FROM OPTICAL TRACKING TO LASER TRACKING
The early years of Satellite Geodesy

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GEODESY WITHOUT SATELLITES
20,842 days B.P.

SITUATION
- No Global Reference Frame – National Datums (ED 50)
- Triangulation Networks (horizontal angles + base lines)
- Elevations from MSL (leveling lines)
- Gravity (gravimeter measurements along lines)

PROBLEMS
- Limited distance between triangulation points (mutual visibility)
- No direct 3D solution
- Defection of the vertical
- Atmospheric refraction (vertical angles)
- Important field work (manpower + time = cost)

ATTEMPTS
- Use of balloons and/or rockets for triangulation
- Use of the moon (solar eclipses, star occultations by the moon)
- Use of airplanes (Aerotriangulation, LORAN, DECCA, HIRAN)

SOLUTION
- Possible use of future artificial satellites (IGY 1957-1958)
OBSERVATIONS OF THE MOON

SOLAR ECCLIPSE

MARKOWITZ MOON CAMERA
HOW CAN WE USE SATELLITES FOR GEODESY

A. FOR STATION POSITIONS

1. In a geometric method
   Observing the direction and/or range of a satellite simultaneously from two or more stations.

2. In a dynamic method
   Observing the direction and/or range of a satellite at any known time (Requires knowledge of the ephemeris)

B. FOR GRAVITY

Analyzing the perturbations of the orbit due to the earth’s gravity field

NOTE: The orbit is crucial. In order to determine the orbit you have to know the stations’ positions. And vice versa!
By photographing the successive positions of a satellite in its orbit from strategically placed camera sites a network of relatively few triangles can be established covering a whole continent.
October 4th, 1957: SPUTNIK was launched. It was a surprise.

International Geophysical Year (IGY), 1957-1958. Planning of artificial satellites was envisioned.

SAO was assigned to develop and operate an optical tracking system (B/N)

NRL was assigned to develop and operate an electronic tracking system (Minitrack)

COSPAR established by ICSU, 1958

NASA created, 1958

CNES established, 1961

IAG-IUGG created study groups, Helsinki, 1960

created Section “Space Technics”, Moscow, 1971

Space research and exploration, became a major interdisciplinary enterprise

in a frame of international cooperation – ILRS is a good example
### FIRST OBSERVATIONS OF SATELLITES from Day Zero, 36116 MJD

#### OPTICAL TRACKING
- Naked eye
- Binoculars and small telescopes
- Theodolites
- Fixed and Tracking Cameras
- B/N camera

#### ELECTRONIC TRACKING
- Radar (range, passive)
- Minitrack (directions-interferometry)

Followed by new observing techniques

<table>
<thead>
<tr>
<th>Year</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960</td>
<td>TRANSIT doppler (frequency shift hyperbolic system)</td>
</tr>
<tr>
<td>1962</td>
<td>SECOR (Sequential Collation of Range)</td>
</tr>
<tr>
<td>1964</td>
<td>Laser Ranging</td>
</tr>
<tr>
<td>Code number</td>
<td>Optical observations</td>
</tr>
<tr>
<td>------------</td>
<td>--------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>0</td>
<td>Naked eye and binoculars, visual.</td>
</tr>
<tr>
<td>1</td>
<td>Standard Moonwatch telescope, visual.</td>
</tr>
<tr>
<td>2</td>
<td>Apogee telescope, astronomical refractor or reflector, theodolite, visual.</td>
</tr>
<tr>
<td>3</td>
<td>Baker-Nunn camera, photographic.</td>
</tr>
<tr>
<td>4</td>
<td>Small missile telecamera, tracking cameras with focal length 20 inches or greater, photographic.</td>
</tr>
<tr>
<td>5</td>
<td>Cinetheodolite, tracking cameras with focal length less than 20 inches, photographic.</td>
</tr>
<tr>
<td>6</td>
<td>Harvard meteor camera (Super-Schmidt), photographic.</td>
</tr>
<tr>
<td>7</td>
<td>Stationary telescope or camera with focal length equal to or less than 10 inches, photographic.</td>
</tr>
<tr>
<td>8</td>
<td>Stationary telescope or camera with focal length greater than 10 inches, photographic.</td>
</tr>
<tr>
<td>9</td>
<td>Other instruments, or instrument unknown.</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
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</tr>
</tbody>
</table>
FIRST OBSERVATIONS OF SATELLITES

Minitrack

Moonwatch team

Cinetheodolite

EARLY PREDICTIONS - VISIBILITY MAPS

Based on approximate orbits for use by the general public (newspapers, networks), distributed by Associated Press.
OPTICAL TRACKING*

B/N Camera 1957

K-37 Camera 1959

BC-4 Camera 1962

* Limited visibility is a problem
Fig. 4—Smithsonian Astrophysical Observatory network of photographic satellite-tracking stations
PHOTOREDUCTION

B/N Film

PHOTOGONIOMETER

DIGITAL COMPARATOR

SAO STAR CATALOG (258.997 stars)
VERY FIRST SCIENTIFIC RESULTS
Based on crude observation

Within a few months:

- New flattening of the earth (0.4%)
- Upper atmosphere densities (x5)
- Existence of the Van Allen radiation belt
- Existence of solar wind

Followed by:

- The pear-shaped earth
- First new station coordinates
<table>
<thead>
<tr>
<th>SATELLITE</th>
<th>YEAR</th>
<th>TRACKING METHOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sputnik</td>
<td>1957</td>
<td>Optical, interferometry</td>
</tr>
<tr>
<td>Explorer</td>
<td>1958</td>
<td>Optical, ...</td>
</tr>
<tr>
<td>Anything in orbit</td>
<td>1957</td>
<td>Optical, RADAR</td>
</tr>
<tr>
<td>TRANSIT</td>
<td>1960</td>
<td>Radio Doppler shift</td>
</tr>
<tr>
<td>ECHO</td>
<td>1960</td>
<td>Optical</td>
</tr>
<tr>
<td>ANNA</td>
<td>1962</td>
<td>Doppler, optical (flashing), R+R/R</td>
</tr>
<tr>
<td>BEB</td>
<td>1964</td>
<td>Laser ranging – (first corner cubes)</td>
</tr>
<tr>
<td>GEOS (1, 2, 3)</td>
<td>1965</td>
<td>Optical, laser ranging, R+R/R</td>
</tr>
<tr>
<td>STARLETTE</td>
<td>1965</td>
<td>Dedicated for laser ranging</td>
</tr>
<tr>
<td>LAGEOS</td>
<td>1966</td>
<td></td>
</tr>
</tbody>
</table>

EARLY GEODETIC SATELITES

- ECHO (1960)
- TRANSIT (1960)
- GEOS 1 (1965)
- ANNA (1962)
- LAGEOS (1966)
ORBITS & EPHEMERIDES

ORBITS (orbital elements + perturbations)

OBSERVATIONS

EPHEMERIDES (predictions)

CELESTIAL MECHANICS
(expansion into series)

COMPUTER ALGEBRA

NUMERICAL INTEGRATION

DIFFERENTIAL ORBIT IMPROVEMENT
(geodetic approach)

ANALYSIS + RESULTS
(coordinates + gravity)
lational radius \( m = GM/c^2 \), eqs. (37) to (40) become
\[
y'_{ij} = -\frac{4m}{r} \left( \frac{\Omega R}{c} \right)^2 \sum_{n=0}^{\infty} \left[ \frac{J_n}{(n+2)!} L_n \left( \frac{R}{r} \right)^n P_n^2(\sin \phi) \cos 2\theta \right].
\]

Taking only the terms up to \( n = 2 \), the components of the fundamental tensor are
\[
g_{11} = -1 - 2m/r \left[ 1 - \sum_{n=0}^{\infty} \frac{J_n}{(n+2)!} L_n \left( \frac{R}{r} \right)^n P_n(\sin \phi) \right] + \left( \frac{\Omega R}{c} \right)^2 \sum_{n=0}^{\infty} \frac{J_n}{(n+2)!} L_n \left( \frac{R}{r} \right)^n P_n^2(\sin \phi) \cos 2\theta.
\]

In order to have a spherically symmetric field the very small terms proportional to \( m/r \) and \( (\Omega R/c)^2 \) will be neglected. In \( g_{44} \) only, the term will be retained and the second-order term
\[
2m/r \left[ 1 - 2J_n(\frac{R}{r})^n P_n(\sin \phi) \right]
\]
will be added according to de Sitter (eq. 29). The reason why \( g_{44} \) is required
### EARLY GEODETIC RESULTS

#### Station Coordinates (1961)

<table>
<thead>
<tr>
<th>Station</th>
<th>$x^1$</th>
<th>$x^2$</th>
<th>$x^3$</th>
<th>Number of observations</th>
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</thead>
<tbody>
<tr>
<td>9001 Organ Pass</td>
<td>-1.535713</td>
<td>-5.157030</td>
<td>3.401099</td>
<td>±15</td>
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<tr>
<td>9002 Olfantfontein</td>
<td>+5.056137</td>
<td>+2.716534</td>
<td>-2.775806</td>
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<td>9003 Woomera</td>
<td>-3.563618</td>
<td>+3.743212</td>
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<td>9004 San Fernando</td>
<td>+5.105602</td>
<td>-0.555230</td>
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<td>9005 Tokyo</td>
<td>-3.945653</td>
<td>+3.366400</td>
<td>3.698678</td>
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<tr>
<td>9006 Malei Tal</td>
<td>+1.018190</td>
<td>+3.471770</td>
<td>3.109601</td>
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<tr>
<td>9007 Arequipa</td>
<td>+1.942755</td>
<td>-5.804100</td>
<td>-1.796895</td>
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<tr>
<td>9008 Shiraz</td>
<td>+3.376916</td>
<td>+4.404028</td>
<td>-3.136311</td>
<td>20</td>
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<tr>
<td>9009 Curacao</td>
<td>+2.251790</td>
<td>-5.816950</td>
<td>1.327212</td>
<td>10</td>
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<tr>
<td>9010 Jupiter</td>
<td>+0.976314</td>
<td>-5.601416</td>
<td>2.806501</td>
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<td>9011 Villa Dolores</td>
<td>+2.286624</td>
<td>-1.924540</td>
<td>-3.55451</td>
<td>12</td>
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<tr>
<td>9012 Maui</td>
<td>-5.466100</td>
<td>-2.404157</td>
<td>2.242555</td>
<td>22</td>
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</tbody>
</table>

#### Gravity field (1962)

### Table 5

<table>
<thead>
<tr>
<th>Source</th>
<th>$J_3 \times 10^6$</th>
<th>$J_4 \times 10^6$</th>
<th>$J_5 \times 10^6$</th>
<th>$J_6 \times 10^6$</th>
<th>$J_7 \times 10^6$</th>
<th>$J_8 \times 10^6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[6]</td>
<td>1082.79 ± 0.15</td>
<td>-1.40 ± 0.20</td>
<td>-0.23 ± 0.30</td>
<td>0.90 ± 0.80</td>
<td>-0.47 ± 0.12</td>
<td>0.12 ± 0.01</td>
</tr>
<tr>
<td>[4]</td>
<td>1082.21 ± 0.04</td>
<td>-2.29 ± 0.03</td>
<td>-2.10 ± 0.06</td>
<td>-0.23 ± 0.03</td>
<td>0.39 ± 0.01</td>
<td>-0.47 ± 0.27</td>
</tr>
<tr>
<td>[15]</td>
<td>1082.48 ± 0.04</td>
<td>-2.56 ± 0.01</td>
<td>-1.84 ± 0.09</td>
<td>0.01 ± 0.07</td>
<td>-0.22 ± 0.09</td>
<td>-0.47 ± 0.02</td>
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<tr>
<td>[17]</td>
<td>1082.49 ± 0.06</td>
<td>-2.39 ± 0.26</td>
<td>-1.70 ± 0.06</td>
<td>0.73 ± 0.08</td>
<td>-0.05 ± 0.10</td>
<td>0.12 ± 0.01</td>
</tr>
<tr>
<td>[5]</td>
<td>1082.61 ± 0.05</td>
<td>-2.90 ± 0.18</td>
<td>-1.52 ± 0.08</td>
<td>0.73 ± 0.10</td>
<td>-0.05 ± 0.15</td>
<td>0.73 ± 0.06</td>
</tr>
<tr>
<td>[11]</td>
<td>1083.15 ± 0.7</td>
<td>-2.37 ± 0.30</td>
<td>-1.40 ± 0.05</td>
<td>0.73 ± 0.10</td>
<td>-0.05 ± 0.15</td>
<td>0.73 ± 0.06</td>
</tr>
<tr>
<td>[13]</td>
<td>1083.3 ± 0.2</td>
<td>-2.20 ± 0.30</td>
<td>-0.70 ± 0.15</td>
<td>0.73 ± 0.10</td>
<td>-0.05 ± 0.15</td>
<td>0.73 ± 0.06</td>
</tr>
<tr>
<td>[14.18]</td>
<td>1083.3 ± 0.18</td>
<td>-2.20 ± 0.30</td>
<td>-0.70 ± 0.15</td>
<td>0.73 ± 0.10</td>
<td>-0.05 ± 0.15</td>
<td>0.73 ± 0.06</td>
</tr>
</tbody>
</table>
SAO STANDARD EARTH (686 pages!)

To establish an Earth model using all available data in mid 60’s

- Gave coordinates in a global geodetic reference system for 19 well distributed stations with an accuracy of 10-15m, with a reference ellipsoid of \( a=63781650, 1/f=298.25 \).

- Gave the gravity field of the earth expressed in 67 spherical harmonic coefficients.

- Time: In Atomic Time.

- Scale: Defined by the adopted value of GM (recommended by IAU and COSPAR)

- Orientation the earth in the celestial system: Based on IPMS data for the pole and BIH for UT1-A1, and for the coordinates of the stars from the SAO Star Catalogue.
Standard Earth was the work of many people and several authors, including visiting scientists from other agencies and different countries.

F.L. Whipple initiated the endeavor and followed it to the end.

It took more than a year to complete in a spirit of interdisciplinarity and international cooperation.

It was followed by Standard Earth II (1970) and Standard Earth III (1973) as well as other Earth Models (GEM-GSFC, GRIM-Toulouse+Munich, ...)

IERS is now responsible for coordinating, on a routine basis and on a much larger scale and complexity, what started as a project.
THE LASER RANGING SYSTEM

• Since 1950 the Geodimeter has been measuring ground distances
• Laser Ranging started in 1964
• It is the most direct way of measuring distance (Eratosthenes used it also)
• The accuracy is extremely high since the unit of length is by definition the velocity of light (since 1969!)
• Directly-measured and accurate (to 1-2cm) ranges were needed in order to improve operations of satellite geodesy, in order to provide the needed scale to the earth models and to the Reference System
• The quality of laser ranging is continually improving
• No doubt it is the most accurate tracking system
LASER RANGING FROM DIONYSOS

Laser No 1
(1967)

Laser No 2
(1968)

Laser No 3
(1973)