable future. Time variations also need to be observed at the same accuracy, at least to degree and order 6. Mantle studies require measurement to degree and order 20. Core studies need 1 mgal at degree and order 8. Finally, the ocean-atmosphere objective needs measurements every 5 years at 0.1 mgal, to degree and order 2.

For magnetic fields, the most demanding requirements again come from the continental evolution and deformation objectives, 1 nT at better than 100 km resolution. The evolution objective also requires a 1 nT measurement in many local regions at 1 km resolution; but this is not now possible from space. Finally, core dynamics studies require a low order and degree field to 1 nT, repeated every 10 years.

### *Recommendations of the Measurement Panel on the Gravity Field*

There are two feasible approaches to global gravity model definition. The orbiting of a gravity gradiometer at low altitudes, and the use of satellite-to-satellite and ground-to-satellite tracking by lasers and radiometric sources. With regard to the latter issue, SLR data from LAGEOS class satellites is critical to measuring the long wavelength time varying components of the gravity field and the recent development of GPS satellite-to-satellite tracking provide opportunities for interim gravity model improvement prior to the gravity gradiometer mission.

The panel notes the excellent progress made in developing the laboratory versions of the Superconducting Gravity Gradiometer. The Mark III instrument has already demonstrated the key technologies required by the high resolution flight mission. The next logical step is to proceed with early prototyping of the flight system (gradiometer, dewar, electronics, etc.), commencing in FY 92. From an engineering standpoint, the technology can be greatly advanced, and confidence in a successful mission greatly enhanced, by another mission, ARISTOTELES. This mission gives an opportunity for wringing out the gradiometer data correction algorithms and offers a first opportunity to work with this data type. A plausible launch date for an SGGM is 1998. In this light, the panel recommendations are:

1. Given the importance of a timely measurement of the gravity field at high surface resolution and sensitivity, and in view of recent progress in instrument de-

velopment, the SGGM is endorsed as the primary approach, and funding for this mission should be accelerated.

2. NASA should use opportunities for early gravity missions by providing GPS receivers for the ARISTOTELES, GP-B, and other low orbiting satellites to collect global gravity data. An on-going program should be established in gravity data analysis, including participation in a joint analysis group for ARISTOTELES with ESA.
3. A Geopotential Research Mission based on a laser doppler technique has been advanced as an alternative to the SGGM. A study is recommended to evaluate the possible doppler accuracy, the accuracy and resolution of the global field obtainable from such data, identification of the necessary technological improvements, and a plausible cost and schedule of an appropriate mission. The panel emphasizes that the SGGM should not be delayed for the results of such a study.

### *Recommendations of the Measurement Panel on the Magnetic Field*

The primary requirements to be met by magnetic missions in space are the global crustal field at a surface resolution of 100 km and a sensitivity of 1 nT, and the core field at the same sensitivity and to degree and order 8. Long term variations in the core field are also very important. Only three missions have been proposed with the potential of satisfying these requirements. In addition, there are several proposed instrument developments, as well as improvements in spacecraft techniques in support of magnetic measurements. The panel recommendations in this area are:

1. The ARISTOTELES mission should be supported by the addition of a 1 nT vector and scalar magnetometer, including an attitude reference system of comparable accuracy, together with an appropriate contribution to the data processing. Also included should be money for algorithm development and a contribution to reducing the interfering fields from the spacecraft. A successful primary mission would satisfy the crustal field requirement; and, if the extended 3 year mission proves feasible, the core field static requirement would be met, along with part of the long term variation requirement.
2. MFE/Magnolia - This is a possible US/French mission to fly two French and two US magnetometers together, for at least 5 years, to measure the core field. Phase A and B studies have been completed in both the US and France. Its advantages over ARISTOTELES are flying several magnetometers of different types, a more stable attitude measurement, a longer duration mission, and a spacecraft designed from the start to accommodate sensitive magnetometers. The recommendation of the panel is that an evaluation of the ARISTOTELES spacecraft, with the suggested added equipment, be performed, with the intent of establishing the accuracy of measuring the field, and separating it from local disturbances. Should this evaluation prove unfavorable, or if the proposed collaboration is dropped, NASA should proceed with MFE/Magnolia.
3. GOS - the only clearly identified project with the ability to monitor long term variations in the core field is the Geomagnetic Observing System (GOS), in which a set of magnetometers aboard the Eos polar platform would operate for up to 15 years. While this is unlikely to fly for several years, a definition study should be initiated when the ARISTOTELES and MFE/Magnolia situations have cleared up.

4. Lack of a magnetically clean star sensor on Magsat led to an elaborate attitude transfer system. A design study looking into the feasibility of a magnetically clean star sensor is recommended.
5. Low level support for new magnetometer developments should be continued, ramping up when a specific flight opportunity nears approval.



## 4.1 Gravity measurement techniques

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### 4.1.1. Satellite-to-Satellite Tracking

Current Status - The first ideas about the application of satellite-to-satellite tracking (SST) as a substitute for satellite tracking from ground stations, and as a means for measuring the Earth's gravity field were published in the 1960's [Wolff, 1969]. Both the high-low and low-low SST concepts were introduced at this time, and experimentally proven for Earth gravity recovery in 1975.

SST requires at least two satellites. The low-low concept is based on following each other along the same orbit, a few hundred kilometers apart: 1 and 2 way microwave inter-satellite tracking systems have been used so far to measure their relative velocities. Continuous tracking is possible. The irregular variations of this velocity convey gravitational information, and the lower the orbit the more pronounced and detailed this information becomes. Alternatively, a main spacecraft (such as an orbiting platform) may track two or more small orbiters in the same orbit. Studies were conducted for such a configuration building an optical interferometer from three spacecraft, with the active laser system installed on the center spacecraft [Balmino *et al.*, 1978].

The high-low concept describes the situation where a high orbiting satellite tracks a low spacecraft. With one high orbiting satellite, tracking data coverage is limited - only about 20% of the coverage from a low-low configuration. Data coverage could be continuous around the globe, if the low satellite is equipped with a receiver for a high multi-satellite tracking system such as GPS. A variant of the high-low SST concept was applied early in the APOLLO program to obtain information about the lunar gravity field [Muller and Sjogren, 1968].

The first application of high-low SST took place in April 1975, with a tracking experiment between the geostationary ATS-6 satellite, and GEOS-3 at an altitude of 840 km, [Schmid *et al.*, 1975]. The key instruments were a 9 m diameter steerable antenna on ATS-6, with its accurately programmed scan and monopulse pointing capability, and a transponder on GEOS-3. This historic first was followed by the ATS-6 tracking of the NIMBUS-6 meteorological satellite, launched in June 1975.

The SST data have been used for orbit computation of the lower-altitude satellites, but the ATS-6/GEOS-3 data have also been used extensively to obtain information about the Earth's gravity field. During this SST experiment both 1 and 2 way range and range-rate data were obtained over the link ground station/ATS-6/GEOS-3. The specially processed range-rate measurements, applied for the gravity field determination, had a precision of about 0.3 mm/s.

A second gravity experiment with SST, in both the high-low and low-low modes, took place during the APOLLO-SOYUZ mission, at an altitude of about 223 km, in July, 1975. During this mission, high-low SST range and range-rate data were collected for 108 orbits, where ATS-6 again served as a tracking and relay satellite. The Doppler

tracking data, with a precision of about 0.5 mm/s, have been used to recover gravity [Kahn *et al.*, 1982].

The pioneering experiments involving ATS-6 have demonstrated that the high-low mode is very attractive for determination of the user satellite orbit and capable of producing good-quality gravity information. The gravity signal recovery results from the low-low APOLLO-SOYUZ experiment were not conclusive; because the range-rate tracking signals were found to be corrupted by an unexpectedly high noise level of about 3 mm/s, preventing unambiguous identification of gravity anomaly signatures. See Table 4.1.1.

Limitations and Error Sources - Past experimental limitations were primarily weak data coverage, limited precision of the range-rate measurement, and the medium altitude of the GEOS-3. Main error sources were signal propagation errors, and mis-modeling of surface forces of the tracked satellites.

Future Missions and Technologies - As shown in Fig. 4.1.1, gravity field recovery, with resolution and precision compatible with the science requirements, is only possible if the satellites tracked are at very low altitudes (200 km or below), if tracking system performances of 1-10 micrometer/s are achievable, and if the non-gravitational acceleration is measured or eliminated with extreme precision. Various mission concepts of this performance level have been studied in the past ten years by NASA and ESA. Most developed are NASA's Geopotential Research Mission (GRM) [Keating *et al.*, 1986] and the POPSAT high-low mission of ESA [Schürenberg *et al.*, 1985].

In GRM, the observable would be a low-low SST Doppler link between two co-orbiting satellites in a 160 km altitude circular polar orbit. The separation between satellites is adjustable from 100 to 600 km. The variation of the relative range rate is measured through a two-way link, at 42 and 91 GHz. These high frequencies effectively eliminate any residual ionospheric propagation errors. The tracking system concept is that a continuous wave signal is transmitted from one satellite to the other, where it is received and compared to an on-board generated signal. At the same time this satellite radiates an incrementally frequency shifted signal to the other, where it is compared to its on-board generated signal. The resultant continuous comparison of the signal serves to measure velocity changes with a precision of 1 micrometer/s. Because of its low altitude, large atmospheric forces would act on the GRM spacecraft. To eliminate these and other forces, both satellites would be flown drag free.

One of the most likely developments in SST is to make use of the GPS or the GLONASS systems. One low spacecraft could carry a GPS/GLONASS receiver to track several of the very high (20,000 km) spacecraft, simultaneously. Data coverage could be continuous, because several of these satellites would be constantly in view. In this way one would get the equivalent of instantaneous fixes on the position of the low spacecraft, using the P-code signal, or on the velocity, using carrier doppler. The orbits of the GPS satellites would be determined from ground stations, possibly with VLBI-determined coordinates and hydrogen maser clocks, providing very precise ephemerides and timing. With the spacecraft in a near polar orbit a dense and uniform coverage with range or range-rate data would be achievable. One possible mission, with this type of satellite in low polar orbit, could be the Gravity Probe-B, whose main purpose is to test general relativity by measuring the effect of Earth rotation on the lo-

cal inertial frame of the satellite. As the orbit altitude would be near 600 km, this will not be a substitute for a dedicated GRM type mission, but it can substantially improve our current knowledge of the gravity field.

**Table 4.1.1. Results Achieved by Past SST Experiments**

Experiment	Mode	Experimeter Reference	Range Rate	Result
Apollo: Soyuz	h-l	SAO [Weiffenbach et al., 1976]	$\pm 48$ mm/sec	no gravity parameter recovery possible
Earth: lunar orbiters IB,IIB,IIIB,IVC, VC	h-l	JPL [Muller and Sjogren, 1968]	$\pm 0.3$ mm/sec	lunar mascons
ATS-6: Apollo-Soyuz	h-l	GSFC [Vonbun et al., 1977]	$\pm 0.3$ mm/sec	recovery of 5 deg $\pm 7$ mgal gravity anomalies
ATS-6: GEOS-3	h-l	JPL [Sjogren et al., 1978]	$\pm 0.5$ mm/sec	qualitative analysis above N. America
ATS-6: GEOS-3	h-l	OSU [Hajela, 1977]		recovery of 5 deg $\pm 12$ mgal gravity anomalies
ATS-6: GEOS-3: Apollo	h-l	GSFC [Kahn et al., 1982]		selected $5 \times 5$ deg $\pm 5$ mgal mean gravity anomalies

Another SST possibility is a laser version of GRM. One concept for such a mission is the Laser Gravity Mapper. For two spacecraft 50 km apart, the required range rate accuracy is  $(0.1/f)$  nm/s-Hz<sup>1/2</sup> in the critical frequency band from roughly  $0.01 \leq f \leq 0.1$  Hz. This corresponds to  $10^{-5}$  E/Hz<sup>1/2</sup> single axis sensitivity for a gravity gradiometer (see next section). The resulting field resolution would be 50 km for 200 km measurement altitude. Nd:YAG lasers, pumped by laser diodes, and locked to Fabry-Perot cavities, appear capable of providing the necessary frequency stability of  $(10^{-16}/f^2)$  Hz<sup>-1/2</sup> over the same frequency band. The lasers, cavities, and range rate measurement systems would be mounted on the intermediate body of a two stage drag free system (see Section 4.1.3), so that disturbances due to thruster firings, momentum wheels, etc. would be minimized.

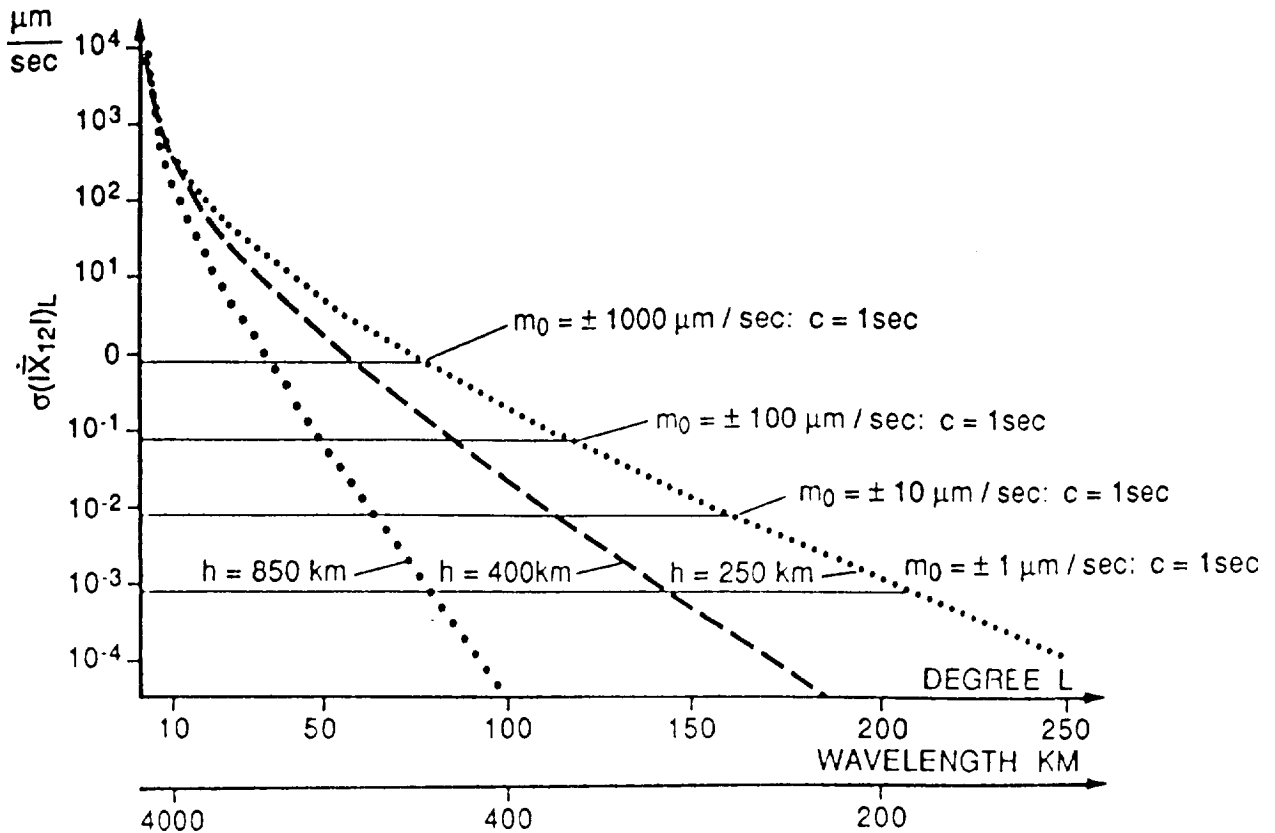


Fig. 4.1.1. Velocity difference spectra at different altitudes vs. noise spectra; high-low mode

As the value of this concept has yet to be examined in any depth, and as a considerably improved drag free performance appears to be required, the panel concludes that a study is needed to evaluate the feasibility. Moreover, due to the importance of timely gravity field measurements, the current plans to obtain the field by gradiometry should not be delayed for the study's results. Approximately 3 work years should be allotted for the study.

**Conclusions** - The ATS 6/GEOS-3 and ATS 6/Apollo experiments have proven that gravity information can be extracted from SST data. Basically the analysis of SST observables for gravity parameter recovery is understood. Recognizing the important scientific returns extractable from inter-satellite tracking measurements on Earth orbiters and space probes parked in orbits around bodies in the solar systems, it is considered important to:

1. Develop space qualified microwave trackers (multi-channel, carrier phase tracking GPS, 2 way PRARE, etc.) for the gradual gravity field improvement of the Earth and planets from inter-satellite range or range rate data.
2. Develop extremely precise and stable accelerometers and drag free systems.
3. Study space qualified laser interferometric SST systems.

4. Make satellite based data relay systems available for fast and reliable communication of data from gravity missions.

#### 4.1.2 Satellite Gravity Gradiometry

**Background** - A pair of separate accelerometers can measure the space rate of change of gravity, which is proportional to the second gradient of the gravity potential. The measurement is a combination of gravitational and rotational effects; so to get information on gravity, it is necessary to eliminate the effects of rotation. A gradiometer tends to be more sensitive to short wavelength components of the Earth gravity, compared to SST. Unlike SST, gravity gradiometry requires only a single spacecraft, and could therefore be extended more easily to planetary missions.

In the early 1970's, various studies were conducted to review the feasibility of an Earth orbiting gravity gradiometer mission. Although there were three DoD funded programs (Hughes, Draper Lab, Textron-Bell) to develop gradiometers of 1–10 E/Hz<sup>1/2</sup> sensitivity, a .01 E/Hz<sup>1/2</sup> instrument, required for satellite gradiometry, was deemed to be too challenging at that time ( $1 \text{ E} = 10^{-9} \text{ s}^{-2}$ ); and SST was chosen for the gravity mission (GRM), planned for the 1980's.

Various requirements in solid Earth geophysics and oceanography of the 1990's and early 21st century correspond to a gradiometer sensitivity of  $10^{-2}$  to  $10^{-4}$  E/Hz<sup>1/2</sup> to achieve a desired horizontal resolution of 50–100 km. The instrumental requirement also depends on spacecraft altitude and mission duration.

**Review of Current Status** - Intense development efforts in the 1970's led to the demonstration of a successful moving base gravity gradiometer by Textron-Bell, albeit with a sensitivity of 10 E/Hz<sup>1/2</sup> far from that required for space geodesy. The Bell gradiometer consists of four room temperature accelerometers, mounted on a rotating platform, for heterodyne detection of the gravity gradient. It seems unlikely that this technology can be extended by over three orders of magnitude, but Bell claims they can do it.

Starting in 1980, NASA supported the development of a single axis superconducting gravity gradiometer (SGG) at the University of Maryland. In this device, persistent currents are used to difference acceleration signals from two superconducting proof masses, and the current signal induced by the gradient is detected by a SQUID (Superconducting QUantum Interference Device). This instrument was designed to have an intrinsic noise level of 0.03 E/Hz<sup>1/2</sup> but its performance was limited to 10 times that, due to uncompensated rotation errors. The SGG now appears to have reached the marginal sensitivity level needed to yield 100 km horizontal resolution; but much engineering needs to be done to qualify the cryogenic instrument for space.

**Current Development Program** - There have been numerous attempts to develop gravity gradiometers for terrestrial and space applications. At present, there are two main projects being sponsored for space geodesy. One is an improved superconducting gravity gradiometer, at the University of Maryland, funded by NASA and the US Air Force. The other is a room temperature gradiometer called GRADIO, at ONERA in France, supported by ESA and the French government.

GRADIO [Balmino *et al.*, 1985] is based on an improved version of the French CACTUS accelerometers, previously flown to measure radiation pressure and air drag on spacecraft. Eight electrostatically levitated three-axis accelerometers are located at the corners of a cube, to make redundant measurements of all five independent components of the gravity gradient tensor. The projected sensitivity of GRADIO is  $.01 \text{ E/Hz}^{1/2}$ . A two-dimensional version of this concept is the candidate for ESA's ARIS-TOTELES mission, planned to fly about 1994.

The University of Maryland device [Paik and Richard, 1986] incorporates a superconducting "negative spring", which effectively turns the SGG into a free mass system, thus improving the sensitivity of the instrument further. So modified, the projected sensitivity of the device is  $10^{-4} \text{ E/Hz}^{1/2}$ . A six axis superconducting accelerometer, capable of measuring six degrees of platform motion will simultaneously provide linear and angular acceleration signals of sufficient sensitivity for drag free operation and attitude control of the instrument. The flight hardware will consist of three diagonal component SGGs, and the six axis accelerometer. This combined instrument is the candidate for NASA's Superconducting Gravity Gradiometer Mission (SGGM) [Morgan and Paik, 1988] which is envisioned to fly in about 2000. A precursor space test of this instrument is now being planned.

In both GRADIO and the SGG, instrument performance could be limited by angular motion sensitivity and self-gravity effects from the spacecraft. Providing an adequate dynamic environment for these sensitive gradiometers will impose severe requirements on spacecraft design and attitude determination and control.

Future Technology - Certain disciplines of geophysics, including oceanography, require 25 km horizontal resolution of gravity at the 1–2 mgal level. This implies a gradiometer with sensitivity better than  $10^{-6} \text{ E/Hz}^{1/2}$  at 160 km altitude, the GRM altitude. While the sensitivity requirement could be relaxed by flying even lower, the GRM design appears to yield the practical lower limit, while flying drag free. A tethered vehicle might fly lower; but as it is tied to a higher satellite, it can't be drag free, and serious scale factor errors would ensue.

It is possible to envision improvement of the SGG beyond  $10^{-6} \text{ E/Hz}^{1/2}$  by achieving a better quality factor ( $Q > 10^7$ ) for the proof masses, and employing lower noise SQUIDS, which already exist as laboratory models. However, the more stringent attitude corrections, imposed by such an instrument, may demand better estimation methods [Sonnabend and McEneaney, 1988, and 4.3 below] or unconventional attitude sensors, such as the superconducting gyroscope or the cryogenic quartz telescope developed for the GP-B mission. One step in this direction would be through still lower temperatures, for lower SQUID noise and still better mechanical stability. The obvious means is developing a space helium dilution refrigerator, as are now under study. The time scale appears to be 10 years or more.

Some relief from noise could come from a longer mission over the same ground path. At constant altitude this would require both more propellant and a longer lived dewar. While servicing both is a possibility, a less expensive alternative could be to fly a little higher, thus needing less propellant, and improving the dewar. IRAS, launched in 1983, operated at 1.7 K, and had a demonstrated hold time of more than 10 months.

COBE and GP-B, scheduled for 1989 and 1993, have projected hold times of 14 and 28 months. Dewars without large aperture telescopes could certainly be made with significantly longer hold times. Another way to stretch the hold time might be to add a solid hydrogen or neon outer tank, thus removing leakage heat with a cryogen having a much higher heat of vaporization.

Further development of SQUIDS may also be anticipated. The detection of a  $10^{-15}$  T field change with a 100 Hz bandwidth has already been demonstrated. Also needed are wider dynamic range, better null stability and absolute calibration, and lower  $1/f$  noise, all under active investigation. "Flux counting" techniques may help achieve all this. High resolution magnetometry may also benefit from these improvements.

Planetary missions will require much less stringent gradiometer sensitivity, perhaps  $0.1-0.01$  E/Hz<sup>1/2</sup>. Several of the room temperature gradiometers under development should be capable of this. Much more sensitive gravity missions, with superconducting gradiometers, may be envisioned, if closed cycle refrigerators, operating below 10 K, become available for space applications. Either they must be mechanically quiet, or helium transfer systems would have to be developed. Alternatively, high temperature superconductors (above 90 K) promise substantial improvements over current instruments.

A challenge in designing the gradiometer system will be slosh and the tidal motion of liquid helium. Helium is the hardest liquid to control, because of its extraordinarily low viscous damping (fortunately there is some damping of large motions in bulk superfluid), and extraordinarily low surface tension (two orders of magnitude below water). To see the problem, the addition of 1 cc (0.13 gm) of helium liquid, 50 cm from the gradiometer, produces a gradient equal to the  $10^{-4}$  E resolution of the instrument.

**Conclusions** - Gravity gradiometers and spacecraft control technology have reached a stage that the highly sensitive gradiometer mission can now be planned. Advanced gravity mapping missions, such as ARISTOTELES and SGGM, will contribute greatly to our understanding of the Earth, and prepare the way for studies of the planets. It is therefore recommended that the highest priority be given to the development of the necessary instruments and ancillary technologies. These and the design of the mission, the spacecraft, and the data analysis techniques would best be accomplished by pooling the resources and talents of ESA, NASA, and other space agencies and scientific institutions. Although less sensitive, ARISTOTELES would serve as a valuable, perhaps necessary, precursor for the more demanding SGGM, needed to meet the gravity measurement requirements of the 21st century. Therefore, it is recommended that both missions be pursued with the highest priority.

#### 4.1.3 Drag Free Systems

A "drag free" spacecraft is one that flies a purely gravitational trajectory, in spite of uncertain disturbances, such as air drag and radiation pressure. These systems generally involve a small, dense, free floating proof mass, contained in a larger structure, which protects it from disturbances. When a collision is imminent, thrusters on the spacecraft are fired to keep it away. Thus, the proof mass follows an almost perfect gravitational trajectory, and the spacecraft does so on average. As both the SST and

gravity gradiometry satellites depend critically on drag free systems, they are discussed separately here.

Review of Current Status - The first drag free satellite was TRIAD, a member of the US Navy's Transit Improvement Program series, flown in 1973. The proof mass was a 22 mm diameter, solid, platinum-gold sphere, contained in a 40 mm spherical cavity. Six plates inside the cavity comprised a three axis RF capacitance bridge to measure relative displacement. Propulsion was by impulsive cold gas (Freon). A performance of better than  $10^{-10}$  m/s<sup>2</sup> average nongravitational acceleration was established by external tracking. The Navy's intent was to extend orbit predictions of navigational satellites, thus easing the tracking and operational requirements. Since then, the Navy has developed a single axis drag free system, which was tested on TIP-II, and used operationally on the NOVA (Transit) satellites.

Gravity Probe B (GP-B) is to use essentially this scheme, to reduce the centering forces of its electrostatically supported gyros to a very low level [Young, 1986]. The principal differences are a much smaller gap, and the use of boil-off helium in continuous proportional thrusters for centering.

The GRM SST [Keating *et al.*, 1986] originally employed TRIAD-like schemes in each satellite. The main differences were that hydrazine propulsion was to be used, and that a much larger hollow proof mass was intended, to increase the capacitances and thus improve the location accuracy of the proof mass, relative to the cavity. It was later recognized that a substantial improvement in system accuracy could be achieved by a two stage drag free system. In this arrangement, an intermediate body, containing the tracking system antennas, is closely centered on the proof mass by magnetically pushing on the outer satellite. Collision between the intermediate and outer bodies is again prevented by an impulsive hydrazine system. In the later GRM studies, the two stage arrangement was clearly preferred.

Space gravity gradiometers pose a somewhat different requirement. Here, "scale factor errors", arising from mismatch of accelerometer gains, or misalignment of their input axes, can be controlled by operating at very low levels of non-gravitational acceleration. Since only the proof mass is really drag free in a TRIAD type system, either the whole ensemble of instruments becomes the proof mass, or a two stage drag-free system is needed, with the instrument package on the intermediate body.

Two proposed gradiometer missions employ forms of the two stage drag-free system. The now dormant ESA/NASA collaboration would put the GRADIO and associated instruments on the intermediate body of the system studied for GRM, while the NASA/University of Maryland SGG would float the whole cryogenic dewar as the intermediate body, and employ its six-axis accelerometer proof mass as its inner body. Control forces and torques on the dewar can be provided either by the helium boil-off, as on GP-B [Parmley, 1986], or by eddy current repulsion against the outer body.

Error Sources and System Performance - The criterion for drag-free performance is how low the non-gravitational accelerations of the proof mass can be made. The two worst sources of error are the build up of electric charge on the proof mass, and the gravitational attraction between the proof mass and the rest of the spacecraft. Other



error sources, such as magnetic effects and proof mass asphericity are well controlled in current designs.

Proof mass charge can result from high energy radiation causing electrons to transfer between the proof mass and its surrounding cavity. A potential arises if this two-way process is unsymmetrical. Even then, there is no disturbing force unless the proof mass is off center. No error from this source was discerned on TRIAD; however, the intervals between tracking passes were much greater than the times between freon firings, so the effect, if present, could have averaged out in the data. Charge effects have been observed in lab tests of electrostatically supported accelerometers; and small disturbances attributed to charge were detected on the French CACTUS flight test. This experience has led ONERA to consider grounding the proof mass by a very thin wire in the GRADIO accelerometers. For really sensitive applications, it may be necessary to consider molecular inhomogeneities in the proof mass and cavity surfaces. Even for conductors such as gold that resist surface oxidation, there may be contaminants or grain boundaries causing local variations from an otherwise spherically symmetric electric field, leading to nuisance forces and torques. While the charge problem needs careful attention in future programs, it will probably not limit the performance of any future mission, and it is certainly well in hand for GP-B.

Unlike charge effects, self-gravity is essentially out of the hands of the instrument designer, and must be dealt with at the spacecraft level. For size a 1 kg mass at 1 m from the proof mass causes an acceleration bias of  $6.67 \times 10^{-11} \text{ m/s}^2$ , declining with the square of the distance. This is distinct from the effect on a gradiometer, where the same mass gives a gradient bias of 0.0667 E (tensor coefficient), declining with the cube of the distance. The primary method of dealing with these biases is an accurate mass survey of the spacecraft, which, for TRIAD, was a very involved undertaking. Moving masses are the worst problem, particularly propellants in partially empty tanks. On GRM, the tanks were to contain a flexible diaphragm, and were to be placed as far outboard as possible.

There is another way to get relief from self-gravity - frequency separation. If the purpose of the mission is the measurement of gravity variations, then the desired signal is contained in a frequency band, bounded below by a few times orbital frequency, and above by the time needed to fly a ground distance equal to the altitude, perhaps .05 Hz at the lowest practical altitudes. In this case, a high bandwidth, low displacement drag compensation system will move vehicle displacements above the measurement band, and discourage high frequency excitation of propellant motions. Tank baffles and diaphragms can also be selected with the same frequency separation idea in mind.

A possible extension of existing technology may be propulsion by thrusters where solid teflon is vaporized. The specific impulse is about a factor of ten higher for teflon than for bipropellants. Teflon thrusters have been demonstrated in orbit. Their advantage for geodesy missions would be either in extending the lifetime at a given altitude, or in operating at lower altitudes. Against this is the need for more power, and hence larger solar panels, which might appreciably increase the drag.

#### 4.1.4 Local Gravity from Aircraft

There are several existing or suggested applications for gravity measurements by gradiometer from aircraft. These include the long time, and rather successful program of the DoD. The newer suggestions use either the DoD gradiometer or the University of Maryland superconducting instrument in a NASA aircraft. The applications range from strengthening the global field by many local measurements, through occasional detailed local gravity surveys, to hazard monitoring of volcanically active areas. Some discussion of each of these is given below.

The DoD program -The Bell/Textron Rotating gradiometer, also mentioned in 4.1.2, has been successfully operated in ships, submarines, a van, a freight train, and a C-135 aircraft. Several units are owned by the U.S. Navy, and one, developed by the U.S. Air Force for aircraft use, is currently owned by the Defense Mapping Agency. While the matter has not been raised with the DMA, a joint arrangement with NASA, and perhaps other agencies, might be possible using a NASA or other aircraft, for any or all of the above applications.

The U. Md. instrument - While intended for use in space, the University of Maryland Superconducting Gravity Gradiometer would be expected to deliver at least 2 orders of magnitude better sensitivity than the Bell instrument, in an aircraft. Thus, although no study has been made, local gravity surveys at sub-mgal accuracy should be possible, and many applications may be imagined. A study to clarify accuracy issues, as well as those of aircraft availability and instrument accomodation would probably not require more than about 1 work year.

Other instruments - Also mentioned in 4.1.2 are the French GRADIO and the Italian cross gradiometers. While neither has, to the panel's knowledge, been considered for aircraft operation, both are more recent room temperature designs whose sensitivities would probably exceed that of the Bell instrument. Again, some sort of cooperative program can be imagined.

Possible Surveys - While a global field is not practical from aircraft, data gaps from a satellite mission such as ARISTOTELES, or areas where the recovery was poor might be filled in by an aircraft survey. In fact, a few well surveyed areas might significantly strengthen global field recovery. In addition, many local areas of particular interest, such as subduction zones or meteorite impact sites, could be surveyed at greater sensitivity and resolution than possible from space. Finally, active areas such as volcanoes could be surveyed and revisited to see changes over time, both for geophysical studies and for hazard prediction.

A Possible NASA Program - Severe budget constraints led the Air Force to drive a van mounted gradiometer aboard a C-135, and would not permit adding a flight control system capable of flying (and repeating) a precise pattern over the ground. The least expensive program, capable of making the local gravity surveys mentioned above, is envisioned as soft mounting a Bell gradiometer directly in an aircraft with a suitable GPS assisted flight control system, and adding attitude determination equipment. Some sort of cooperative arrangement with the DMA could be pursued. Later, an upgrade to a GRADIO, an IFSI cross, or even a superconducting instrument would be

possible for improved sensitivity, although the cost of reducing aircraft self gravity and other effects might be considerable. About a 2 work year study could make the benefits and equipment operating costs much clearer.

## 4.2 Magnetic measurement techniques

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### 4.2.1 Introduction: Objectives and Requirements

The Earth's magnetic field is made up of three contributions: the main field generated by a self sustaining dynamo in the liquid core, the surface anomaly field resulting from the magnetization of crustal materials, and the external field, due to ionospheric, magnetospheric, and field aligned currents. These fields are measured to study their properties and the properties of their sources. Measurement of crustal fields calls for acquiring data at as low an altitude as possible, consistent with spacecraft operations. To date the lowest altitude measurements were acquired by Magsat. The average Magsat altitude was about 400 km; the lowest altitude at which data were acquired (1 pass) was 190 km. In contrast, measurement of the main field can be accomplished readily at altitudes of 400 to 800 km. In this case, the primary data need is for long term, continuous data acquisition, i.e. a mission with long lifetime. Data acquisition at any near Earth altitude is useful for measurement of external fields. However, for a complete picture of the physics associated with external fields, accompanying measurements of electric fields, of particle fluxes, and of auroral imaging are highly desirable.

Magnetic field instrumentation has the same requirements/goals regardless of the orbital characteristics of the mission. These are as follows:

#### Accuracy:

- Scalar: 1.0 nT rss; Vector: 2.0 nT rss.
- Discontinuities due to attitude solution to be less than 2.0 nT, absolute.
- (Note: errors include all sources - instrument, position, spacecraft contamination, attitude determination, etc.)

#### Data Rate:

- 1 sample/second is sufficient for internal fields.
- 16 samples/second for the vector measurements is desirable for field aligned current measurements.
- Data readouts should be synchronized between the two instruments and, if possible, with the attitude measurements.

#### Geographic Coverage:

- Data spacing no more than 1000 km between points every 4 days.
- Data spacing no more than 60 km between points every 3 months.

#### Local Time Coverage:

- It is desirable that all local times be sampled at least once every 6 months.

The data rates required are modest and easily achievable by fluxgate and optical pumping magnetometers. The geographic coverage and local time coverage are determined by the spacecraft orbit. These are not hard and fast requirements, but goals; and typically there are trade offs with requirements imposed by other aspects of the launch or mission.

It is important to realize that the accuracies required include all sources of error, not just that from the magnetometer. For past missions, position or orbit error has been an important factor. As a guideline, the Table 4.2.1 shows the effect of orbit error on near Earth satellite magnetic field measurements.

**Table 4.2.1. Effect of Orbit Error on Near Earth Satellite Magnetic Field Measurements.**

Component	Maximum gradient (nT/km)			Mean of gradient magnitude (nT/km)		
	Vertical	N.-S.	E.-W.	Vertical	N.-S.	E.-W.
$B_r$	-28.0	-13.3	6.8	14.9	5.3	2.0
$B_\phi$	8.4	-2.0	23.3	2.6	0.7	2.1
$B_\theta$	18.0	-6.5	23.4	7.6	3.0	1.7
$B$	-28.0	-6.1	5.7	18.4	2.5	1.6

In the table, the first three rows are the maximum and mean components of the gradient tensor. The fourth row is the (vector) gradient of the magnitude of  $B$ .

Modern satellite positioning methods are readily able to give the position better than 10 m, in which case the error due to orbit position uncertainty is  $<0.3$  nT everywhere. An error in the time assigned to a satellite measurement is equivalent to an error in position. In particular, the time at which the measurement is taken must be known to a millisecond or better if it is not to be a factor in the error budget.

Obviously, what we wish to measure is the in situ magnetic field, as though the spacecraft were not present. Any appreciable spacecraft fields at the magnetometer will contaminate the measurement. To reduce these fields usually requires the use of a boom to separate the magnetic sensor from the spacecraft. The length of the boom should be chosen so that the spacecraft field is less than 0.5 nT at the magnetometer. For small, relatively magnetically clean spacecraft, such as Magsat, a typical boom length is 6 m. For nadir-oriented spacecraft, typical for this type of measurement, it is theoretically possible to separate a constant spacecraft field from the in situ field uniquely. This was demonstrated for Magsat. However, for this to be possible the spacecraft field must be very small compared to the in situ field and it must be constant over the time of determination. Spacecraft fields due to magnetically "soft" materials or time varying fields from changing currents or instrumentation, cannot be determined with this method. (An attempt was made to use data from the DMSP F-7 spacecraft, solving for the very high,  $>1000$  nT, fields; but the attempt failed.) There is, in principle, an alternative method for dealing with spacecraft fields in cases where the boom cannot be made long enough, even when those fields are "soft" or time variable. This is to position a second magnetometer inboard on the boom from the primary sensor. The two point measurement will suffice to determine the spacecraft field, pro-

vided both are in the far field where the field components decay as the cube of the distance, and their positions and attitudes are accurately known.

For vector measurements the orientation of the axes of the magnetometer must be known with respect to an inertial coordinate system. This means that the attitude of the magnetometer must be measured. Traditional approaches, with a pre-launch measurement of sensor attitude in the spacecraft frame and then the use of Earth horizon scanners and solar sensors to determine the vehicle attitude are, in general, inadequate for this task. A star sensing system co-mounted with the vector magnetometer is optimum. Alternatively, a very accurate system must be used to transfer the attitude knowledge of spacecraft body-mounted star sensors to the boom-mounted magnetometer, as was done for Magsat. To put the accuracy requirements of such a system into perspective, note that a 20 arcsec error in attitude in the Earth's field results in a component error of about 5 nT. Ideally, the magnetometer attitude should be known to a few arcsec. This requires extreme mechanical and thermal stability, accurate measurement of the attitude of the magnetometer relative to the star measurements, and accurate measurement of the star positions. Again, given adequate in-orbit stability, small errors of calibration, or small mechanical changes can be calibrated out in space.

#### 4.2.2 Instruments

In typical applications two instruments are required, a scalar and a vector magnetometer. Available vector magnetometers are not absolute instruments. The measurement of the vector components always involve servo loop driven nulling currents in small coils and they are subject to problems such as zero offset drifts and gain changes as components age and are exposed to radiation. On the other hand, scalar instruments are absolute. They are nuclear or atomic resonance devices whose frequency of oscillation, a readily measured quantity, is only a function of field magnitude and fundamental constants of nature. In the Magsat project, *Lancaster et al.* [1980] demonstrated how to utilize data from the scalar instrument to calibrate the vector instrument in flight. This proved extremely successful and results in simplification of the requirements for the scalar instrument data rate, since scalar points are not then required at a high data rate.

There are a variety of different types of magnetometers used for geophysical purposes on the ground: proton precession, fluxgate, alkali metal, and metastable helium optical pumping and Overhauser effect proton magnetometers. However, building a space qualified, high accuracy and stability instrument is not a routine task. These instruments must be highly reliable, autonomous, low in mass and power, specially engineered to withstand variable solar inputs, vacuum, and radiation, and be equally sensitive to fields oriented in a variety of directions, due to spacecraft orbital motion. Over the years, considerable effort has gone into the development of certain types of instruments now regarded as proven. The tendency is to continue to rely on those types of instruments. Wisdom would dictate the desirability of investigating other possibilities, while not abandoning the experience of the past. It is therefore recommended that NASA expend some effort to investigate/develop the potential of both existing magnetometers, and of magnetometer types not currently in use.

#### *4.2.2.1 Scalar Magnetometers*

Scalar magnetometers for space flight use have been of two types: proton precession and alkali vapor (rubidium or cesium). In addition, the vector helium magnetometers routinely used on planetary and interplanetary missions are intrinsically scalar devices, and can be adapted to make scalar measurements; and recent developments of instruments using the Overhauser effect are promising for future space applications. All of these instruments have the common characteristics of making absolute measurements, i.e. the response of the instrument is proportional to a constant times the in situ magnetic field strength, where the constant is strictly dependent on known atomic properties.

It is "comfortable" to go along with proven technology. Proton precession and alkali vapor scalar magnetometers are space proven. Even so, proton magnetometers have fallen into disuse since the early 1960's, due to their high power requirements, slow sample rates, and large dead zones; and the alkali vapor magnetometer flown on Magsat did not operate satisfactorily. Further, development of the Magsat cesium vapor magnetometer was difficult. The personnel and experience that had been gained on the POGO project was lost with the passing of time, and experience with instruments designed for aircraft use was not sufficient to bridge the gap. The optical pumping and thermal design technology needed for these instruments require hands on experience, and not merely the inheritance of records and drawings from previous projects. At present, NASA is doing nothing to maintain or develop such experience.

As an alternative to proton precession and alkali vapor magnetometers for projects such as MFE/Magnolia and the Geomagnetic Observing system (selected for Eos), a scalar helium magnetometer has been selected. This is an adaptation of the JPL vector helium magnetometer which has been highly successful in planetary missions. In the scalar configuration, and for near Earth applications, this instrument has not flown before. It would be highly desirable to pre-fund its development, i.e. prior to approval of specific missions.

A major development which may be realized in the near term is the use of a laser to pump a resonance type magnetometer optically. The helium and alkali vapor magnetometers now use a gas discharge lamp as a source of resonance radiation. The helium magnetometer operates on spectral radiation at  $1.08 \mu\text{m}$ , an infrared wavelength that is within the band now being used for fiber optic communication. Development of a small solid state laser operating at  $1.08 \mu\text{m}$  seems within the state of the art. Optical pumping of helium with a laboratory laser has demonstrated an increase in sensitivity by a factor of  $\approx 100$  (making the sensitivity comparable to that of cryogenic magnetometers) with a corresponding increase in absolute accuracy being possible. In addition to improved performance, the use of fiber optics to transmit the radiation to and from the sensor could result in a significant simplification of the sensor, with an accompanying reduction in mass, power, and size. Both consequences could enable wide spread use in space (and on Earth) of magnetic gradiometers.

The new kid on the block is the Overhauser effect proton precession magnetometer. In this instrument, "free electrons" are added to a proton rich sample to enhance dynamic polarization. Unlike the classical proton precession magnetometer, this instru-

ment can run continuously in a self-oscillating arrangement, and it does not require the very large polarizing fields which can interfere with nearby instruments. Such instruments are currently manufactured by industry in France and in Canada. The French scalar magnetometer, proposed for MFE/Magnolia, is of this type. In principle, this instrument is easily capable of exceeding the accuracy and sensitivity needed for geophysical applications, once a space qualified design is developed. However, to our knowledge, there is no development effort underway within the U.S., and certainly not by NASA. It is highly recommended that NASA begin and pursue such development at a university or field center.

#### *4.2.2.2 Vector Magnetometers*

Near Earth vector magnetic measurements have been exclusively carried out with fluxgate magnetometers. These instruments are relatively simple, highly reliable, and their cost is reasonable. They are also capable of a very wide dynamic range. For commercial use they are available from a large number of manufacturers; and they are widely used for geophysical, space, and industrial applications. However, for near Earth geophysical applications, the accuracies required are pushing the state of the art. Particular care was needed for Magsat in the selection of materials and components in order to achieve the required accuracy and stability. Even then the instruments drifted to some extent during the mission lifetime. To our knowledge, no comparable instruments have been produced since. Fluxgate technology is not stagnant. A development effort is underway at GSFC which encompasses materials, fabrication, and improved circuits. This should be encouraged and supported.

At the same time it is desirable to develop alternative technologies. The vector helium magnetometer has been successful in planetary applications. However, while these applications have extreme sensitivity requirements, they do not have the stringent accuracy requirements in fields of comparable strength to that of the Earth as do magnetometers for geophysical applications. Development and testing is needed if these instruments are to be considered for geomagnetic applications. Recently, new laser and optical fiber technology has given promise of increased accuracy and sensitivity, together with reductions in power and size for these instruments. If such techniques are proven to increase the accuracy of the vector helium instrument, it would be of great benefit for near Earth measurements.

#### *4.2.3 Attitude Determination*

The limiting factor in accuracy for the Magsat vector measurements was the determination of the magnetometer attitude. Star trackers/cameras generally have been highly magnetic instruments. For Magsat this necessitated their location at some distance from the magnetometer, and the design and use of an optical attitude transfer system to determine the magnetometer attitude relative to the star trackers. This situation has changed with the advent of new solid state precision star tracking devices. Both Perkin-Elmer (PE) and Ball Aerospace Systems Division (BASD) have the capability of building such trackers. Detectors are either charge coupled devices (PE) or charge injection devices (BASD) with the capability of tracking 6th magnitude stars in an 8 x 8 deg field of view to an accuracy of 2 to 4 arcsec (one sigma). Three or more stars would be tracked simultaneously (rather than serially, as with the old NASA



standard star tracker) in each tracker, and digital data on star magnitude and position read out to the telemetry.

Such devices are much less magnetic than their predecessors. Ideally, the star trackers would be located as close to the vector magnetometer as possible without contaminating the measurements. However, laboratory measurements indicate that the current versions of solid state trackers are sufficiently magnetic that they would still need to be located a considerable distance from the magnetometer. Most of the causes of this magnetic contamination seem to have been identified, and, in principle, can be corrected. In practice carrying this out means building a prototype camera incorporating a strictly non-magnetic design. This has not been done and is not currently planned, except as proposed in missions still waiting approval. It is recommended that development of non-magnetic star trackers be funded off-line from flight projects, so that they will be available in a timely manner when required.

#### 4.2.4 Magnetic Gradiometers

Another possibility for studying shorter wavelength features is to use a magnetic gradiometer. The gradient of a periodic magnetic field of a certain wavelength is obtained by dividing by the appropriate wavelength. The result of this is that if a structure gives a peak in its field power spectrum at a certain wavelength, the peak in the power spectrum of the gradient will be shifted to a shorter wavelength. Of more importance is that the core field is of very long wavelength, some external fields have very long wavelength signals, and local fields from field aligned currents contribute a curl in the gradient measurement. Thus, measurement of the total gradient tensor should, in principle, permit more accurate separation of fields from these sources from fields due to crustal sources.

All 9 components of the tensor must be measured because currents do flow at the satellite position, so the field is not curl free. In addition, the vector field should be measured. It is possible to produce several rotationally invariant quantities from these combined fields, should high precision attitude be unavailable. Orientation for the gradient tensor is less critical than for the field vector, as the core field component in the tensor is relatively weaker than in the field vector.

The sensitivity requirements for measuring gradients due to crustal fields can be roughly estimated by consideration of a spherical harmonic representation of the field potential. For each degree and order, the elements of the gradient tensor have the form,

$$T_{ij} = f_{nm} c(m\phi) L_n^m(\theta) [a/r]^{n+3} / a$$

where  $a$  is the mean Earth radius,  $c(m\phi)$  is the sine or cosine function,  $n$  and  $m$  are the degree and order, and  $L$  is an associated Legendre function or its first or second derivative,  $f_{nm}$  is a multiplying factor which depends upon the degree and order; for large  $n$  it goes as  $n^2$ ,  $n$ ,  $m$ ,  $nm$ , or 1. For estimation purposes, neglect  $c$  and  $L_n^m$  and assume that the gradient goes as

$$T = f_n [a/r]^{n+3} [R_n]^{1/2} / a$$

where  $f_n$  is taken to be 1,  $n$ , or  $n^2$ ;  $R_n$  is the crustal component of the spectrum,  $R_n = (n+1)\sigma_m[(g_n^m)^2 + (h_n^m)^2]$ ; and  $a=6371.2$  km, the mean radius of the Earth. A conservative estimate of  $R_n$  is that it is equal to  $20(.99994)^n$ . Using this estimate, the gradients are shown in Fig. 4.2.1. The lower curve is for  $f_n = 1$ , and gives an estimate of the sensitivity of gradient measurement necessary if the smallest meaningful gradients are to be detected. The top curve is for  $f_n=n^2$ , which also gives information about terms in nm, and applies particularly to radial gradients of the radial and eastward field, and to longitudinal gradients of the radial and eastward field. The most difficult gradient to detect will be the latitudinal gradient of the north component. From this figure it is apparent that useful gradient information should be obtainable with sensitivities of  $10^{-4}$  nT/m and better, but that sensitivities of the order of  $10^{-7}$  nT/m will be necessary to detect the smaller gradients.

The gradients from field aligned currents will be larger, often reaching 0.01 nT/m or higher. Detection of the main features of insitu currents in the auroral belt should be possible with gradiometers of minimal sensitivity. The gradients expected of meridional currents at lower latitudes are unknown. For example, if an interfering spacecraft dipole produces a flux density  $B$  at the sensor, and is a distance  $D$  away, then the extra gradient is of order  $3B/D$ . For, say, a 5 m boom, and the dipole and additional 1 m away, a gradient increment of 0.01 nT/m would correspond to a field change of 0.02 nT. Thus even with a boom, magnetic cleanliness of the spacecraft is crucial, if the gradients from field aligned currents are to be observed.

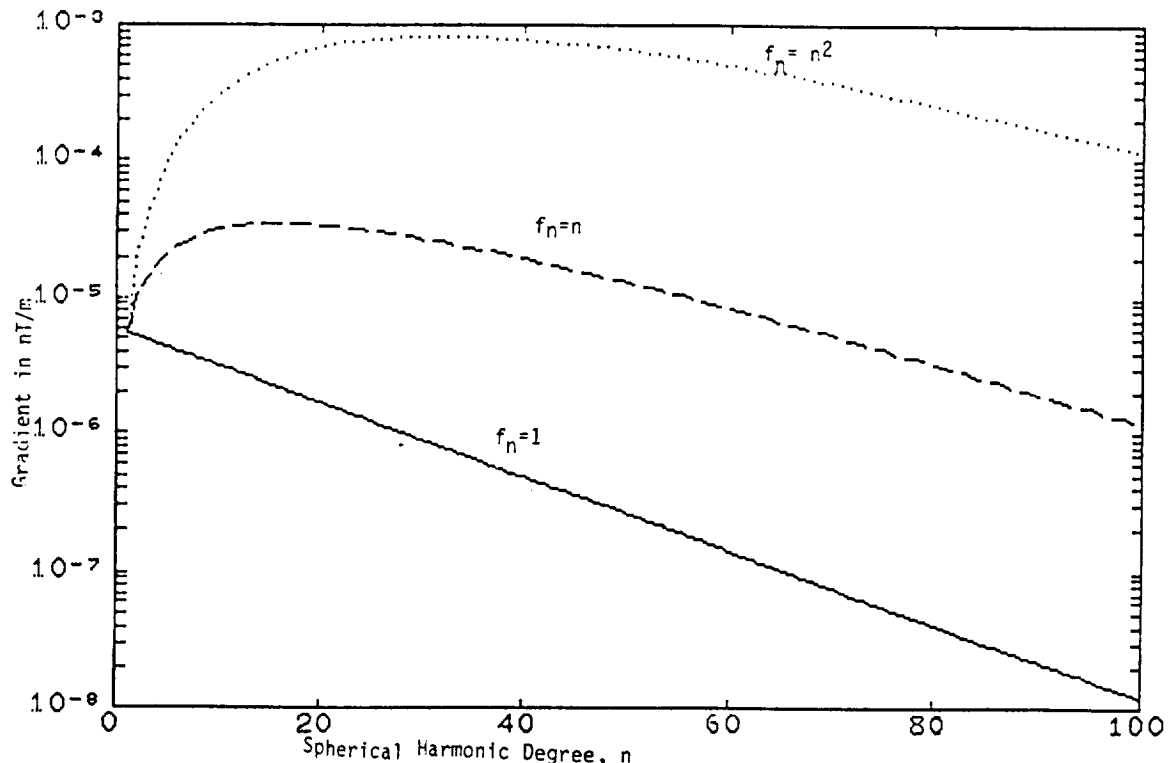


Figure 4.2.1 Expected magnitudes of magnetic gradients as a function of spherical harmonic degree (see text for discussion).

Several approaches to magnetic gradiometry have been considered. The obvious approach is to measure the field with two highly accurate magnetometers separated by the required distance. However, suppose the accuracy of measurement is 0.01 nT. Then to measure the gradient to  $10^{-4}$  nT/m would require a minimum separation of 100 m. This is practical only for measuring vertical gradients using a tether; highly desirable but the requirements are not met.

A second approach is to use superconducting quantum interference device (SQUID) magnetometers. A SQUID magnetometer designed as a gradient device measures the difference in flux linkage through two parallel coils separated by a known distance. Sensitivities as low as  $5 \times 10^{-7}$  have been claimed in the laboratory. In order to improve sensitivity, it is necessary to increase the area of the coils and/or increase their separation. The sensitivity is directly related to the product of these quantities, *i.e.* to the volume of the instrument. The present state of the art in such magnetometers is at the Naval Coastal Systems Center, Panama City, Florida, under the direction of G. Kekelis. The work is at least partly carried out through contractors; formerly Sperry Corp., presently IBM.

SQUIDs pose special problems. If we are willing to consider spacecraft designs incorporating both cryogenic devices and stringent magnetic cleanliness, then NASA should commit to the development of SQUID gradiometers for near Earth measurements in the next decade. Some attention should be paid to the plasma environment in which the instrument will operate. Local currents will be present, and it is important to measure the curl of the magnetic field. A complicating factor may be size. A typical sensor dimension is about 0.5 m. At 300 km altitude the plasma temperature is about 1000–1300 K. The gyro radius of a proton is given by  $R = 1.643 T^{1/2}/B$ , with  $R$  in cm,  $B$  in Gauss and  $T$  in K. For  $B = 0.3$  and  $T = 10^3$ , the gyro radius of a proton is 1.73 m, larger than the instrument dimension. A study should be made to determine exactly what such an instrument will measure.

Another possibility is the use of a laser pumped helium magnetometer, discussed above. Success in this effort could lead to a number of improvements of importance to gradiometry. Both the sensitivity and accuracy of such a magnetometer could make it comparable to superconducting devices without the need for cryogenic fluids. The transmission of the infrared beam used for the optical pumping may be possible with optical fibers which would reduce the volume, mass, and power required by each sensor significantly (to only 0.1 m, 0.2 kg, and 0.1 w).

## 4.2.5 Missions

### 4.2.5.1 Background

The first global measurements suitable for solid Earth studies were those acquired by the POGO spacecraft from 1964 through 1971. However, only the scalar field was measured, which limited the accuracy and usefulness of the resulting studies.

A big step forward was Magsat [Moblely *et al.*, 1980; Langel *et al.*, 1982], a sun synchronous, low altitude satellite flown from November 1979 through early May 1980. It measured the field to about 2 nT in field magnitude and 5 nT in each vector component,

counting all errors. The instruments were on a boom to avoid the spacecraft field, and star cameras and an attitude transfer system were used to obtain accurate attitude. No similar mission has flown since, and no space geomagnetism program is currently funded.

As noted above, a mission to measure the crustal field should be at as low an altitude as possible, and a mission to measure the main field and its temporal change should be at or below 1000 km, preferably in the 600–800 km range, to ensure long lifetime and to attenuate the crustal fields, while permitting measurement of the full range of the main field. Magnetometers for the two applications would be identical, except that gradiometers apply mainly to crustal and external field measurements. Potential missions are described briefly below.

#### *4.2.5.2 Main Field*

MFE/Magnolia is a joint US/French program for long term (5–6 years) monitoring of the main field and its temporal variations. Launch would be aboard an Ariane, piggyback with another spacecraft, into a sun synchronous orbit. The orbit would then be modified to about 525 km, circular, at an inclination of about 86 deg. The intent is a global description of the geomagnetic field for accurate mapping of the motions of the core, study of core-mantle interactions, investigation of mantle conductivity and study of external fields. The instrument complement includes vector and scalar magnetometers augmented by 3 axis electric field probes and charged particle detectors. GOS, for Geomagnetic Observing System, is at present selected for the second Polar Platform of Eos. Launch is scheduled for no sooner than 1998 into a sun synchronous orbit at about 800 km altitude, with a 1330 local time equator crossing. Objectives are the same as for MFE/Magnolia, except that the temporal base of the measurements will be longer—15 years.

#### *4.2.5.3 Crustal Field*

ARISTOTELES is a mission planned by ESA for measurement of the gravity field. The mission profile calls for a sun synchronous orbit. Initially the altitude will be 780 km. It will then descend slowly to 760 km over an eight month period after which it will be moved to 200 km altitude where it will make gravity measurements for 6 months. If enough fuel remains it will be boosted to 700 km where positioning measurements will be acquired for 3 years. The 200 km altitude makes this an ideal mission for improving knowledge of the crustal magnetic field. NASA and ESA are currently in discussion as to the feasibility and desirability of including a magnetometer experiment. Such an experiment complicates the gravity measurements because of increased drag and torques on the spacecraft. However, preliminary studies indicate that inclusion of a magnetometer is feasible. The mission profile also provides a useful platform for main field monitoring, provided that the 3 year high altitude phase becomes a reality.

Tethered measurements from the shuttle are planned as a feasibility investigation. The first such measurements are scheduled in 1991. In this case the magnetometer will not be at a low altitude. Future measurements are planned, but not yet approved, in which the tether will lower a magnetometer to about 150 km. Such measurements were proposed but not approved for the Space Station.

#### *4.2.5.4 Relationship of Missions*

Extension of the Magsat crustal studies requires a lower altitude mission. With the demise of GRM, ARISTOTELES and Tether remain the only candidates. Tethered measurements are inherently limited to a few passes over limited areas. However, they can in principle acquire lower altitude measurements than a free flyer, and so may be the source of our highest resolution measurements. ARISTOTELES is the only candidate in this decade, and probably the next, for acquisition of global crustal field measurements. As such it should be given very high priority.

The need in main field investigations is for long time measurements. POGO and Magsat data can contribute. However the gaps between POGO and Magsat and between Magsat and its yet to be decided successor mean that shorter period phenomena are being missed, and that aliasing will be a problem. Continuous measurements are needed for at least 2 solar cycles. The planned Eos experiment will go a long way in making such measurements, but will not do the complete job. Also, if no intervening mission is flown, the time gap between Magsat and Eos will be about 20 years, which severely limits the usefulness of the 2 data sets. Measurements are needed to fill that gap. These can be provided nicely by ARISTOTELES and MFE/Magnolia. If, as seems likely, the Eos experiment is delayed until the late 1990's, then both ARISTOTELES and MFE/Magnolia will be necessary for continuous data acquisition. The most likely sequence is to do ARISTOTELES first. It is desirable that missions overlap. This is to verify the accuracy and compatibility of each; but also, to acquire data at 2 local times for a more complete characterization of the external field morphology.

## 4.3 Quantifying mission quality

D. Sonnabend

For any kind of global mapping mission it is very valuable to have an analytic measure of mission performance, in order to compare different designs, or to establish the optimal values of parameters open to the designer. In this area, global gravity and magnetic field determination poses some unique problems that have only recently received attention. First among these is the measure of performance. For, say, a radar mission, the ideas of resolution and accuracy are readily understood by both the scientific community and the engineers who design the hardware. For gravity, the scientists speak of km and mgal; while the engineers are delivering satellite tracking accuracy and either range rate between satellites or  $E/Hz^{1/2}$ . Communication has been difficult, even for magnetic fields.

In large part the difficulties arise from the enormous number of parameters needed to characterize a potential at very high resolution. The suggested representations of potential include spherical and ellipsoidal harmonics, various kinds of mascons (or discrete dipoles), or a mixture of these. For any choice, it will be required to extract on the order of  $10^5$  parameters. The filter which does this extraction will measure its own performance by means of a covariance matrix containing something like  $(10^5)^2 = 10^{10}$  elements. Somehow, the covariance must be boiled down to an understandable measure of performance.

Many measures have been proposed. Simple statistical measures include the trace of the covariance, or its determinant, or an appropriate root. If one could determine the relative importance of each parameter, a weighting could be included. Problems with these are that most of the information in the covariance has been lost, and that the result is not in a meaningful form for the scientist. A more useful condensation can be achieved if the potential is a linear function of the parameters to be estimated. Then, it's fairly easy to form the variance of the potential at any desired location from the covariance of the parameters. Averaging this variance over a suitable surface outside the Earth produces an average potential error, which may then be expressed either as a field error in mgals, or in the case of gravity, a geoid error in meters, or both. Even if these ideas prove adequate for measuring the performance, an engineering/scientific collaboration will still be necessary to construct suitable software for mission evaluation.

Another problem in mission evaluation is proper modeling of the measurements. In all of the missions discussed here, a field is fit to a global grid of measurements. The simplest case is magnetic fields, where either a scalar or a vector field (or both) is assumed to be measured at many places. However, this "measurement" is actually the result of corrections from whatever means are used to monitor residual fields from the spacecraft, and from attitude sensors. Other kinds of data might then be used in separating the Earth's field from that due to currents in the ionosphere and magnetosphere.

For SST, the measurement ensemble includes the range rate (two frequencies in the microwave version), the drag free proof mass vector velocity estimate, the spacecraft attitude, and possibly strain measurements on the structure connecting the drag free instrument to the antennas or telescopes. For gravity gradiometry, recall that gra-

diometers actually measure a mixture of gradient and rotation effects; so the gradiometer and the attitude instruments constitute an ensemble for the joint estimation of attitude and gradient.

In all cases, the "measurement" must be corrected for the results of alignments and in-flight calibrations; and in all cases errors in spacecraft tracking can affect the final accuracy. In this respect, magnetometry is less critical than any of the gravity techniques in that the magnetic field doesn't affect the orbit, and thus complicate the data processing; and that the desired fractional sensitivity in the field determination is not as small.

The point of all this is that mission analysis software usually starts from an input covariance of the "measurements", and calculates the covariance of the estimated parameters, an enormous matrix, as was shown above. Besides boiling this down, a realistic analysis should recognize that a believable "measurements" covariance can only come from a model of the ensemble of actual measurements, together with these individual error covariances, a model of the estimation process leading to the "measurements", and a model of the statistics of the desired field. No such end-to-end mission analysis software exists for any of the mission types discussed here.

## 4.4 Data requirements

D. Sonnabend

Compared to other mapping missions, field measurements have relatively low data storage and transmission rates; nor do they require much on-board processing. This is because the fields are correlated over distances of the order of the satellite altitude; so, even at the lowest likely altitude of 180 km (a magnetometer on a tether might fly a bit lower), sampling much oftener than every 3 sec is unproductive. For SGM, with a resolution of about .0001 E, and a maximum swing of the gradient of less than 5000 E, 26 bits will encode a measurement, without compression. With three gradient channels, two SQUIDs per channel, and over-sampling at 1/sec, we need 156 bps. Doubling this to include the 6 axis accelerometer, adding that much again for temperatures, pressures, etc. within the dewar, plus something for parity and data correction, comes to about 500 bps. After adding in the gyros and star trackers outside the dewar, the total is still under 1 Kbps.



## 5. GROUND BASED MEASUREMENTS

### 5.1 Absolute Gravity Measurements

J. Faller

Future prospects for absolute gravity measurements are very bright. The expected 1 microgal accuracy (corresponding to 3 mm in height change), is at the geodynamically interesting level. Though gravity gives simultaneous information on height and integrated subsurface density, changes are separable by using gravity in combination with one of the geometrical height measuring techniques. Absolute gravity in itself could be used as a reconnaissance tool to assist in the decision process as to where to deploy the more expensive satellite techniques. Further, solutions using space techniques and gravity changes will yield information on both height changes and underlying density changes.

We discuss here only absolute gravity (rather than relative gravity) since the timescales associated with geophysical change require the existence of stable reference (comparison) areas for use with relative instruments (awkward at best), or a technique which measures the absolute value itself. Technical capability will exist within a few years to make gravity measurements with absolute accuracies at the 1 microgal level and relative precisions of 0.1 microgal.

The justification for stating that this capability will soon exist lies in a simple extrapolation on the performance already achieved in the field with the most recent generation of absolute instruments at JILA, which have achieved an accuracy of about 6 microgals and show a reproducibility (on reoccupying the same site) of 1 to 2 microgals. The new instrument, which is presently being developed, will address the two existing uncertainties in the present instruments which are tilt sensitivity and lack of symmetry in the timing process. Both of these effects could introduce a difficult-to-characterize and not necessarily reproducible systematic error at the few parts in  $10^9$  level. To address the tilt problem, the instrument is being modified to a straight-line design which will result in only a second order sensitivity to tilt. To address the timing problem, we are looking at an up and down (throwing as opposed to just dropping) measurement approach. We have recently finished the construction of a thrower along rather "simple" lines which performs successfully at a level that would permit measurement accuracies of 1/3 microgal before systematic (rotation) effects would become important.

## 5.2 Terrestrial observatories

A. Dziewonski, T. Clark

In many disciplines of Earth sciences related to the Solid Earth Science Program, ground measurements are necessary in addition to observations from space. It is proposed that modern, modular terrestrial observatories with a two-way satellite communication link would accommodate various needs of Earth sciences as well as measurements in other fields, such as meteorology, atmospheric chemistry or soil properties. The concept of a terrestrial observatory should also be extended to permanent installations on the ocean bottom. Programs such as Global Change and International Decade of Hazards Reduction require a world-wide system of data acquisition, transmission, dissemination, and archiving. The following are examples of ground based measurements related to the Geodynamics Program:

1. Permanent GPS-receiver installations consisting of individual sensors or their arrays connected through a local telemetry system.
2. Volcanological observations.
3. Geomagnetic field measurements.
4. Seismic observations.
5. Gravity measurements with a superconducting gravimeter.

It is expected that a terrestrial observatory would have a modular design allowing for future expansion or modification of measurements and be equipped with a computer system, or a local computer network, capable of a variety of "intelligent" decisions in addition to routine data reduction tasks, merging of different data streams, and scheduling of individual measurements. Local telemetry could be used in cases when arrays of instruments are used or a common site might be inappropriate for certain subsets of measurements. The stations would have a built-in common recording system using mass-storage media such as large capacity cassettes or optical disks, but the primary mode of data transmittal would be satellite telemetry. The capacity of this system would determine whether all the data or their selected subsets would be transmitted in realtime or nearly real time.

Because of the two-way communications, the personnel at a terrestrial observatory could also request data from other stations or other information. In this mode, the role of a terrestrial observatory could be expanded from passive gathering of data to a research and training function. This is particularly important in the Third World countries, where there is the greatest shortage of personnel capable of operating and maintaining sophisticated equipment and where the benefits of co-locating different measuring systems would be most substantial. Integration of observations is, of course, also important in uninhabited locations such as ocean islands or interiors of deserts.

A global observing system requires international cooperation. The International Commission on the Lithosphere recently created a Coordinating Committee for Terrestrial Observatories whose task is to help to establish standards for data collection and exchange.

It is recommended that two or three prototype systems of multi-disciplinary terrestrial observatories with a different mix of measurements be developed and deployed in the United States and that an existing satellite telemetry system be used in the early stages of the experiment. The development of a long-term data transmission, dissemination and archival system should proceed in parallel. It is expected that some 100 globally distributed terrestrial observatories, each generating about 10 megabytes of data per day, will be needed to meet the program objectives. In addition, there is a need to transmit data from simpler, single-purpose measurement systems.

Real-time data transfer either requires dedicated terrestrial communications channels (telephone lines, point-to-point radio links etc.) or channels on geostationary communications satellites. An attractive alternative for low-rate data is the use of low-Earth orbit (LEO) satellite store-and-forward communications.

Remote data collection through satellites has been demonstrated using ARGOS, ATS, MARISAT, and other systems. The 400 BPS one-way ARGOS links are the most commonly used.

It would be desirable to design new data collection systems that would enable those responsible for acquiring data during interesting periods to interrogate "smart" remote instruments to supply concentrated data for specific periods. This requires two-way communications.

Recent developments have made it feasible to launch low-cost (<\$1 million, including all launch service costs) two-way store-and-forward satellites which work with small, low-cost (<\$3000) ground terminals. With such inexpensive systems, it is feasible to dedicate one or more such satellites to special scientific measurement programs.

An example of these satellites are the small "microsat" satellites developed for radio amateurs by AMSAT (the Radio Amateurs Satellite Corp.); the Microsats are 24 cm cubes with 10 kg mass which cost \$3-400,000 each. The satellite group at the University of Surrey (UoS) have developed and demonstrated similar techniques with the Digital Communication Experiments (DCEs) on several UoSats.

To launch such small satellites, Arianespace has made available the new ASAP (Ariane Structure for Auxiliary Payloads) which permits up to eight small satellites to "hitchhike" rides with a primary payload. Arianespace has suggested that the cost of including the ASAP and providing "piggyback" launches will be \$1 million total—*i.e.* <\$125,000 per satellite. Four Microsats plus two UoSATS will fly from the ASAP that will be launched with SPOT 2 in November 1989. Other interesting launch opportunities involve the new private launch vehicles (Pegasus and AMROC) being developed in the United States.

## 6. DATA AND INFORMATION SYSTEMS

The information management for the Solid Earth Sciences (SES) will be demanding during the coming decade due to the complexity and volume of the different data sets used for scientific research. The new NASA SES program represents a merging of the existing NASA Geodynamics and Geology Programs into one program. The Geodynamics and Geology Programs are bringing with them operational data systems that are crucial to the scientific investigations of each discipline. It is proposed that these data systems be integrated under a common umbrella, the Solid Earth Sciences Data and Information System (SESDIS). Each existing system will become a major component of the SESDIS, but will also be capable of functioning quasi independently for a certain amount of time, thus providing for the immediate data needs of the discipline investigators. This concept is consistent with that of the Earth Science and Applications Data System (ESADS) and other system architectures being developed by NASA Code E.

The SESDIS functions will include location, retrieval, archiving and timely distribution of all relevant data products and all information about these data products. Careful planning and coordination is required because much of the required SES data are produced and archived in computing or analysis centers distributed within the U.S. or worldwide, in addition to the data systems at NASA centers.

### *Recommendations*

Because of the complexity and volume of data needed to meet research objectives in Earth sciences in the coming decade, data systems will be an integral part of the SES program. Therefore, the SESDIS must be designed carefully and planning must commence immediately in order to meet the short- and long-term needs of the SES community. We recommend:

1. Recommend against the development of a new data system or the purchase of new computer systems for an Interactive Data and Information System (IDIS). Rather, it is recommended that existing systems (i.e., CDDIS, and PLDS) be augmented and integrated to support the SES investigation community.
2. Recommend limited scale funding to commence in FY90, at the latest FY91, so that management/implementation planning can begin. During FY91, the actual implementation of the dual system integration should begin.
3. Recommend the future funding of PLDS must be decided at the NASA HQ level. It is recommended that the SES assume responsibility for SES-specific data managed by PLDS. These data sets include spectral and ancillary geologic data required for the interpretation of remotely sensed data. Aircraft and satellite data held in PLDS is useful to all Earth scientists, not simply SES scientists. Therefore, a joint funding of the operational PLDS aircraft-satellite data archives is recommended which would include SES and other appropriate Earth Science and Applications Division programs.

4. Recommend augmentation of CDDIS in FY91 with data resulting in NASA sponsored GPS experiments.
5. Recommend assembling a SES Science Working Group in FY90 to discuss specific data system requirements so that initial phases of the system design and integration and management planning can begin.

## 6.1 SES System

H. Linder, E. Paylor, C. Noll

### 6.1.1. Data Requirements

Table 1 shows a preliminary list of known data sets (both existing and future) that are required by the SES science community. For a description of each instrument and data set, the reader is referred to previous sections of the Measurements and Techniques report. The panel does not intend to make this list an all inclusive one. Refined requirements will be synthesized when the SESDIS Science Working Group (SWG) is formulated and meets in FY90.

### 6.1.2. Functional Requirements

Basic functional requirements for the SESDIS are:

- Provide directory of available data inventories of relevance to SES researchers.
- Provide inventory of all SES data holdings.
- Search inventory based on (at minimum) spatial, temporal, and data type inputs.
- Browse abbreviated copy of inventory.
- Browse detailed descriptions of SES data holdings.
- Order elements from data holdings.
- Establish connections to other related data systems for location and retrieval of data.
- Promote electronic communication among SES investigator community.
- Allow easy integration of data management and data analysis capabilities.

Existing elements of the SESDIS (CDDIS, PLDS) currently have these capabilities and will be maintained during systems integration. New and/or refined functional requirements will be formulated during the first meeting of the SES SWG during FY90.

**TABLE 6.1-1. SES Data Requirements**

<u>Category</u>	<u>Data Type</u>	<u>Comments</u>
Laser Ranging	SLR	Including LAGEOS, Starlette, Ajisai, and Etalon-I and -II
Radio	LLR VLBI GPS DORIS PRARE	
Aircraft Remote Sensing	Geobeacons TIMS AVIRIS/AIS SAR L,C,P Scatterometer	

TABLE 6.1.1. (Continued) SES Data Requirements

<u>Category</u>	<u>Data Type</u>	<u>Comments</u>
Spaceborne Remote Sensing	Quad--Pole SAR	
	NS001/TMS	
	Aerial Photos	
	Daedalus/TMS	
	Sun Photometer	
	SIR-A,-B,-C	
	Seasat	
	AVHRR	
	TM	
	MSS	
	LFC	
	SPOT	
	SEASAT	
	Magsat	
	TOMS	
	GLRS	
	HIRIS	
	SAR	
	MISR	
	MODIS	
ITIR/TIGER		
LASA		
HMMR		
Ancillary	Survey coordinates	
	System eccentricities	
	Site descriptions	
	Angular momentum	
	Seismic	
	Gravity	
	Magnetic	
	Bore-hole	
	Rock samples	
	Mineralogical	
	Topographic	
	Atmospheric	
	Field/Lab Spectral	PIDIS
PFES		..
PFRS		..
VIRIS		..
PRT-5		..
Parabola		..
Beckman/JPL		Lab Spectra
FTIR/JPL		..
RELAB		..

TABLE 6.1.1. (Continued) SES Data Requirements

<u>Category</u>	<u>Data Type</u>	<u>Comments</u>
Derived, Interpretive Products	Baselines Station Positions Polar Motion Earth Rotation Length of Day Maps/Interpretations derived from images	

### 6.1.3 SES Data System Implementation

#### 6.1.3.1. Existing SES Components

Initially, the SESDIS will contain two main components, one to service the Geodynamics related research and one to service the Geologic related research. They will be integrated to function as a single data system and will become the core of the SESDIS. These components will utilize two existing data systems: the (CDDIS), created to support the CDP, and the Pilot Land Data System (PLDS) a distributed data system created to support land scientists in the Land Processes Branch (Code EEL) of NASA. These systems are described below.

##### 6.1.3.1.1 Crustal Dynamics Data Information System (CDDIS)

As part of its data management, the CDP has designed and implemented a centralized CDDIS (see Figure 6.1.1). The CDDIS has been fully operational since September, 1982. The main purpose of the CDDIS is to store and distribute all geodetic data products acquired by the Project in a central data bank and to maintain information about the archival of all Project related data. The CDDIS is operational on a dedicated DEC MicroVAX II computer. All authorized Project investigators, staff, and cooperating institutions have access to the system through the Space Physics Analysis Network (SPAN), INTERNET, BITnet, and the GTE TELENET facilities as well as dial-up telephone lines. The menu-driven system (shown in Figure 6.1.2) provides the user with access to the different parts of the CDDIS, and data retrievals or queries are possible with user friendly interfaces.

In addition to the on-line, menu-driven user view, the CDDIS is tasked to assist the investigator community with their data requirements. These data services of the CDDIS consist primarily of receiving and archiving CDP-related data on magnetic tape and cataloging this data in the CDDIS data base. All data received by the CDDIS from the many contributing global sites must be verified and often reformatted prior to distribution. The CDDIS is then responsible for the dissemination of this data to authorized investigators of the CDP located in the United States and various global institutions. Data can be made available in the form of magnetic tape or floppy disk, network files, or printout listings.



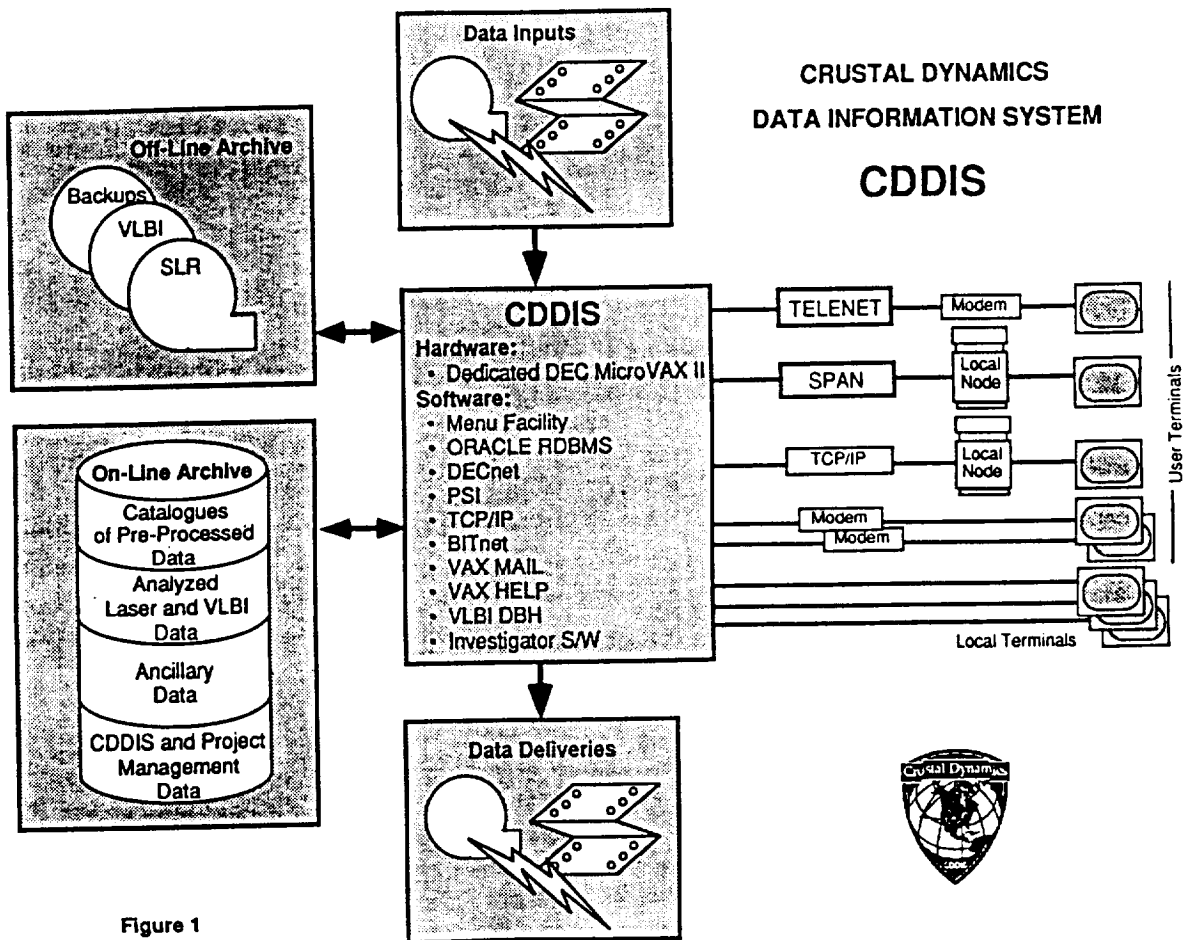


Figure 1

Fig. 6.1.1 Crustal Dynamics Data Information System

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OF POOR QUALITY

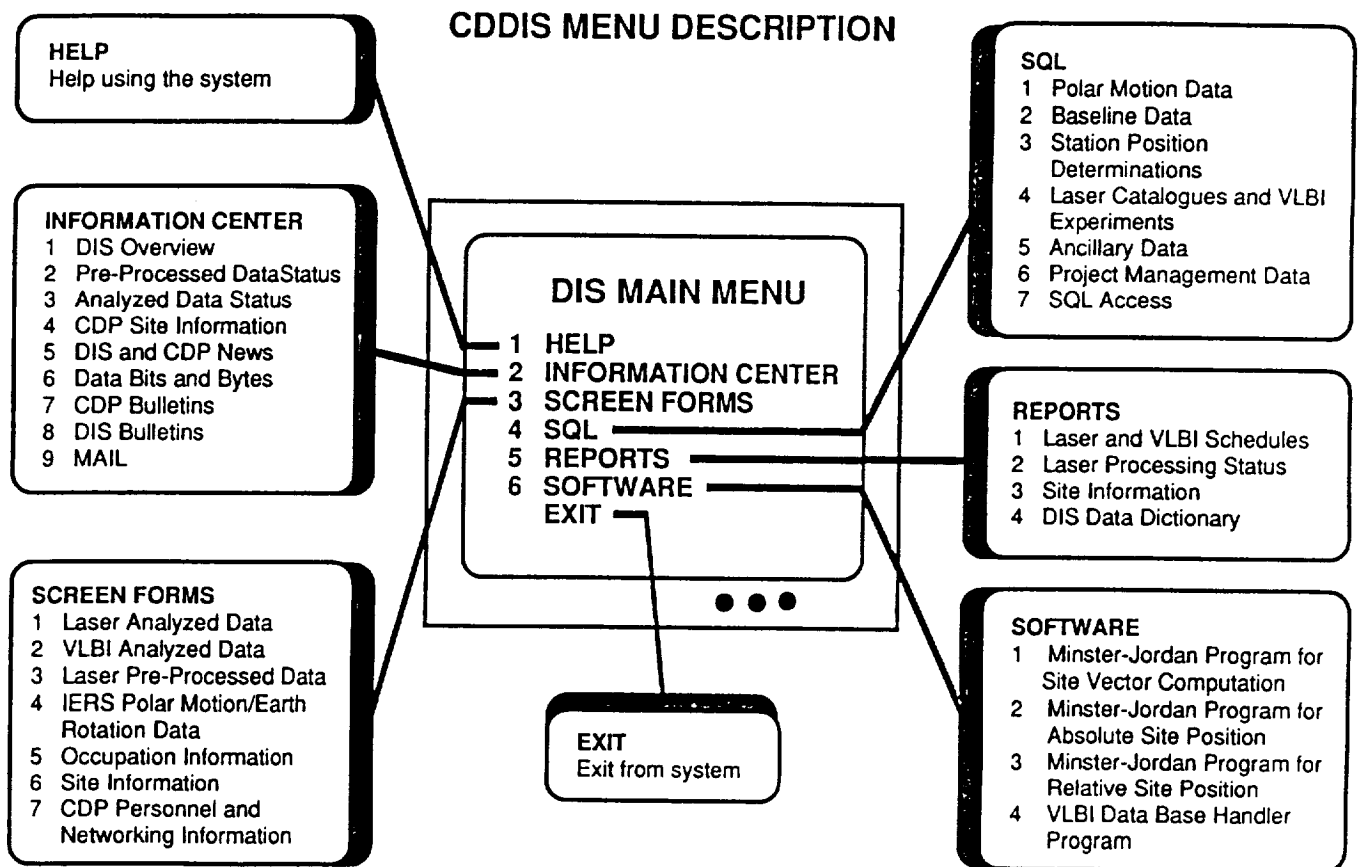


Fig. 6.1.2 CDDIS menu description

*Data Types:* The laser and VLBI data sets accessible through the CDDIS fall into four major categories: preprocessed, analyzed, ancillary, and project management data. Because of data volume, portions of the preprocessed data archive are retained off-line in the CDDIS tape library; catalogues and inventories of this information are stored on-line and are accessible to the user community. All other information, as well as the preprocessed data catalogues, can be accessed through a data base utilizing the ORACLE data base management system (DBMS).

*Preprocessed Data:* The archive of preprocessed laser and raw, correlated VLBI data is retained off-line in the CDDIS tape library. Once these tapes are submitted to the CDDIS from the processing centers, programs are executed to summarize the data and load the information into the CDDIS ORACLE data base. These include catalogues of preprocessed SLR from 1976 through the present, LLR normal and mini-normal point data from 1969 through the present, and VLBI data from 1976 through the present. The VLBI data consists of on-line experiment listings in the data base and a magnetic tape archive of the actual experiment data.

*Analyzed Data:* These include SLR, LLR, VLBI, and combined analyzed results supplied by the Project's Science Support Groups and other analysis centers, and Project investigators at GSFC, JPL, NGS, the University of Texas, and many other global institutions. These analyzed results currently span different periods from 1976 through the present and are accessible through the data base management system. They include precision baseline distances, Earth rotation and polar motion determinations, length-of-day values, and calculated station positions.

*Ancillary Data:* This information includes descriptions of CDP site locations, *a priori* monument coordinates and calibration data, and *a priori* star coordinates. These data sets are contained in the on-line data base.

*Project Management Information:* This category is accessible through the CDDIS data base to authorized Project personnel only and includes mobile system schedules, occupation information, and configuration control information. In addition, CDDIS operational information is kept in the data base and is accessible to CDDIS staff only. These data includes logs of all laser and VLBI tapes received from the many global sources, as well as logs of all tapes created by the CDDIS for outside users and listings of CDDIS back-up tapes.

#### *Data Sources*

*Preprocessed SLR Data:* GLTN SLR data is directly sent to the BFEC data services group for processing, verification, and merging. CFLN (Cooperating Foreign Laser Network) stations supply the Deutsches Geodatisches Forschungsinstitut (DGFI) their data in monthly sets. DGFI merges these European data into a monthly submission that is then delivered to the CDDIS approximately one month following the end of the observation month. Several other SLR stations (e.g., Shanghai, China and Simosato, Japan) send their full-rate data to the CDDIS directly. The CDDIS is responsible for an initial quality check of the data and reporting any problems to the data source. Following verification of the foreign data sets, the CDDIS sends copies of the data to BFEC for inclusion in the earliest possible version of the full-rate SLR

data release. All foreign stations submit their data in the MERIT II SLR format; the final releases from BFEC are also in this format. The CDDIS supplies all SLR data users tapes in MERIT II format. Figure 6.1.3 illustrates the SLR data flow.

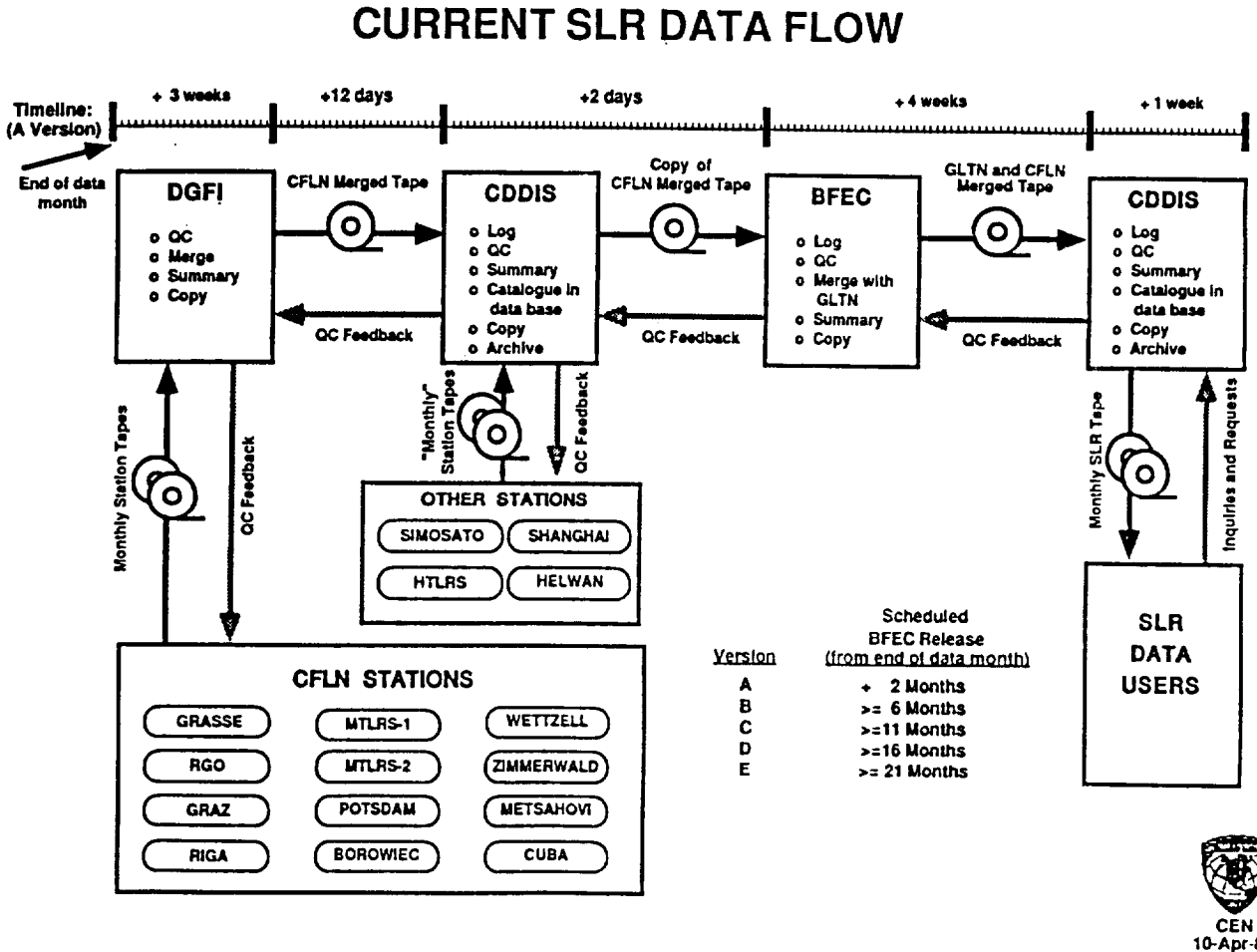


Fig. 6.1.3 Current SLR data flow

The final full-rate SLR data sets are delivered to the CDDIS in monthly increments. The initial, or A, version of a monthly data set is sent 60 days following the end of the observation month. Subsequent versions (e.g., B, C, D, etc.) are delivered four to twelve months later. All versions of the SLR full-rate data sets are archived off-line in the CDDIS tape library and distributed to Project analysis groups within one week of receipt.

Summaries are extracted from each full-rate SLR release. These pass-by-pass listings are loaded into the CDDIS data base for access by any user thus providing information as to the availability of SLR data for stations. Only the latest release is accessible to the general user community in this fashion; for tracking purposes, previous release information can be viewed by the CDDIS staff for tracking purposes.

*Preprocessed LLR Data:* LLR mini-normal points are received in six month intervals from the University of Texas, the University of Hawaii, and CERGA, France. These data are stored on-line in the CDDIS ORACLE data base and accessible to all users. In addition, the University of Texas supplies the monthly data processing reports to the CDDIS. These reports are stored off-line in the CDDIS tape library.

*Preprocessed VLBI Data:* VLBI experiments are currently provided to the CDDIS in Data Base Handler (DBH) format by the GSFC and NGS VLBI analysis groups. Earlier experiments supplied by JPL are also available. Upon receipt, the most recent experiments are downloaded to the CDDIS MicroVAX and are accessible to the user community through the VLBI DBH running within the CDDIS.

*Analyzed Data:* Typically, any analyzed data set supplied to the CDDIS will be loaded into the ORACLE data base for perusal by any authorized user. The time period of these results vary as does the release of updated information to the CDDIS. Table 6.1.2 to this document lists the current analyzed data holdings of the CDDIS.

The type of analyzed data received also varies. Currently, the CDDIS contains base-line, station position, polar motion, and Earth rotation information computed by the SLR and VLBI analysis groups at GSFC, NGS, JPL, the University of Texas, and many other global institutions.

#### *6.1.3.1.2 Pilot Land Data System (PLDS)*

The PLDS is a data and information management system being developed to support land science research in NASA by facilitating the location, retrieval, archiving, and transferring of data by science investigators. The PLDS, sponsored by the Communications and Information Systems Office and the Land Processes Branch of NASA's Office of Space Science and Applications, is a joint project with participation from the GSFC, ARC, and JPL.

The PLDS is distributed between three locations (nodes) at GSFC, ARC, and JPL. Each node is responsible for different types of land data and serves a slightly different scientific discipline. The system is designed around DEC MicroVAX and Sun-4 computer systems (Figures 6.1.4-6.1.6 ) that run the following software: VAX VMS and UNIX operating systems; C, FORTRAN, and MACRO programming languages; ORACLE database management systems; TAE executive for a user interface; and TCP/IP and DECnet communications protocols. The PLDS relies on the NASA Master Directory and the NASA Climate Data Systems (NCDS) for its directory and catalog functions. Connections to other data systems include: NCDS and National Space Science Data Center (NSSDC) at GSFC; SAR Data Catalog System, AVIRIS data processing system, TIMS data processing system, Geologic Remote Sensing Computer System, and Spectral Analysis System at JPL; and the Earth Science Data Directory at USGS.

#### *PLDS Data Types*

The PLDS inventory is a collection of information that describes the various data holdings on-line, in PLDS archives, and in other applicable data systems. Aircraft and

TABLE 6.1.2

CDDIS Data Base Contents Organized by Discipline  
As Of 01-May-89

Disc.	Inst.	Type	Time Coverage	Date Rec.	Comments	Data Base Table Name
SLR	DGFI	Polar Mo	09/83-10/84	02/86	MERIT	PMOTIONM_SLRDGFI
		Position	09/83-10/84	02/86	MERIT	POSITIONSM_SLRDGFI
	DUT	Rotation	01/88- ---	Month	IERS	ROTATIONIERS_SLRDUT
	GAOUA	Polar Mo	09/83-05/84	02/86	MERIT	PMOTIONM_SLRGAOUA
	GRGS	Polar Mo	01/83-10/84	02/86	MERIT	PMOTIONM_SLRGRGS
	GSFC	Baseline	1976-1987	02/89	SL-7.1A	BASELINEyr_SLRGSFC
		Baseline	1979-1988	04/89	SL-7.1A	BASELINEQTr_Yr_SLRGSFC
		Position	1976-1987	02/89	SL-7.1A	POSITIONSyr_SLRGSFC
		Position	1979-1988	04/89	SL-7.1A	POSITIONSQTr_Yr_SLRGSFC
		Position	09/83-10/84	09/85	MERIT	POSITIONSM_SLRGSFC
		Polar Mo	1979-1983	07/85	SL-6	PMOTIONyr_SLRGSFC
		Polar Mo	09/83-10/84	09/85	MERIT	PMOTIONM_SLRGSFC
	Len./Day	09/83-10/84	09/85	MERIT	LENGTHOFDAYM_SLRGSFC	
	NAL	Polar Mo	09/83-10/84	02/86	MERIT	PMOTIONM_SLRNAL
	SHA	Polar Mo	09/83-06/84	02/86	MERIT	PMOTIONM_SLRSHA
UPAD	Polar Mo	09/83-10/84	02/86	MERIT	PMOTIONM_SLRUPAD	
TEXAS	Baseline	03/77-03/84	10/86		BASELINE_SLRTEXAS	
	Position	03/77-03/84	10/86		POSITIONS_SLRTEXAS	
	Position	05/76-12/87	05/88		POSITIONS_SLRCSR	
	Rotation	03/77-03/84	10/86		ROTATION_SLRTEXAS	
	Rotation	05/76-12/87	05/88		ROTATION_SLRCSR	
	Rotation	01/88- ---	Month	IERS	ROTATIONIERS_SLRCSR	
	Polar Mo	1983-1988	Month		PMOTIONyr_SLRTEXAS	
ZIPE	Polar Mo	09/83-10/84	02/86	MERIT	PMOTIONM_SLRZIPE	
LLR	CERGA	Polar Mo	10/83-10/84	05/86	MERIT	PMOTIONM_LLCERGA
		Polar Mo	10/83-10/84	02/86	MERIT	PMOTIONM_LLCERGA
		Rotation	01/88- ---	Month	IERS	ROTATIONIERS_LLCERGA
	JPL	UT1 Val.	04/70-05/82		McDon.	UT1VALUESMCD_LLJPL
		Polar Mo	09/83-10/84	02/86	MERIT	PMOTIONM_LLJPL
		Polar Mo	09/83-10/84	05/86	MERIT	PMOTIONM_LLJPL
		Rotation	07/83-01/86	02/86		ROTATION_LLJPL
		Rotation	09/70-05/82		McDon.	ROTATIONMCD_LLJPL
		Rotation	01/88- ---	Month	IERS	ROTATIONIERS_LLJPL

TABLE 6.1.2 (Continued)

CDDIS Data Base Contents Organized by Discipline  
As Of 01-May-89

Disc.	Inst.	Type	Time Coverage	Date Rec.	Comments	Data Base Table Name
VLBI	CFA	Polar Mo	01/84-10/84	02/86	MERIT	PMOTIONM_VLBICFA
	GSFC	Baseline	08/79-12/88	02/89		BASELINE_VLBIGSFC
		Position	08/79-12/88	02/89		POSITIONS_VLBIGSFC
		Rotation	08/79-12/88	02/89		ROTATION_VLBIGSFC
		Nutation	08/79-12/88	02/89		NUTATION_VLBIGSFC
		Velocity	08/79-12/88	02/89		VELOCITIES_VLBIGSFC
		Polar Mo	09/83-10/84	02/86	MERIT	PMOTIONM_VLBIGSFC
	JPL	Baseline	01/80-10/84	02/86	Mobile	BASELINE_VLBIJPL
		Baseline	---	02/86	DSN	BASELINE_DSN_VLBIJPL
		Position	01/80-10/84	02/86	Mobile	POSITIONS_VLBIJPL
		Polar Mo	01/80-10/84	02/86	Mobile	PMOTION_VLBIJPL
		Polar Mo	09/83-10/84	05/86	MERIT	PMOTIONM_VLBIJPL
		Polar Mo	09/83-10/84	02/86	MERIT	PMOTIONM_VLBIJPL
		Rotation	09/78-08/85	02/86	DSN	ROTATION_DSN_VLBIJPL
		Rotation	01/88- ---	Month	IERS	ROTATION_IERS_VLBIJPL
	NGS	Baseline	06/83-08/86	03/87	Mobile	BASELINE_MV_VLBINGS
		Baseline	---	07/85	IRIS	BASELINE_VLBINGS
		Position	06/83-03/87	06/87	Mobile	POSITIONS_MV_VLBINGS
		Position	10/87-03/87	07/87	Mobile	POSITIONS_MV_UPD_VLBINGS
		Polar Mo	09/80- ---	---	IRIS	PMOTION_VLBINGS
		Polar Mo	09/83-10/84	05/86	MERIT	PMOTIONM_VLBINGS
		Polar Mo	09/83-10/84	02/86	MERIT	PMOTIONM_VLBINGS
		Len./Day	09/80-01/86	05/86	IRIS	LENGTH_OF_DAY_VLBINGS
		Rotation	01/88- ---	Month	IERS	ROTATION_IERS_VLBINGS
	USNO	Polar Mo	09/83-10/84	02/86	MERIT	PMOTIONM_VLBIUSNO
		Polar Mo	09/83-10/84	05/86	MERIT	PMOTIONM_VLBIUSNO
Cir D	BIH	Polar Mo	09/83-10/84	05/86	MERIT	PMOTIONM_CIRBIH
		Polar Mo	08/83-11/84	02/86	MERIT	PMOTIONM_CIRBIH
Comb.	BIH	Polar Mo	08/62-10/86	12/86		PMOTION_BIH
	IERS	Duration	01/88- ---	Month	IERS	DURATION_IERS
		Polar Mo	01/88- ---	Month	IERS	PMOTION_IERS
		Polar Mo	01/88- ---	Month	IERS	PMOTION_DAILY_IERS
	JPL	Chi Val.	01/62-03/87	01/88		CHIVALUESCOMB_JPL
			05/76-03/87	01/88		CHIVALUESSPACE_JPL
		Polar Mo	01/62-03/87	01/88		PMOTIONCOMB_JPL
			05/76-03/87	01/88		PMOTIONSPACE_JPL
			05/76-03/87	01/88		PMOTIONPRIME_JPL
			01/62-03/87	01/88		PMOTIONRATECOMB_JPL
			01/62-03/87	01/88		IATUT1COMB_JPL
	MIT	Rotation	12/68-01/83			ROTATION_MIT

**TABLE 6.1.2 (Continued)**

CDDIS Data Base Contents Organized by Discipline  
As Of 01-May-89

Disc.	Inst.	Type	Time Coverage	Date Rec.	Comments	Data Base Table Name
Dopp.	DMA	Polar Mo	09/83-10/84	05/86	MERIT	PMOTIONMO_DOPPLERDMA
Opt A	BIH	Polar Mo	09/83-10/84	05/86	MERIT	PMOTIONMO_ASTBIH
		Polar Mo	09/83-10/84	02/86	MERIT	PMOTIONM_ASTBIH
	IPMS	Polar Mo	09/83-10/84	05/86	MERIT	PMOTIONMO_ASTIPMS
		Polar Mo	09/83-10/84	02/86	MERIT	PMOTIONM_ASTIPMS



satellite remotely sensed data, as well as ancillary data used to either calibrate or describe in more detail the remotely sensed data are inventoried. Table 6.1-3 below summarized the PLDS data holdings.

Because of the size of individual remote sensing scenes (satellite and aircraft), the actual scientific data are stored off-line in tape archives or are archived in other data systems: only descriptive information regarding these data are stored on-line in PLDS. Smaller data sets such as spectral data and other ancillary data are stored on-line and are accessible directly by users.

### *PLDS Functions*

The overall requirements for the PLDS were developed and compiled from 1984-1986 by a committee of scientists representing the subdisciplines of the Land Processes Branch (Code EEL) of NASA. The system as it exists presently has four basic functions: 1) a directory describing entire data sets (e.g., Landsat TM data) and information regarding the data system holding that data; 2) a catalog which contains text information that defines sensors and the data they produce; 3) a two-level inventory that, at the top level describes all the PLDS data holdings, and at the lower level is specific to and describes in detail the data held at each PLDS node; and 4) a remote computer access and message service. The system is necessarily distributed. Full operations will commence in mid FY90. These basic functions are installed at each PLDS node; however, optional and site-specific functions customized to meet discipline-specific requirements at each node are also available.

The GSFC node (Figure 6.1.4) is responsible for inventorying NASA-owned satellite remote sensing data. Specifically, Landsat MSS and TM, AVHRR, SPOT data, and global products for snow and vegetation are the highest priority data sets. Other data types inventoried are listed in Table 3, and are mostly specific to the International Satellite Land Surface Climatology Project. The FIFE Information System, Image Analysis Facility, NSSDC and NCDS at GSFC are also available through this node. The main user community served by this node are scientists associated with the Hydrology and Remote Sensing Science Programs (Code EEL).

The ARC node (Figure 6.1.5) inventories NS-001 and Deadalus Thematic Mapper Simulator (TMS), Aerial Photographs, and Sun Photometer data. These data sets are acquired by sensors that are operated by and flown on ARC-based NASA aircraft. The user community associated mainly with this node is the Terrestrial Ecosystems Program (Code EEL). Site-specific data and functions are therefore related to the scientific needs of these scientists.

The JPL node (Figures 6.1.6, 6.1.7) main responsibility is inventorying data from aircraft sensors developed and operated by the JPL. These priority data sets include the TIMS, AVIRIS, and SAR systems, as well as satellite and ancillary data (Table 3) needed for calibration of the aircraft data. For example, field and laboratory spectral reflectance data from a variety of instruments. Connections to the SAR Data Catalog System (a catalog and archive system for all SAR Data), the AVIRIS data archive system, the Geologic Remote Sensing Computer System are a few of the systems accessible through the JPL node. The main user community served through this node are scientists associated with the Geology and Remote Sensing Science Programs (Code

EEL). A site-specific function for this node is integration of data analysis and data management capabilities; analysis capabilities include a Spectral Analysis Package for retrieving, analyzing, and plotting spectral data or other X-Y data, and the VICAR image processing package for analysis and display of image data, both used in conjunction with calibration and analysis of the aircraft data.

**TABLE 6.1-3 PLDS DATA HOLDINGS**

Type of Data	ARC	GSFC	JPL
AMS		X	
AVHRR (GAC,LAC)		X	
AVIRIS			X
Botanical Science			X
Digital Elevation Models			X
Geological Science			X
Geographical Science			X
Aerial Photographs	X		
Maps			X
Landsat MSS			X
NERDAS		X	
TMS (NS-001)	X		
SAR (Seasat,SIR,Aircraft)			X
SMMR-TAT		X	
Spectra-FTIR Analect			
Spectra-Beckman			X
Spectra-field			X
Spectra-X-ray diff			X
SPOT (NASA-owned)		X	
Sun Photometer	X		
TIMS			X
Landsat TM		X	X
TMS (Daedalus)	X		
VISSR		X	
SMMR Snowcover		X	
SMMR Polarization			
Differences Index		X	

*Access to PLDS*

The PLDS can be accessed via a variety of methods including direct connection, dial-up modem, or network. Each node of PLDS has several local user terminals that can be used to access the system directly. Once connected, however, PLDS provides the capability to easily change from one node to another. Dial-up modem access to all nodes is available for 300, 1200, and 2400 baud modems and communications software and also for GTE TELENET asynchronous dial-up service: VT-100 terminal emulation software is needed. Access to PLDS via national communications networks is also available including NASA Science Network (NSN) and Space Physics Analysis Net-

work (SPAN) and the major networks connected to them (e.g., NSFnet, ARPAnet, JANET, BITnet, CSNet).

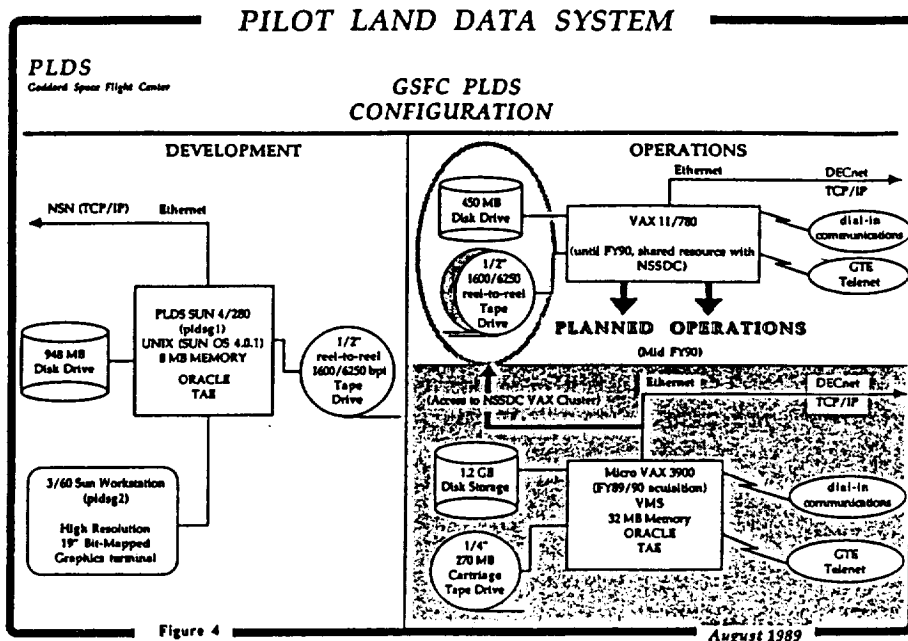


Figure 6.1.4 Pilot Land Data System (PLDS)

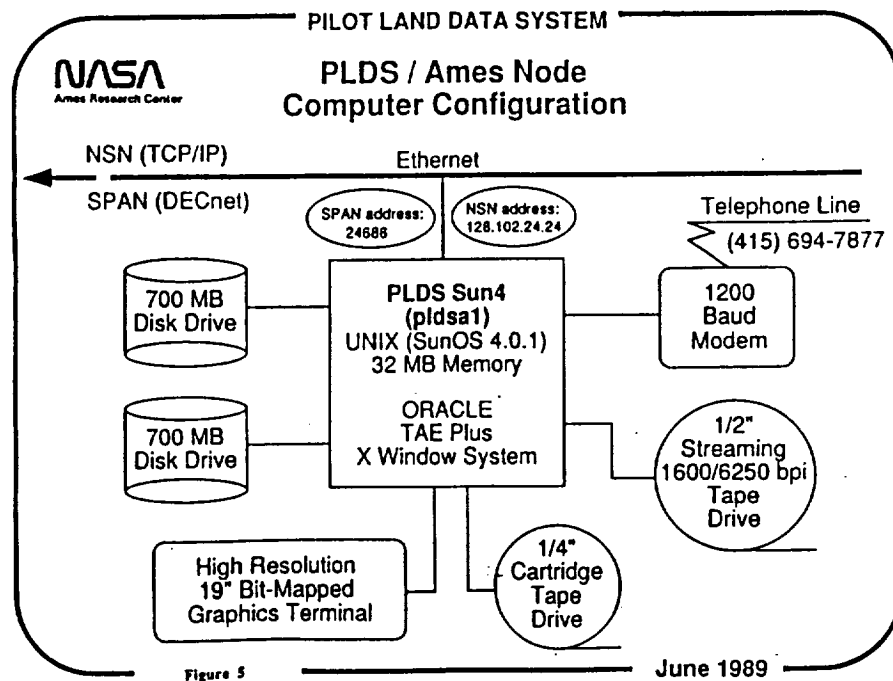


Figure 6.1.5 PLDS/Ames Node Computer Configuration

### *6.1.3.1.3 Other Related Data Systems*

Numerous data systems exist world-wide that support and archive data sets of interest to the SES user community. The SESDIS will establish electronic connections to these remote data systems so that SES scientists can locate and access their relevant data holdings of these various systems. Some of these existing and future systems are detailed in the sections below.

#### *NSSDC*

The National Space Science Data Center (NSSDC) assembles, reprocesses, stores and distributes virtually all data acquired by NASA space and Earth science satellites. These data sets, or information about the data, are accessible through networks such as the Space Physics Analysis Network (SPAN) with speeds currently ranging up to 9.6 k baud. In addition, the NSSDC offers data manipulation, display, graphics and reproduction services to the world's space and Earth sciences community.

#### *NOAA/NESDIS*

The National Oceanic and Atmospheric Administration / National Environmental Satellite, Data, and Information Service (NOAA/NESDIS) is responsible for the development and operation of the nation's civil operational environmental satellites. (GOES and the NOAA series TIROS satellites). In addition, NESDIS manages the nations long term global data bases for meteorology, oceanography, solid Earth physics, and solar-terrestrial sciences. A wide variety of digital and non-digital data come to NOAA's national climatic, oceanographic and geophysical data centers after the original collection purposes have been served.

#### *SDCS*

The SAR Data Catalog System is an interactive computer data base at JPL designed to allow users to determine if SAR data (Seasat, SIR-A, SIR-B, Aircraft SAR) exist for a particular site, and under what conditions they were collected. The system will also transmit digital coverage maps to users with the proper facilities.

#### *EDC*

The EROS Data Center is operated by the United States Geologic Survey, in Sioux Falls South Dakota.

#### *ESDD*

The USGS Earth Science Data Center contains a master directory of all USGS data bases. The USGS Earth Science Data Directory is an interactive computer directory providing referral to and information about Earth science-related data holdings. The data base is composed of descriptions of major data bases which are supported by the U.S. Geological Survey. The system also includes descriptions of data bases which are supported by various individual state agencies.

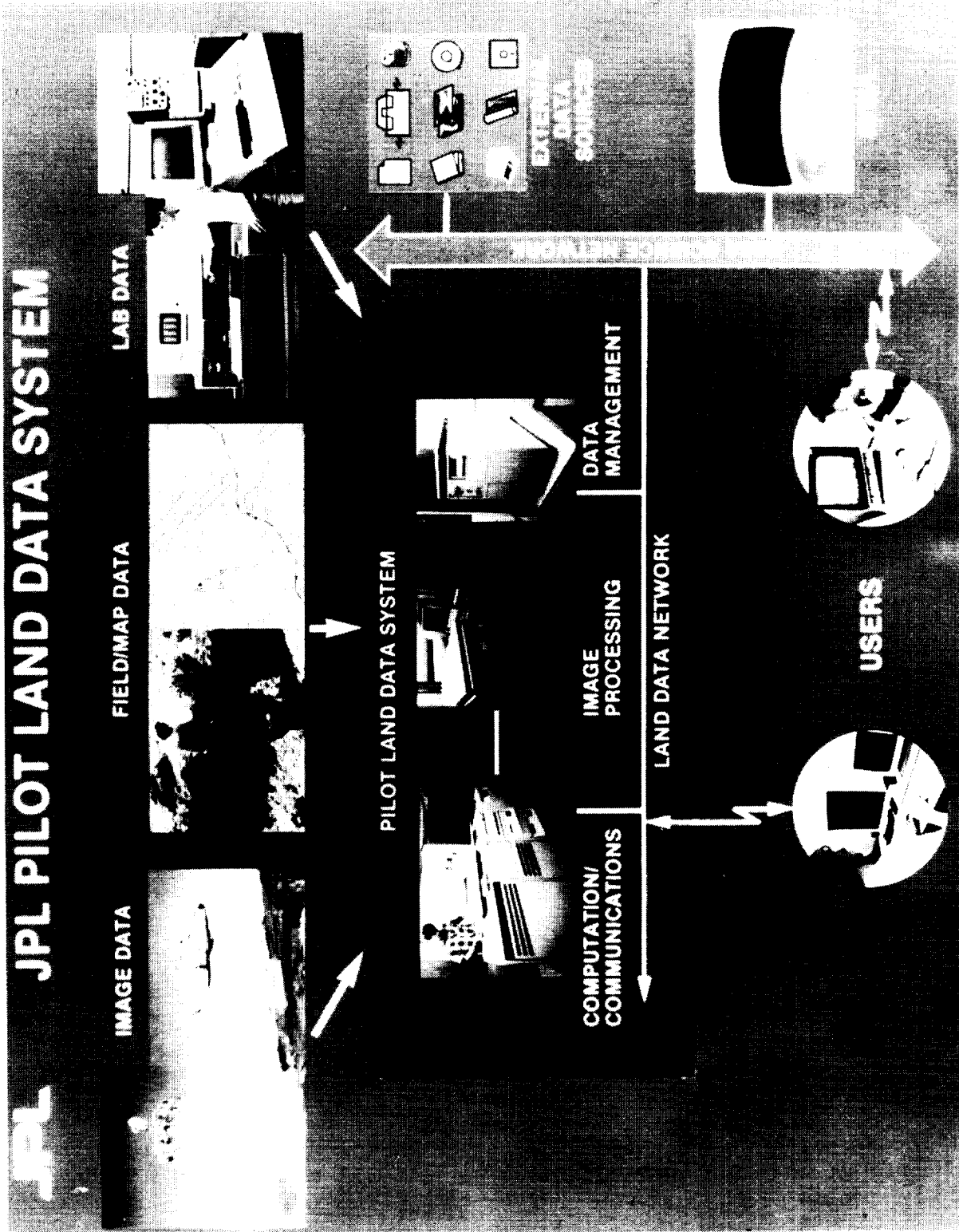
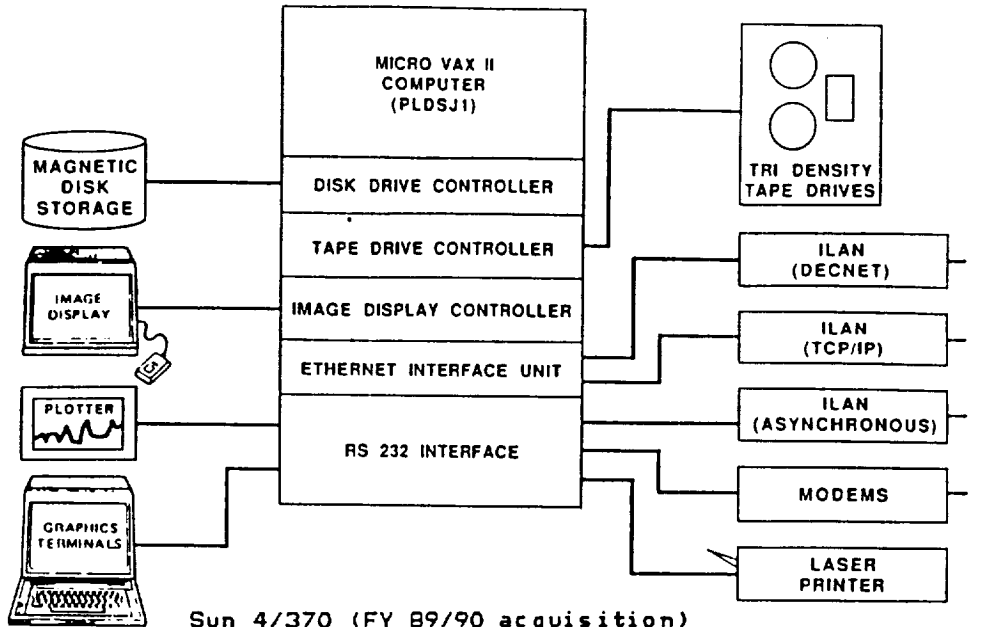


Fig. 6.1.6 JPL Pilot Land Data System

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**JPL**

### PILOT LAND DATA SYSTEM HARDWARE



Sun 4/370 (FY B9/90 acquisition)  
32 MB memory  
981 MB disk storage  
1/4" cartridge tape  
1/2" reel-reel tape  
Laser printer  
TCP/IP, Decnet, Dial-in, LAN communications  
Oracle

**JPL**

### PILOT LAND DATA SYSTEM SOFTWARE

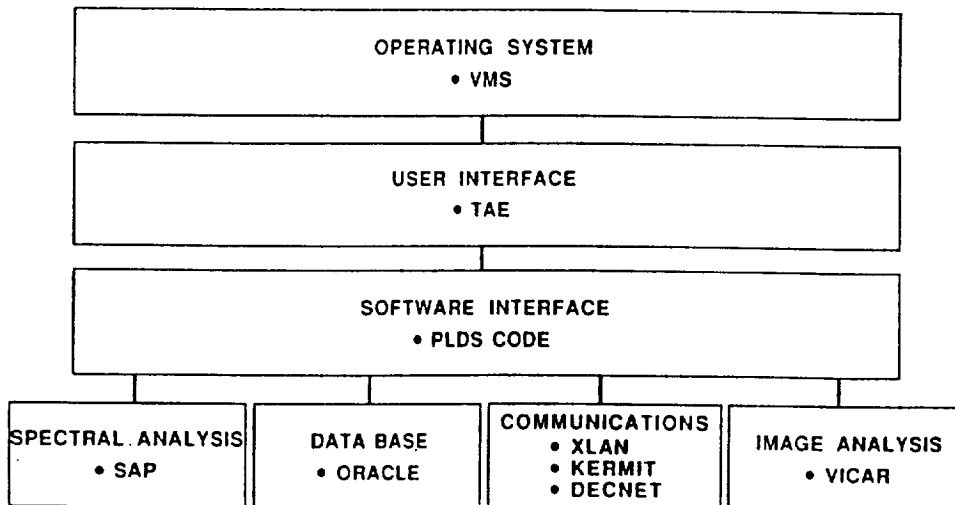


Fig. 6.1.7 Pilot Land Data System hardware

### *NCIC*

The National Cartographic Information Center is a repository of cartographic and topographic data. The NCIC is the map locator service for the USGS. The NCIC collects, sorts, and describes all types of cartographic information from federal, state, and local government agencies and from private companies in the mapping business.

### *NOAA/NGDC*

The National Geophysical Data Center is a repository of a wide variety of Earth science data. Some of the broad categories of data available include marine, solid Earth, solar-terrestrial, and glaciological. Geologic hazards slide sets are also available. Data is available via hard copy publications, maps, and digitally (including magnetic tapes and floppy disks). The NGDC is primarily a products-oriented data base.

### *NODS*

NASA's National Oceans Data System is located at JPL and houses an archive of oceanographic data. It archives and distributes data from spaceborne sensors and in situ measurements relevant to ocean sciences. NODS provides a catalog of data holdings, data at various processing levels, interactive browse files, graphics display of data, and transfer of data via electronic networks, hardcopy, tapes, or optical disks.

### *NCDS*

NASA's National Climate Data System is located at GSFC and is an interactive, on-line climate-related information system. The NCDS provides a data catalog, an inventory, access methods, and manipulation and display tools for Earth, ocean, and atmospheric data. Data which is archived on the system can be compared and studied. The system is also capable of producing sophisticated graphics. Areas of research supported by NCDS include statistical climatology, the International Satellite Cloud Climatology Project (ISSCP), global ozone distribution, Earth Radiation Budget (ERB) studies, continental vegetation indices, and the distribution of gravity/magnetic anomalies.

### *Eos Data Information System (EosDIS)*

The launch for the initial Eos payload is planned for December, 1996. Data produced by the various Eos instruments will be of interest to SES investigators. Therefore, the SESDIS must provide an interface to the EosDIS for data information and retrieval. The functionality of EosDIS must be understood to make this interface effective for the SESDIS user community. As presently envisioned, the EosDIS will be responsible for:

1. Planning, scheduling, and control for the Eos mission and its instruments,
2. Production of standard and special data products,
3. Computational facilities for support of research,
4. Archival and distribution of data, and
5. Communication

The EosDIS is composed of several subsystems, including:

1. Science Data Processing System (SDPS) responsible for:
  - generation of standard products for U.S. Facility and PI instruments on all Eos platforms and payloads
  - active archive for processed data
  - supporting information about all processed and archived data to the scientist including directories, catalogues, inventories, etc.
2. Central Data Handling Facility (CDHF) responsible for:
  - high rate data I/O management and control
  - standard data product production
  - product transfer to DADS
  - algorithm development and support
  - all products are generated using scientist-supplied and validated algorithms
  - data products to be routinely produced are selected by PI oversight committee recommendations
3. Data Archive and Distribution System (DADS) responsible for:
  - on-line data storage and access
  - storage and archiving of all instrument and science study data products, meta data, correlative data, algorithms, and documentation
  - data browse support
  - data distribution to approved Eos users, etc.
  - provide subsetting, averaging, reformatting, and data compaction
4. Information Management Center (IMC) responsible for:
  - single point user interface
  - provide information about data holdings including those in EosDIS and other participating archives
  - accept orders for Eos data
5. Communications system responsible for providing communications between EosDIS elements and other systems/users (e.g., other data centers)

#### 6.1.3.2. Proposed System Architecture

A proposed system architecture for the SESDIS is shown in Figure 6.1.8. Basically, the SESDIS will be equivalent to Discipline Data Systems which exist in NASA today (e.g., PLDS, NCDS, NODS). Connections to long term archives, large data centers, and mission-specific data systems will be provided at a high level so that SES investigators can locate and access relevant data products needed for research. Internally, the SESDIS will consist of two major components, a node responsible for remote sensing data handling and a node responsible for geodetic data handling: the SES disciplines served by these nodes will be principally the Geology- and Geodynamics-related research respectively. These two components will contain all functional capabilities of the SESDIS and will be accessible through a common user interface and communications network. Similarly, SES subdiscipline data processing



centers or specific user sites will have access to the SESDIS through the common user interface and communications network.

#### 6.1.3.3. Implementation Plan Concepts

Based on our current knowledge of the requirements of the data system, we propose a phased implementation of an SESDIS to occur over a several year period. SESDIS will be based on existing data system technology at GSFC and JPL. Initial implementation will be the integration of the CDDIS and the SES-specific portions of PLDS at JPL. These systems will be integrated in FY90 by providing menu items while a common menu structure can be designed in FY91. Connections and interfaces to the ARC and GSFC nodes of the PLDS, which handle other Earth science remote sensing data, will be maintained throughout the SESDIS design and implementation phases of system development. An SWG will be formulated and will meet in FY90 to refine requirements and architecture of the proposed system. Beginning in FY91, connections to other data systems will be established particularly to those holding data sets needed by SES investigators; NASA data systems will be the first priority: SESDIS will take full advantage of existing connections provided by the PLDS and CDDIS. In the near future, the CDDIS should be augmented with an archive of data from NASA sponsored GPS experiments. A long term goal would be the establishment of a third SESDIS node to support geophysics data.

#### 6.1.3.4 Cost Plan

Implementation of the SESDIS will require a four-year phased development period commencing in FY90. Resources required for development are needed for integration of existing data systems (PLDS/JPL and CDDIS) and not development of an entirely new system. Both existing systems must also be maintained operationally until fully integrated into the SESDIS.

#### 6.1.4. Recommendations

Because of the complexity and volume of data needed to meet research objectives in Earth sciences in the coming decade, data systems will be an integral part of the SES program. Therefore, the SESDIS must be designed carefully and planning must commence immediately in order to meet the short- and long-term needs of the SES community. We recommend:

1. Against the development of a new data system or the purchase of new computer systems for an Interactive Data and Information System (IDIS). Rather, it is recommended that existing systems (i.e., CDDIS, and PLDS) be augmented and integrated to support the SES investigation community.
2. Limited scale funding to commence in FY90, at the latest FY91, so that management/implementation planning can begin. During FY91, the actual implementation of the dual system integration should begin.
3. The future funding of PLDS must be decided at the NASA HQ level. It is recommended that the SES assume responsibility for SES-specific data

managed by PLDS. These data sets include spectral and ancillary geologic data required for the interpretation of remotely sensed data. Aircraft and satellite data held in PLDS is useful to all Earth scientists, not simply SES scientists. Therefore, a joint funding of the operational PLDS aircraft-satellite data archives is recommended which would include SES and other appropriate Earth Science and Applications Division programs.

4. Augmentation of CDDIS in FY91 with data resulting in NASA sponsored GPS experiments.
5. Assembling a SES Science Working Group in FY90 to discuss specific data system requirements so that initial phases of the system design and integration and management planning can begin.

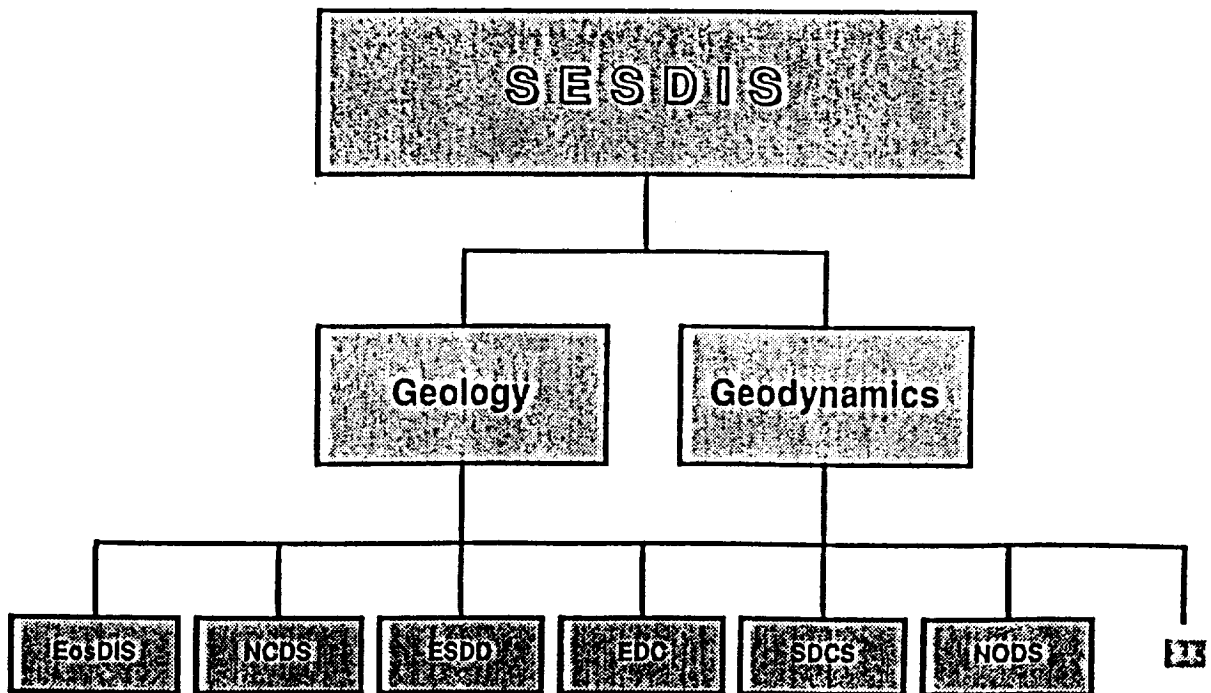


Figure 6.1.8 Proposed SEDIS System Architecture

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## APPENDIX A

### GLOSSARY OF ACRONYMS AND ABBREVIATIONS

ACRE	Advanced Clock Ranging Experiment (USN)
AIS	Advanced Imaging Scanner
A jisai	Satellite with CCRs (Japan)
AlGaAs	Aluminum/Gallium/Arsenic
AMSAT	Amateur Satellite
ARGOS	Data storage and forward channels on European satellites
ARISTOTELES	Applications and Research Involving Space Techniques Observing the Earth's Field from Low Earth Orbiting Satellite
ASF	Alaska SAR Facility
ASI	Agenzia Spaziale Italiana
ATS	Applications Technology Satellite
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible and Infrared Imaging Spectrometer
BFEC	Bendix Field Engineering Corporation
BIH	Bureau International de l'Heure
BMTF	Bundesministerium fur Forschung uad Technologic (FRG)
bps	Bits Per Second
CACTUS	Accelerometer (France)
CALC	GSFC program to CALCulate VLBI theoretical delays
CASA	Central And South America (GPS campaign)
CDDIS	Crustal Dynamics Data Information System
CDP	Crustal Dynamics Project
CfA	Havard Center for Astrophysics
CFLN	Cooperating Foreign Laser Network
CIGNET	Cooperative International GPS Network
cm	Centimeter
CNES	Centre Nationale d'Etudes Spatiales (France)
CNR	Consiglio Nazionale della Ricerche (Italy)
CSTG	Commission for Coordination of Space Techniques for Geodesy and Geodynamics
DGFI	Deutsches Geodatisches Forschungsinsitut (FRG)
DIS	Data Information System
DMA	Defense Mapping Agency (DoD)
DMSP	Defense Meteorological Satellite Program (DoD)
DoD	Department of Defense
DORIS	Radio beacon transmitter (France)
DSGS	Densely Spaced Geodetic Systems
E	Eotvos unit ( $10^{-9} \text{ sec}^{-2}$ )
EDM	Electromagnetic Distance Measurement
EOS	Earth Observing System
EOSAT	Earth Observing Satellite company
EOSDIS	Earth Observing System Data Information System
ERS-1	ESA Remote Sensing Satellite
ESA	European Space Agency

ESA	European Space Agency
ESADS	Earth Science and Applications Data System
ESSC	Earth Science System Committee
Etalon	Satellite with CCRs (USSR)
FICA	Floating-point Integer Character Ascii (GPS data format)
FLINN	Fiducial Laboratory for an International Natural science Network
FRG	Federal Republic of Germany
GAMIT	GPS At MIT (MIT GPS data analysis programs)
GeoBeacon	Satellite based proposed geodetic positioning system
GEOS	Geodynamic Experimental Ocean Satellite
Geosat	Geodetic Satellite with altimeter (USN) Geosat/ERM Geosat/Exact Repeat Mission
GGN	Global Geophysical Networks
GIPSY	GPS Inferred Position System (JPL)
GLONASS	Global Navigation Satellite System (USSR)
GLRS	Geoscience Laser Ranging System
GOES	Geostationary Operational Environmental Satellite
GOS	Geomagnetic Observing System (EOS)
GP-B	Gravity Probe-B
GPS	Global Positioning System
GRADIO	Gravity gradiometer (France)
GRM	Geopotential Research Mission
GSFC	Goddard Space Flight Center
HH	Horizontal-Horizontal polarization
HIRIS	High Resolution Imaging Spectrometer
HMMR	High-Resolution Multifrequency Microwave Radiometer
HV	Horizontal-Vertical polarization
Hz	Hertz (frequency—cycles per second)
IAG	International Association of Geodesy
IAU	International Astronomical Union
ICSU	International Council of Scientific Unions
IDIS	Interactive Data and Information System
IERS	International Earth Rotation Service
IfAG	Institut fur Angewandte Geodaesie (FRG)
IFOV	Instantaneous Field Of View
IFSI	Instituto di Fisica dello Spazio Interplanetario
IR	Infrared
IRIS	International Radio Interferometric Surveying
ISRO	India Space Research Organization
ITIR	Intermediate Thermal Infrared Radiometer
IUGG	International Union for Geodesy and Geodynamics
IUGS	International Union of Geological Sciences
IWG	Investigator's Working Group
JERS	Japanese Earth Remote Sensing satellite
JGR	Journal Geophysical Research
JPL	Jet Propulsion Laboratory
K	Kelvin
Km	Kilometer
LAGEOS-I	Laser Geodynamics Satellite (U.S.)



LAGEOS-II	Laser Geodynamics Satellite (Italy)
Landsat	Land Monitoring Satellite
LASA	Lidar Atmosphere Sounder and Altimeter
LCP	Left Circular Polarization
LEO	Low Earth Orbit
LFC	Large Format Camera
LLR	Lunar Laser Ranging
m	Meter
Magnolia	Magnetic Field Satellite (France)
Magsat	Magnetic Field Satellite (U.S.)
MARISAT	Maritime Satellite
mas	Milliarcsecond
MCP	MultiChannel Plate (photomultiplier)
Medlas	Mediterranean Laser Project (WEGENER)
MERIT	Monitoring Earth Rotation and Intercomparison of Techniques
MFE	Magnetic Field Explorer (U.S.)
mgal	Milligal (10 <sup>-3</sup> cm sec <sup>-2</sup> , approximately 10 <sup>-6</sup> g)
MISR	Multi-angle Imaging Spectro-Radiometer
MIT	Massachusetts Institute of Technology
MLRS	McDonald Laser Ranging Station
μm	Micrometer
mm	Millimeter
MOBLAS	Mobile Laser
MODIS	Moderate Resolution Imaging Spectrometer
MODIS	Moderate resolution Imaging Spectrometer
MOS	Marine Observation Satellite (Japan)
mr	Milliradian
ms	Milli-time-second
MSFC	Marshall Space Flight Center
MSS	MultiSpectral Scanner
MTLRS	Modular Transportable Laser Ranging System
mts	Milli-time-seconds
NASA	National Aeronautics and Space Administration
Nd:YAG	Neodymium:Yttrium/Aluminum/Garnet
NGS	National Geodetic Survey
NIMBUS	Meteorological Satellite (NASA)
nm	Nanometer (10 <sup>-9</sup> m)
NMC	Naval Meteorological Center
NOAA	National Oceanic and Atmospheric Administration
NPOP	NASA Polar Orbiting Platform
NRL	Naval Research Laboratory
ns	Nanosecond (10 <sup>-9</sup> s)
NSF	National Science Foundation
NSSDC	National Space Science Data Center
nT	NanoTesla (10 <sup>-9</sup> T)
OSSA	Office of Space Science and Applications (NASA)
OVO	Orbiting Volcanological Observatory
OVRO	Owens Valley Radio Observatory
PLDS	Pilot Land Data System

POGO	Polar Orbiting Geophysical Observatory
pps	Pulses per second
PRARE	Precise Range and Range-rate Experiment
PRAREE	PRARE Extended Version
PRC	People's Republic of China
ps	Picosecond ( $10^{-12}$ s)
R&D	Research and Development
RCP	Right Circular Polarization
RF	Radio Frequency
rss	Root square sum
SAR	Synthetic Aperture Radar
SBLR	Spaceborne Laser Ranging System
Seasat	Ocean Dynamics Monitoring Satellite
SES	Solid Earth Science
SESDIS	Solid Earth Science Data Information System
SGG	Superconducting Gravity Gradiometer
SGGM	Superconducting Gravity Gradiometer Mission
SIR	Shuttle Imaging Radar
SLR	Satellite Laser Ranging
SOLV3	NOAA VLBI data analysis program (Least squares)
SOLVE	GSFC VLBI data analysis program (Least squares)
SOLVK	Kalman Filter Program (VLBI)
SpinSat	Satellite with altimeter (USN)
SPOT	Systeme Probatori d'Observatoir de la Terre
SQUID	Superconducting QUantum Interference Device
SST	Satellite-Satellite-Tracking
Starlette	Passive laser satellite (France)
Stella	Satellite with CCRs (France)
TDRSS	Tracking and Data Relay Satellite System
TIGER	Thermal Infrared Ground Emission Radiometer
TIIS	Thermal Infrared Imaging Spectrometer
TIMS	Thermal Infrared Multispectral Scanner
TIR	Thermal Infrared
TIU	Time Interval Unit
TLRS	Transportable Laser Ranging System
TM	Thematic Mapper
TOMS	Total Ozone Mapping Spectrometer
TOPEX	Ocean Topography Experiment
TPD	TNO Institute of Applied Physics (Netherlands)
TSWG	Topographic Science Working Group
UNAVCO	University Navstar Consortium
USGS	United States Geological Survey
USNO	United States Naval Observatory
VH	Vertical-Horizontal polarization
VLBI	Very Long Baseline Interferometry
VLSI	Very Large Scale Integrated circuit
VNIR	Visible Near Infrared
VV	Vertical-Vertical polarization

**WEGENER** Working Group of European Geo-Scientists for the Establishment of  
Networks for Earthquake Research  
**WVR** Water Vapor Radiometer







# Report Documentation Page

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16. Abstract <p>This report is contained in three volumes. Volume 1, Program Plan, outlines a plan for solid earth science research for the next decade. Volume 2, Panel Reports, was compiled from papers prepared by the science and program-related panels of a workshop held at Coolfont, W.V., in July 1989. Volume 3, Measurement Techniques and Technology, was prepared to support the science panels.</p> <p>Volume 3 contains reports from the NASA workshop on Solid Earth Science in the 1990s; the techniques and technologies needed to address the program objectives are discussed. The Measurement Technique and Technology Panel identified (1) candidate measurement systems for each of the measurements required for the Solid Earth Science Program that would fall under the NASA purview, (2) the capabilities and limitations of each technique, and (3) the developments necessary for each technique to meet the science panel requirements. In nearly all cases, current technology or a development path with existing technology was identified as capable of meeting the requirements of the science panels. This report discusses these technologies and development paths.</p>					
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