The NASA Crustal Dynamics Project's Use of Satellite Laser Ranging and Lunar Laser Ranging

To Meet its Science Objectives

Pre-CDP History

- in October 1964 Satellite Laser Ranging measurements were made by a team led by GSFC's Dr. Henry Plotkin to Beacon Explorer-B.
- Plotkin reported meter level precision ranges to the satellite-an order of magnitude improvement over contemporary techniques for global measurements of position and distance.
- Predictions of improvements in accuracy by two orders of magnitude were being made by engineers and scientists at Goddard and elsewhere
- NASA gave the go-ahead for retroreflectors on the GEOS I and II spacecrafts and on the Moon. It also expanded the development of SLR stations and the first Lunar Laser Ranging stations.

The Williamstown Conference

- In August 1969, NASA convened a major scientific conference chaired by Dr. William Kaula to explore "What contributions accurate space-derived positions, velocity and acceleration measurements could make to solving problems in solid Earth and ocean physics"

- 69 participants from 48 US universities/institutes; 4 US agencies; and 3 US companies met for the week long meeting

- For SLR, they recommended further technical development to achieve 2 centimeter accuracy systems to monitor at unprecedented levels:
  - Directions with respect to the Inertial reference frame to 0.001 arcsecond accuracy
  - Relative plate motion of the Earth's tectonic plates to infer irregularities
  - Earth's wobble and rotational variations to infer their excitations and dampings.

- NASA's response to Williamstown was to create the NASA Earth and Ocean Physics Application Program (EOPAP) in 1972-the forerunner of CDP

EOPAP Early Laser Pilot Experiments

- NASA EOPAP launched the LAGEOS-1
- NASA EOPAP also established several pilot experiments in SLR and VLBI to:
  - Focus system hardware and software developments
  - Obtain new science results
  - Develop International Cooperation
- The SLR and LLR pilot experiments were:
  - **SAFE** (San Andreas Fault Experiment) SLR campaign to measure North American-Pacific Plate motion across the San Andreas Fault in California
  - **LED** (Laser Earth Dynamics) Refined SLR analysis techniques to determine Lageos orbits, station positions and polar motion. Further developed the GSFC GEODYN set of software programs
  - **LURE** (LUnar Ranging Experiment) Furthered the development of LLR for lunar orbit dynamics, variations in earth rotation rates, and polar motion
  - The first **collocation tests of VLBI, SLR and LLR** were developed to determine systems' biases and accuracies

Development of the Global SLR Network in the 1970s

- The NASA Spaceflight Tracking and Data Network (STDN) had a major role in the development and operation of the early NASA SLR network:
  - MOBLAS 1 and 2 were developed and deployed for GEOS -1 SLR support
  - STDN funded The Smithsonian Astrophysical Observatory for SLR stations in Brazil, Peru and South Africa
  - STDN developed Moblas-3 to support LAGEOS-1
  - STDN built and deployed 5 new stations: MOBLAS 4-8For SEASAT support,

- Many countries participated in the development of SLR.
  - France with the launch of the STARLETTE, D1C AND D1D Retroreflector satellites , lunar retroreflector arrays for the Russian LUNAKHOD missions and development of SLR and LLR stations
  - Netherlands, Germany and Greece developed and operated SLR stations and later MTLRS 1&2
  - Japan began experimental SLR and LLR stations.

- By the end of 1979 there were approximately 20 SLR stations operating world wide

Evolution of SLR from an R&D program to a Project

- Previous to 1979, all NASA work in SLR had been done as an open ended, technology driven activity with long-term goals and constant level funding

- The specific scientific objectives emerging from the consensus of domestic and international scientists, led to the need for a project-like structure with the following attributes:
  - Detailed science objectives
  - Well defined measurement plans for accomplishment of objectives
  - Commitment of funding for the project's life cycle phases
    - Field operations for both fixed and mobile SLR Stations
    - Data Processing, Analysis and Archiving
    - Further development of the SLR technique
    - Development of cooperative agreements with global partners

Formation of the Crustal Dynamics Project

- By 1979, progress in the development of the SLR and VLBI techniques led to a consensus that there could be meaningful progress in measuring contemporary crustal dynamics in a definable period. Scientists were convinced that centimeter accuracies could be achieved in a few years.

- Skillful work by the NASA Headquarters Program Manager, Tom Fischetti and the Program Scientist, Dr. Ted Flinn had brought together a number of US Agencies, International Committees and the world's leading scientists in the field to push NASA and Congress for a concerted effort to take advantage of these techniques for a great leap forward in in this area of Earth Science.

- In the US, an interagency agreement between five major agencies (NOAA, NASA, USGS, NSF, DMA) established a joint program for "The Application of Space Technology to Crustal Dynamics and Earthquake Research"

- Internationally, the IUGG and IAU jointly established Project MERIT (Monitor Earth Rotation and Inter-comparison of Techniques)

- After much deliberation NASA agreed to support these new initiatives by forming the Crustal Dynamics Project

CDP Science Community

- Early in the project, NASA Headquarters issued an Announcement of Opportunity for Crustal Dynamics Research
- Hundreds of proposals were received
- 61 science teams were selected with over 150 investigators from 55 institutions and 16 countries
- A CDP Investigators Working Group made up of the Principal Investigators (PIs) was immediately established which was very active during the life of the project
- GSFC's Dr. Herbert Frey was responsible for coordinating with the PIs to make sure that the CDP measurement program would meet their needs

The Five Scientific Objectives of CDP

1. **Regional deformation** and strain accumulation at the tectonic plate boundary in western North America-San Andreas Fault
2. **Contemporary relative plate motions** of the North American, Pacific, South American, Eurasian, Australian, Nazca, and Caribbean plates
3. **Internal deformation** away from the plate boundaries with emphasis on North America
4. **Polar motion and variations in Earth rotation** and the correlation with earthquakes, plate motion and other phenomena
5. **Crustal motion** and deformation **in other regions** of high earthquake activity

- For success, site velocity measurement accuracy of **1 cm/year** for relative motions over a period of **five years** would be required
- CDP set an SLR **accuracy requirement of 4 cm. and a goal of 1cm** for its SLR systems**.**

Accomplishing CDP Science Objectives
Three Strategies

- **Strategy 1**-Support NASA SLR systems at critical global locations:
  - MOB 5-Yarragadee, Australia
  - MOB-1-Papeete, French Polynesia
  - MOB-6-Mazatlan, Mexico
  - SAO stations at Orroral Valley, Australia, Arequipa, Peru
  - TLRS-1 to Santiago, Chile
  - TLRS-2 to Easter Island, Chile
  - TLRS-3 to prepared sites at Cabo San Lucas and Ensenada, Mexico
  - MLRS at McDonald Observatory, Texas
  - Upgrade of the LURE Station at Mt. Haleakala, Hawaii

- SLR upgrades perfected at MOB-7 and STALAS were quickly migrated to these field stations

Accomplishing CDP Science Objectives
Three Strategies

- **Strategy 2**-Loan NASA SLR systems to International partners for operations to meet common objectives:
  - Upgraded SAO system loaned to Matera, Italy
  - Upgraded MOB-3 loaned to Bar Giyyora, Israel
  - Former USAF and NASA components loaned to Orroral, Australia to create a dual SLR/LLR station
  - Further cooperative efforts with Australia created the NATMAP SLR station at Orroral

Accomplishing CDP Science Objectives
Three Strategies

- **Strategy 3**-Support international partners in the development and operation of their own SLR Systems
  - Promoted open exchange of technology and methods between all groups and set a 1 cm. goal for SLR ranging accuracy
  - SLR technique precision improved by an order of magnitude per decade from 1964 to 1994
  - Global SLR network grew:
    - year 1980--18 stations in 7 countries
    - year 2010--42 stations in 23 countries
  - Supported the multi-year WEGENER-MEDLAS project with European and NASA transportable stations operating in key sites along the Eurasian-African plate boundary
  - In turn, European mobile stations supported US measurement campaigns in the western US and Mexico

International SLR Improvements

- By 1984 the following SLR stations were achieving **sub-decimeter** ranging performance:
  - Simosato, Japan
  - Orroral, Australia
  - Graz, Austria
  - Wettzell, Germany
  - Herstmonceaux, England
  - Zimmerwald, Switzerland
  - Grasse, France
- Grasse LLR also achieved 2cm normal point accuracy

Establishment of the CDDIS (Crustal Dynamics Data Information System)

- CDP required that all the data acquired should be made available to all its participants-national and international
- A CDDIS was quickly established early in the project's life
- Processed and analyzed data can be made available through a number of electronic means
- CDDIS also functioned as a direct means of communications within the project and with all the participants.

CDP Highlights

- CDP existed as a project from 1979 to 1992
- All its science objectives were accomplished in that span
- CDP support to SLR technology brought it from decimeter to sub-centimeter accuracy levels-well beyond expectations
- Retro-equipped satellites grew to over 45 missions
- International coordinated operations grew to over 30 countries in SLR alone
- Many repeat measurement campaigns at prepared sites for regional deformation investigations in active tectonic regions-American West and Mediterranean made new findings
- Several successor programs were created due to its success: DOSE, FLINN network, etc.

The Global Array of SLR/LLR Stations