CONTEMPORARY PLATE MOTIONS
FROM LAGEOS:
A DECADE LATER

BY

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20771

PAPER PRESENTED AT
XXVI COSPAR
TOULOUSE, FRANCE
30 JUNE TO 12 JULY, 1986
SCIENTIFIC OBJECTIVES

RESEARCH IN EARTH SCIENCES MADE POSSIBLE THROUGH VERY PRECISE SATELLITE GEODESY WITH PARTICULAR EMPHASIS ON FURTHERING OUR UNDERSTANDING OF:

- GLOBAL PLATE TECTONICS
- REGIONAL CRUSTAL DEFORMATIONS
- GEODETIC REFERENCE DATUM AND EARTH ORIENTATION
- GEOPOTENTIAL MODELING
- EARTH AND OCEAN TIDES
LAGEOS
(LASER GEODYNAMICS SATELLITE)

LAUNCH: MAY 4, 1976

SPACECRAFT: SPHERICAL, 60 cm DIAMETER
406.965 kg
426 LASER RETRO-REFLECTORS, 3.8 cm DIAMETER

ORBIT: SEMIMAJOR AXIS 12265 KM
INCLINATION 109.8 DEGREES
ECCENTRICITY 0.004
PERIGEE HEIGHT 5858 KM
APOGEE HEIGHT 5958 KM

NODE RATE +0.343 DEG/DAY
PERIGEE RATE -0.214 DEG/DAY
SEMIMAJOR AXIS RATE -1.1 MM/DAY
LAGEOS MISSION OBJECTIVES:

- "RELATIVE TECTONIC PLATE MOTION ON A GLOBAL SCALE TO WITHIN 1.0 CM/YEAR AVERAGED OVER FOUR YEARS;
- MOTIONS ACROSS SELECTED FAULTS TO WITHIN 0.5 CM/YEAR AVERAGED OVER TWO YEARS;
- RELATIVE VERTICAL MOTIONS BETWEEN LOCAL SITES TO WITHIN 2.0 CM/YEAR AVERAGED OVER FOUR YEARS; (and)
- STATION LOCATIONS TO WITHIN 10 CM;" ....

Project Plan
for
Lageos Earth Dynamics
August 1975
DYNAMIC SATELLITE GEODESY

OBSERVABLES: RANGE (PS) (GIVEN SPEED OF LIGHT) AND EPOCH OF MEASUREMENT (T).

RECOVERABLES: ORBIT (OS); STATION POSITIONS (OP); PARAMETERS DEFINING THE FORCE FIELD (INCLUDING GM), EARTH ORIENTATION, ETC.

METHOD: NUMERICAL INTEGRATION OF EQUATIONS OF MOTION OF SATELLITE IN AN INERTIAL COORDINATE SYSTEM.
RESEARCH OBJECTIVES

- **Measurement** of tectonic plate kinematics through the use of satellite geodesy.

- **Comparison** of observed contemporary plate motions with million-year averaged motions predicted from geologic models.

- **Assessment** of the contribution of space geodesy to the further understanding of global and regional tectonic activity.
MEDITERRANEAN SITES

HERST MONCEAUX
KOOTWIJK
WETZELL
GRASSE
ZIMMERWALD
SAN FERNANDO
MATERA
MATMATA
KOYMYVARION
SPARTA
MENGEN
YOZGAT
ULU DAG
DIYARBAKIR
KARAMAN
EMBONA
JERUSALEM
MERSA MATRUH
ASWAN

• FIXED LASER
▲ MOBILE LASER

NASA HQ EE84-1776(1)
7-6-84
EVOLUTION OF THE GFSC SL-6 SOLUTION

SL-4 (1981) 5 YR. SOLUTION

- GRAVITY
  - USED GEM-L2

- TIDES
  - USED MERIT TIDES: WAHR SCHWIDERSKI

- DATA QUALITY
  - USED NORMAL POINTS

- EARTH ROTATION
  - SOLVED FOR: POLAR MOTION A1 - UT1

SL-5 (1983) 6 YR. SOLUTION

- PRECESS/NUTATION
  - USED WAHR

- LOCAL STA. MOTION
  - IMPROVED $h_2 \frac{l_2}{(\text{OCEAN LOADING})}$

- DATA QUALITY
  - IMPROVED NORMAL POINTS LOCATED DATA PROBLEMS

- FORCE MODELS
  - $a \text{ DERIVATIVE}$ (ALBEDO)

SL-6 (1985)
SYSTEM ACCURACY GOAL FOR 1995: 1 mm
GSFC SL-6 GEODETIC SOLUTION

- **REFERENCE FRAME**
  - SL6 TRACKING STATION LOCATIONS
  - LAGEOS EARTH ROTATION AND ORIENTATION (EVERY 5 DAYS)
  - WAHR'S NUTATION SERIES
  - JPL DE-718 PLANETARY EPHEMERIDES: FK4 REFERENCE SYSTEM

- **FORCE MODEL**
  - PGS-1680 GRAVITY FIELD (COMPLETE TO DEGREE AND ORDER 20)
  - LUNI-SOLAR AND PLANETARY GRAVITATIONAL PERTURBATIONS (VENUS THROUGH SATURN)
  - LAGEOS DERIVED GM = 398600.436 km³/s²
  - WAHR'S SOLID EARTH TIDES (o₁, p₁, res₂, k₁, res₁, ψ₁, M₂, S₂, K₂)
  - SCHWIDERSKI OCEAN TIDES. DEGREES 2-3 ADJUSTED, 4-6 FIXED
  - DIRECT SOLAR RADIATION PRESSURE
  - ALONG TRACK ACCELERATION
  - GENERAL AND SPECIAL RELATIVISTIC EFFECTS ARE NOT APPLIED

- **MEASUREMENTS**
  - MARINI-MURRAY TROPOSPHERIC REFRACTION MODEL WITH EXCLUSIVELY SURFACE METEOROLOGICAL MEASUREMENTS
  - VELOCITY OF LIGHT (299792458 M/S)
  - VERTICAL AND HORIZONTAL TIDE DISPLACEMENT (h₂ = 0.60, l₂ = 0.075)
  - NORMAL POINTS (2 MINUTE BINS)

- **DATA SPAN**
  - JANUARY 1979 TO DECEMBER 1984
LAGEOS NORMAL POINT DISTRIBUTION

PTS. (1000s)

YEAR

RMS OF FIT TO ANNUAL SOLUTIONS (CM)
GLOBAL GEODETIC STATION POSITIONS FOR A LASER REFERENCE FRAME

<table>
<thead>
<tr>
<th>TEMPORAL RESOLUTION</th>
<th>ESTIMATED PRECISION</th>
<th>HORIZONTAL</th>
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<tr>
<td>MULTI-YEAR SOLUTION</td>
<td>± 1 cm</td>
<td>± 2 cm</td>
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<tr>
<td>ANNUAL SOLUTION</td>
<td>± 2 cm</td>
<td>± 3 cm</td>
</tr>
<tr>
<td>MONTHLY SOLUTIONS</td>
<td>± 6 cm</td>
<td>± 6 cm</td>
</tr>
</tbody>
</table>
Baseline, Ellipsoidal Chord, Geodesic

Earth's surface

Ellipsoid

Baseline

Geodesic

Ellipsoidal Chord

Laser monument

$\phi, \lambda, h$

$(\phi, \lambda, 0)$
GREENBELT, MD TO MONUMENT PEAK, CA

GEODESIC CHORD 3607003 + M

M-J RATE: 0.016 M/yr

SLOPE: 0.002 +/- 0.017 M/yr

[Map showing two locations with error bars indicating measurements over the years 1975 to 1985.]
GREENBELT, MD TO HAWAII

GEODESIC CHORD 7701094 + M
M-J RATE: 0.017 M/yr

SLOPE: 0.025 +/- 0.012 M/yr

METERS

-0.20 -0.15 -0.10 -0.05 0.00 0.05 0.10 0.15 0.20

75 76 77 78 79 80 81 82 83 84 85

Map showing the geographic locations of Greenbelt, MD and Hawaii.
PLATTEVILLE, CO TO MONUMENT PEAK, CA

GEODESIC CHORD 1321521 + M
M-J RATE: -0.001 M/YR

SLOPE: 0.017 +/- 0.025 M/YR

MAP OF AMERICA WITH MARKERS
YARAGADEE, AUSTRALIA TO GREENBELT, MD

GEODESIC CHORD 18440885 M
M-J RATE: -0.089 M/yr

SLOPE: -0.075 +/- 0.014 M/yr

METERS

75 76 77 78 79 80 81 82 83 84 85

MAP OF THE WORLD WITH POINTS MARKED FOR YARAGADEE AND GREENBELT.
YARAGADEE, AUSTRALIA TO OWENS VALLEY, CA

GEODESIC CHORD 15005222 M

M-J RATE: -0.080 M/yr

SLOPE: -0.058 ± 0.027 M/yr

METERS

75 76 77 78 79 80 81 82 83 84 85
GREENBELT, MD TO AREQUIPA, PERU

GEODESIC CHORD 6167083 + M

M-J RATE: -0.006 M/YR

SLOPE: 0.004 +/- 0.010 M/YR

METERS

0.50
0.75
1.00
1.25

75 76 77 78 79 80 81 82 83 84 85

MAP OF THE WORLD WITH MARKERS
AREQUIPA, PERU TO FORT DAVIS, TX

GEODESIC CHORD 6272179 + m  
M-J RATE: -0.011 m/yr

SLOPE: -0.008 +/- 0.016 m/yr

METERS

-0.20
-0.15
-0.10
-0.05
0.00
0.05
0.10
0.15
0.20


[Map showing geographic locations]
AREQUIPA, PERU TO OWENS VALLEY, CA

GEODESIC CHORD 7704701 + M

M-J RATE: -0.012 M/YR

SLOPE: -0.018 +/- 0.025 M/YR

METERS

75 76 77 78 79 80 81 82 83 84 85
YARAGA DEE, AUSTRALIA TO HAWAII

GEODESTIC CHORD 1D956242 + M

M-J RATE: -D. 103 M/YR

SLOPE: -D. 091 +/- D. 015 M/YR

METERS

75 76 77 78 79 80 81 82 83 84 85
AREQUIPA, PERU TO HAWAII

GEODESIC CHORD 1D126053 + M  M-J RATE: 0.066 M/yr

SLOPE: 0.067 +/- 0.009 M/yr

METERS

75 76 77 78 79 80 81 82 83 84 85

MAP OF THE WORLD WITH A MARKED PATHWAY FROM AREQUIPA TO HAWAII.
AREQUIPA, PERU TO WETTZELL, W. GERMANY

GEODESIC CHORD 10975838 + M
M-J RATE: 0.021 M/yr

SLOPE: 0.024 +/- 0.010 M/yr
YARAGADEE, AUSTRALIA TO AREQUIPA, PERU

GEODESIC CHORD 14915516 + M

M-J RATE: 0.061 M/YR

SLOPE: 0.060 +/- 0.021 M/YR

MAP SHOWING THE LOCATION OF YARAGADEE AND AREQUIPA.
GREENBELT, MD TO OWENS VALLEY, CA

GEODESIC CHORD 3609664 + M

M-J RATE: 0.000 M/YR

SLOPE: -0.004 +/- 0.021 M/YR
PLATTEVILLE, CO TO QUINCY, CA

GEODESIC CHORD 1381231 + M

M-J RATE: 0.000 M/YR

SLOPE: 0.005 +/- 0.021 M/YR

METERS

75 76 77 78 79 80 81 82 83 84 85

MAP OF NORTH AMERICA WITH MARKERS
## COMPARISON OF OBSERVED SLR GLOBAL CHORD RATES WITH THOSE OF MINSTER/JORDAN

1979 to 1984

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<thead>
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<th></th>
<th>SL6</th>
<th>CM/YEAR</th>
<th>M/J</th>
<th>SL6 AVERAGE</th>
<th>M/J</th>
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</table>
- SL6 LASER CHORD RATES
  SLOPE = 0.86, CORRELATION COEFFICIENT = 0.91

- YLBI CHORD RATES
"EXTERNAL" SLR NETWORK

"INTERNAL" SLR NETWORK
## COMPARISON OF GEODESIC RATES FOR EXTERNAL NETWORK STATIONS

<table>
<thead>
<tr>
<th>FROM</th>
<th>TO</th>
<th>SL-6 OBSERVED</th>
<th>MINSTER/JORDAN</th>
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<tbody>
<tr>
<td>GSFC (NA)</td>
<td>AREQ (SA)</td>
<td>-0.9 ±0.4</td>
<td>-0.6</td>
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<tr>
<td>GSFC (NA)</td>
<td>YARG (AUS)</td>
<td>-0.4 ±0.4</td>
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<tr>
<td>AREQ (SA)</td>
<td>YARG (AUS)</td>
<td>0.4 ±0.4</td>
<td>0.2</td>
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</table>
ABSOLUTE MOTIONS

GSFC

OWENS

COMPRESSON

AREQUIPA

VARG
Internal/Internal Case

\[ x_1 \cos(\alpha_{x1} - \alpha_{12}) \]

External/Internal Case

The \( C_i \) represent the component of the internal station's absolute motion in the direction of external station \( i \).
### COMPARISON OF ABSOLUTE STATION MOTIONS

<table>
<thead>
<tr>
<th>STATION (yrs of obs.)</th>
<th>PLATE</th>
<th>RATE</th>
<th>AZIMUTH</th>
<th>MINSTER/ JORDAN</th>
<th>SL - 6</th>
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<td>NA</td>
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<td>MON. PK. (5)</td>
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</tr>
<tr>
<td>OWENS (3)</td>
<td>NA</td>
<td>2.5</td>
<td>236</td>
<td></td>
<td>4.5</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>175 (w)</td>
</tr>
<tr>
<td>MAZAT. (3)</td>
<td>NA</td>
<td>2.7</td>
<td>241</td>
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<td>4.7</td>
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</tbody>
</table>

#### KEY:

- : WELL DETERMINED STATION DIFFERING FROM M/J PREDICTION.
- : MODERATELY WELL DETERMINED STATION DIFFERING FROM M/J.
- (w) : WEAKLY DETERMINED STATION.
"INTERNAL" SLR NETWORK
"ABSOLUTE" VELOCITY VECTORS (cm/yr)
SAFE: MONUMENT PEAK TO QUINCY, 1981 to 1984
USING SHORT ARC TECHNIQUE

SLOPE:  
1982 - 1984: -2.14 cm/yr
1981 - 1984: -2.56 cm/yr

RMS:
1.21 cm
1.39 cm
OBSERVED ABSOLUTE MOTIONS
FOR N. AMER./PACIFIC SITES

LASER SL - 6 SOLUTION VS. MINSTER/JORDAN AM1-2
LAGEOS-I OBSERVATIONS HAVE BEEN OBTAINED AND ANALYSED FOR TEN YEARS

CURRENT SCIENTIFIC ACCOMPLISHMENTS

- GLOBAL TECTONIC MOTIONS HAVE BEEN OBSERVED.

- REGIONAL MOTIONS LIKE THOSE FOUND ALONG THE SAN ANDREAS FAULT IN CALIFORNIA HAVE BEEN EXTENSIVELY MONITORED.

- POLAR MOTION ACCURATE TO 1–2 masec AND LOD ACCURATE TO 0.1 msec ARE BEING MEASURED.

- FORCE MODEL IMPROVEMENTS HAVE BEEN ACHIEVED.
SLR IN THE 1990's

GLOBAL DISTRIBUTION

- Permanent Occupations
- Regular Re-occupations
- Local Networks

SYSTEM IMPROVEMENTS

- Improved Systems Accuracy \(\leq 5\) mm.
- Improved Models
- Compact Systems
- Full Automation
- Cost Reduction

LASER SATELLITES

- LAGEOS II
- POPSAT
- EGP (JAPAN)
SLR PRODUCTS IN THE 1990's

Positioning
- Altimetric Missions
- Global Datums
- Tectonic Motion
- Plate Deformation

Earth Orientation
- Polar Motion Frequency Structure
- Polar Wander
- Earthquake Excitation
- Atmospheric Excitation

Earth Orientation
- P. Motion < 0.6 msec
- LOD < 0.03 msec

Geopotential
- Rheology - Post Glacial Response
- Mantle Convection
- Polar Wander
- Ice Loading
- Mission Support (Altimetry, Navigation)
- Gravitational Constant

Surface Forces
- Albedo
- Drag

Earth and Ocean Tides
- Tidal Dissipation
- Earth Moon Separation
- Zonal Tides and Departure from Equilibrium
- Improved Length of Day
- 18.6 yr. Tide for Q at Intermediate Frequencies
- Core-Mantle Resonances (K1 Tide)
- Love Numbers of Load Tides