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)

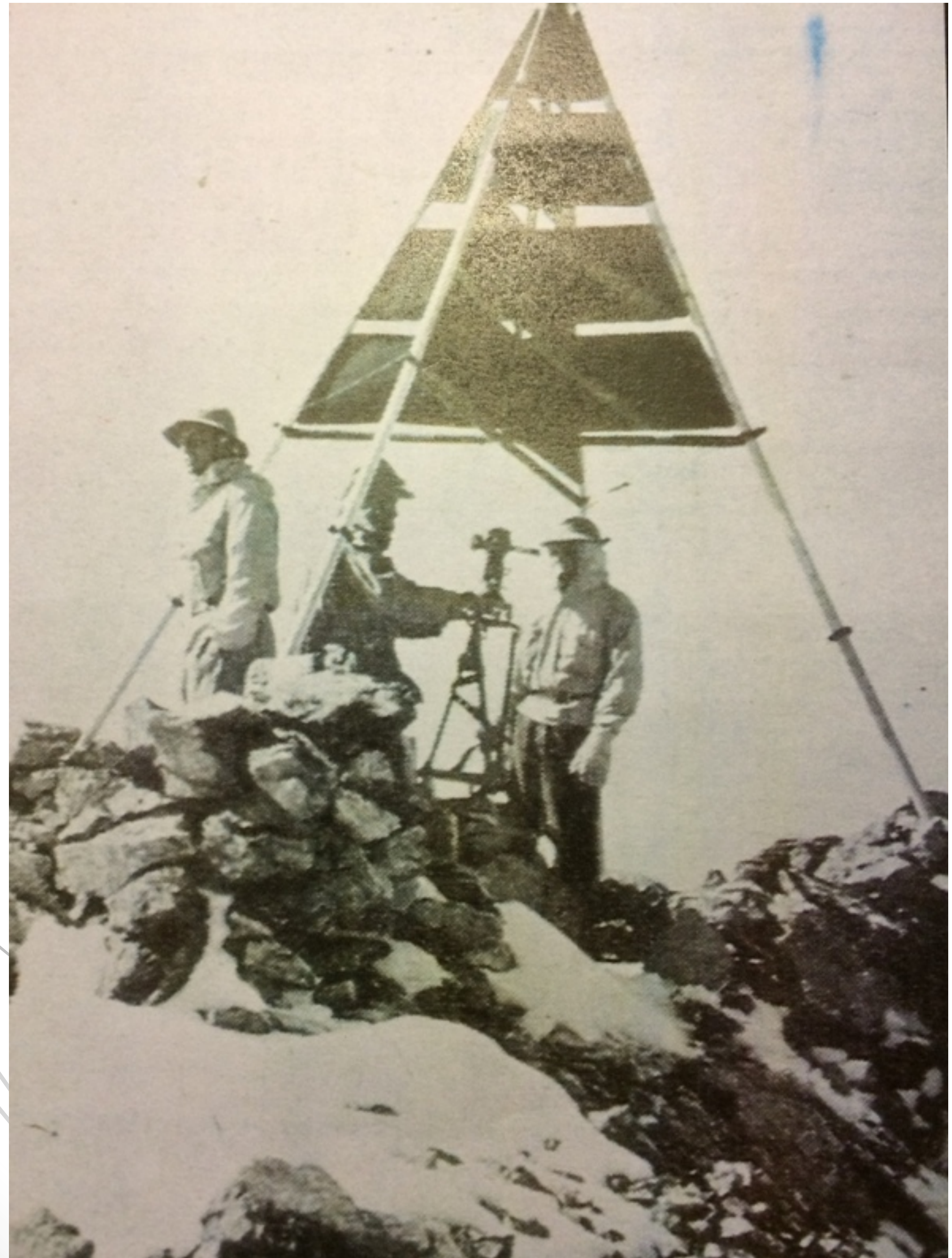
SOLUTION

- Possible use of future artificial satellites (IGY 1957-1958)

OBSERVATIONS OF THE MOON

SOLAR ECCLIPSE

MARKOWITZ MOON CAMERA



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

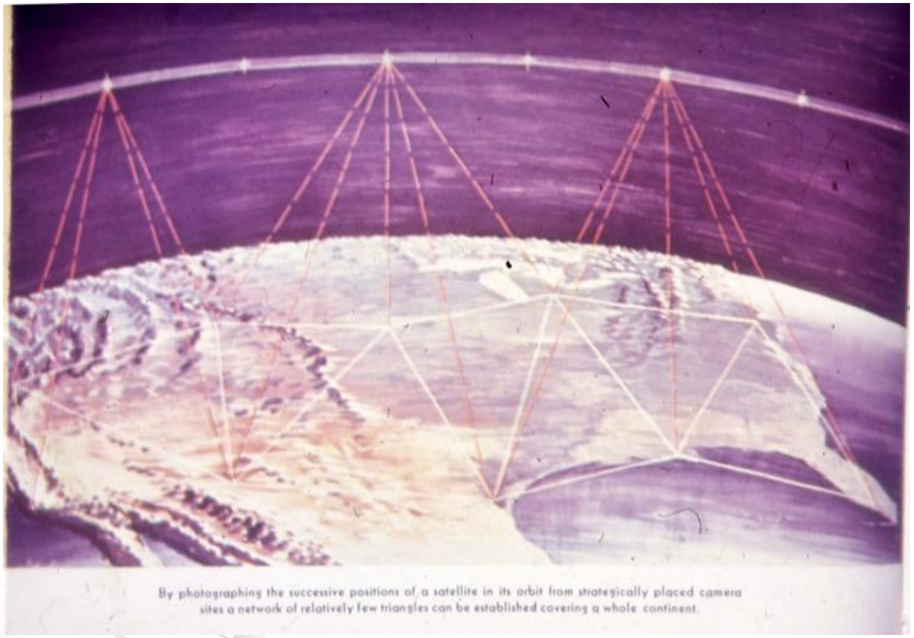
(Requires knowledge of the ephemeris)

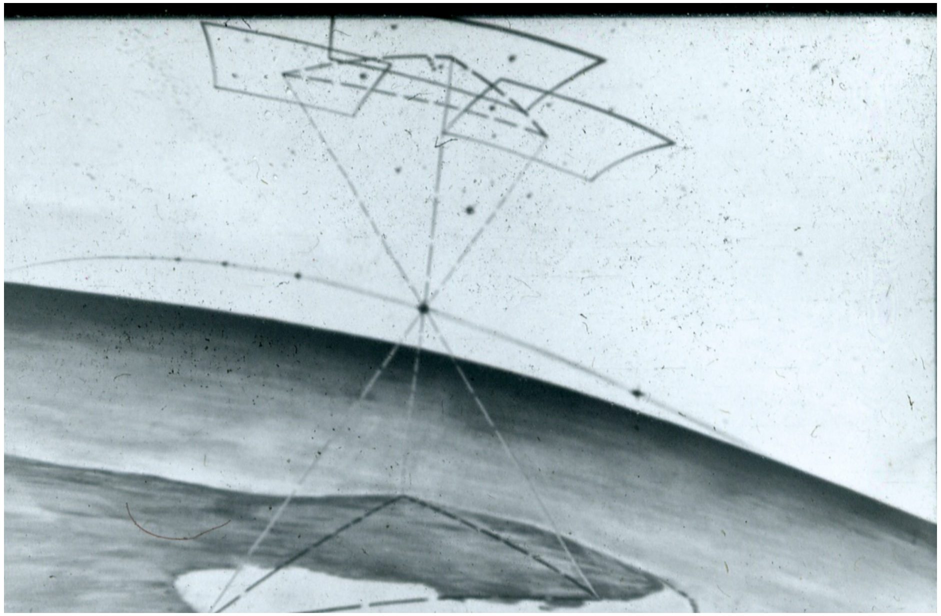
B. FOR GRAVITY

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!*

STATION POSITIONS
Geometric Method





THE BEGINNING

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)

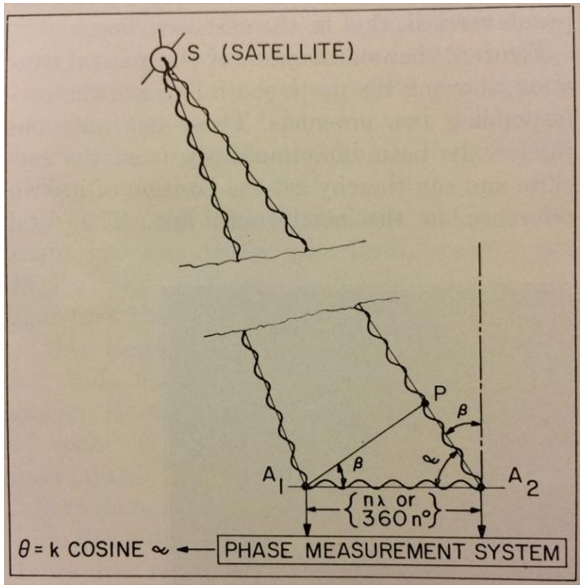
Followed by new observing techniques

1960	TRANSIT doppler (frequency shift hyperbolic system)
1962	SECOR (Sequential Collation of Range)
1964	Laser Ranging

INDEX OF TYPE OF INSTRUMENTATION USED AS CODE FOR THE FIRST OBSERVATIONS OF SATELLITES

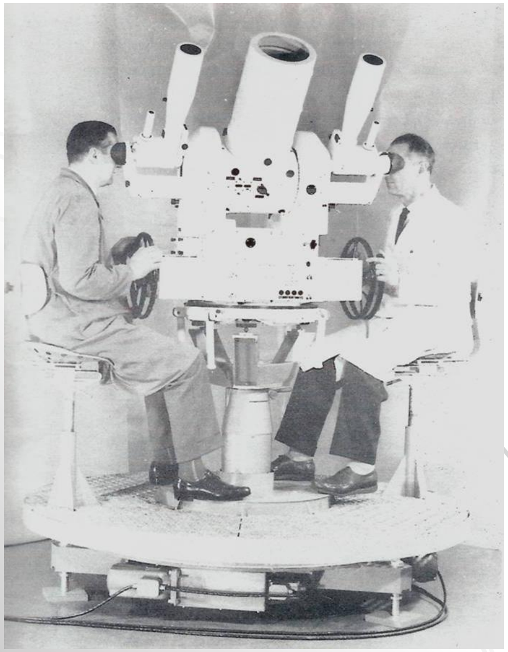
Code number	Optical observations	Code number	Electronic observations
0	Naked eye and binoculars, visual.	0	Minitrack Mark 1.
1	Standard Moonwatch telescope, visual.	1	Minitrack Mark 2.
2	Apogee telescope, astronomical refractor or reflector, theodolite, visual.	2	Interferometer observations from radio observatories.
3	Baker-Nunn camera, photographic.	3	Doppler observations from radio observatories.
4	Small missile telecamera, tracking cameras with focal length 20 inches or greater, photographic.	4	Microlock.
5	Cinetheodolite, tracking cameras with focal length less than 20 inches, photographic.	5	Doppler observations from communications systems.
6	Harvard meteor camera (Super-Schmidt), photographic.	6	Doppler observations from missile ranges.
7	Stationary telescope or camera with focal length equal to or less than 10 inches, photographic.	7	Radar.
8	Stationary telescope or camera with focal length greater than 10 inches, photographic.	8	Unused digit.
9	Other instruments, or instrument unknown.	9	Miscellaneous.

FIRST OBSERVATIONS OF SATELLITES



Minitrack

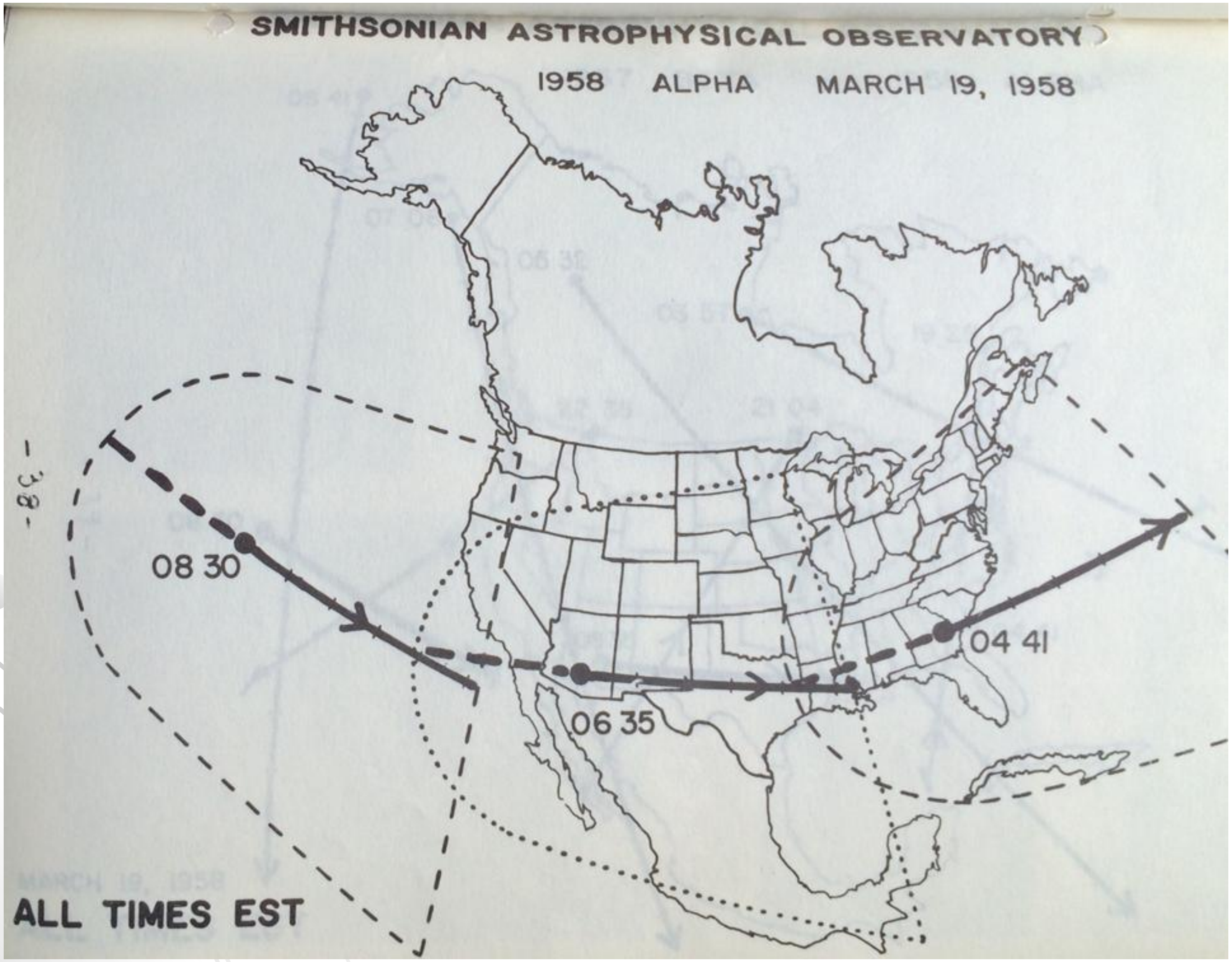
Moonwatch team



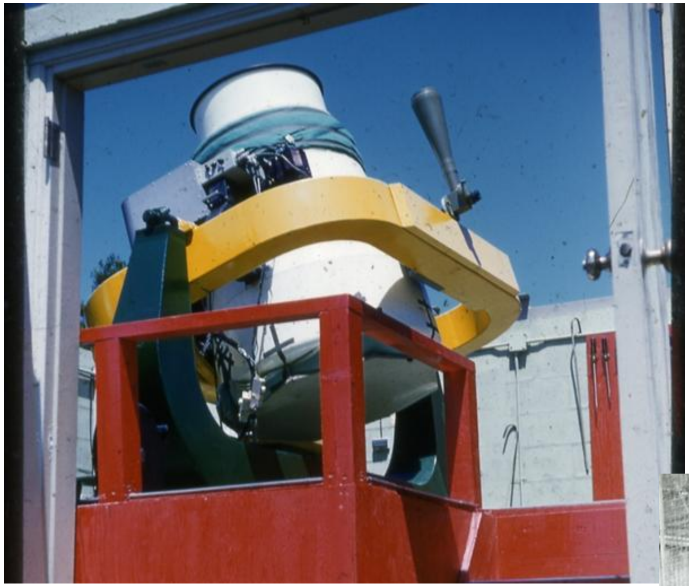
Cinetheodolite

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

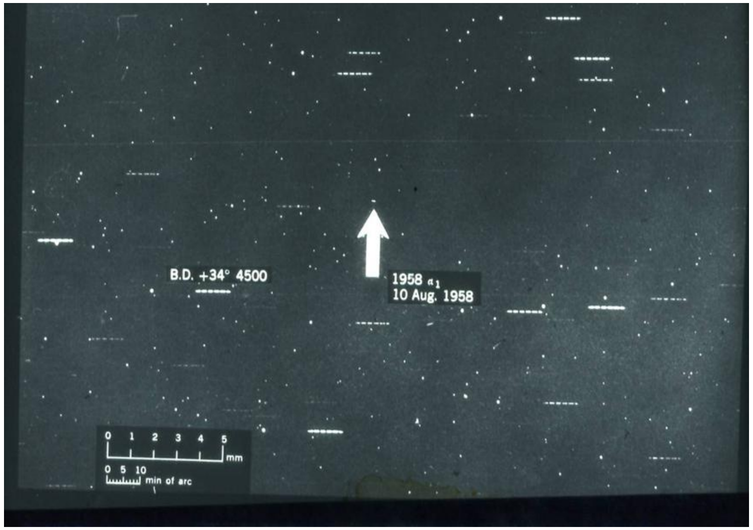
BC-4 Camera
1962

* Limited visibility is a problem

B/N NETWORK 1958

FIG. 4—Smithsonian Astrophysical Observatory network of photographic satellite-tracking stations

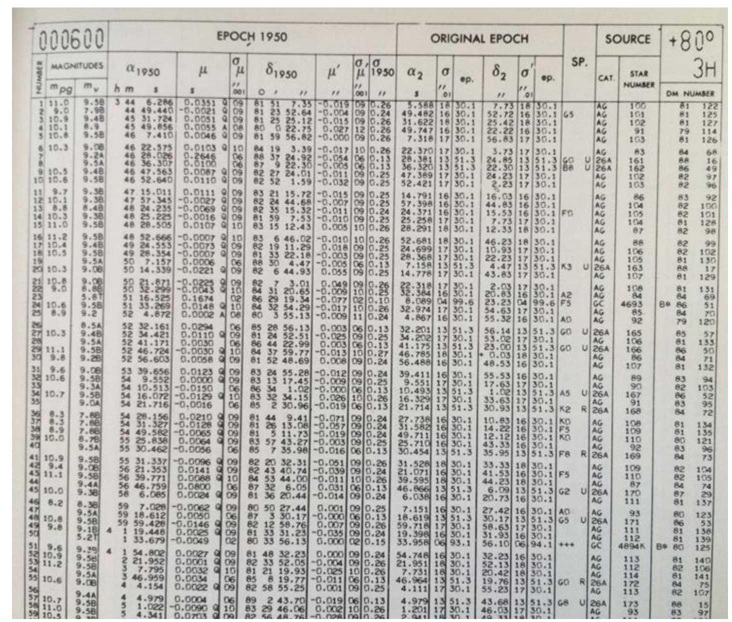
PHOTOREDUCTION



B/N Film

PHOTOGONIOMETER

DIGITAL COMPARATOR



NUMBER	m_{pg}	m_v	α_{1950} h m s	μ s		σ_μ ″.001	δ_{1950} ° ′ ″	μ' ″	$\sigma_{\mu'}$ ″.001	σ_{1950} ″	α_2 s	σ ″.01	ep.	δ_2 ″	σ' ″.01	ep.	SP.	CAT.	STAR NUMBER	DM NUMBER +80° 3H
1	11.0	9.5B	3 44 6.286	0.0351	Q	09	81 51 7.35	-0.019	09	0.26	5.588	18	30.1	7.73	18	30.1		AG	100	81 122
2	9.0	7.9B	44 49.440	-0.0021	Q	09	81 23 52.64	-0.004	09	0.24	49.482	16	30.1	52.72	16	30.1	G5	AG	101	81 125
3	10.9	9.4B	45 31.724	0.0051	Q	09	81 25 25.12	-0.015	09	0.26	31.622	18	30.1	25.42	18	30.1		AG	102	81 127
4	10.1	8.9	45 49.856	0.0055	A	08	80 0 22.75	0.027	12	0.26	49.747	16	30.1	22.22	16	30.1		AG	91	79 114
5	10.8	9.5B	46 7.410	0.0046	Q	09	81 59 56.82	-0.000	09	0.26	7.318	17	30.1	56.83	17	30.1		AG	103	81 126
6	10.3	9.0B	46 22.575	0.0103	Q	10	84 19 3.39	-0.017	10	0.26	22.370	17	30.1	3.73	17	30.1		AG	83	84 68
7		9.2A	46 28.026	0.2646		06	88 37 24.92	-0.054	06	0.13	28.381	13	51.3	24.85	13	51.3	G0 U	26A	161	88 16
8		9.5A	46 36.307	0.0100		06	87 9 22.30	-0.005	06	0.13	36.320	13	51.3	22.30	13	51.3	B8 U	26A	162	86 49
9	10.5	9.4B	46 47.563	0.0087	Q	09	82 27 24.01	-0.011	09	0.25	47.389	17	30.1	24.23	17	30.1		AG	102	82 97
10	10.6	9.5B	46 52.640	0.0110	Q	09	82 52 1.59	-0.032	09	0.25	52.421	17	30.1	2.23	17	30.1		AG	103	82 96

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

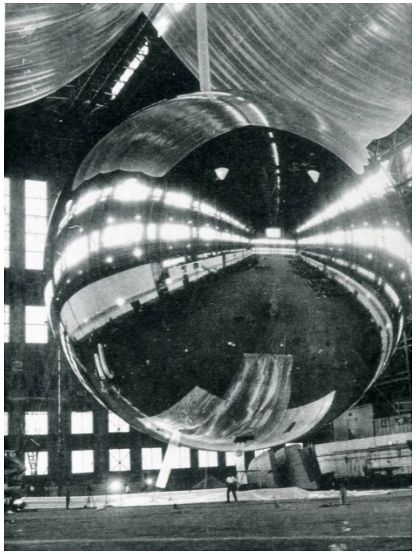
Followed by:

- The pear-shaped earth
- First new station coordinates

SATELLITES USED DURING THE FIRST YEARS FOR GRAVITY FIELD, STATION POSITIONS, AND PHYSICS OF UPPER ATMOSPHERE

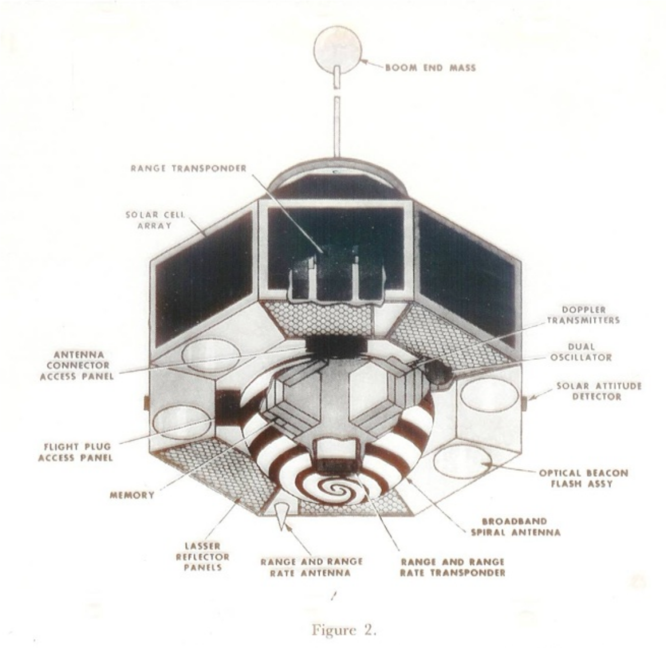
SATELLITE	YEAR	TRACKING METHOD
Sputnik	1957	Optical, interferometry
Explorer	1958	Optical, ...
Anything in orbit	1957	Optical, RADAR
TRANSIT	1960	Radio Doppler shift
ECHO	1960	Optical
ANNA	1962	Doppler, optical (flashing), R+R/R
BEB	1964	Laser ranging – (first corner cubes)
GEOS (1, 2, 3)	1965	Optical, laser ranging, R+R/R
STARLETTE LAGEOS	1965 1966	Dedicated for laser ranging

EARLY GEODETIC SATELITES

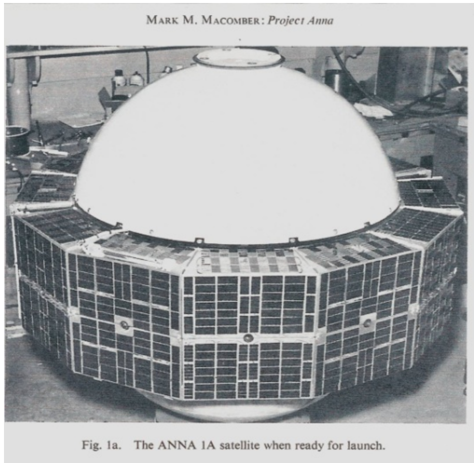


ECHO (1960)

TRANSIT (1960)



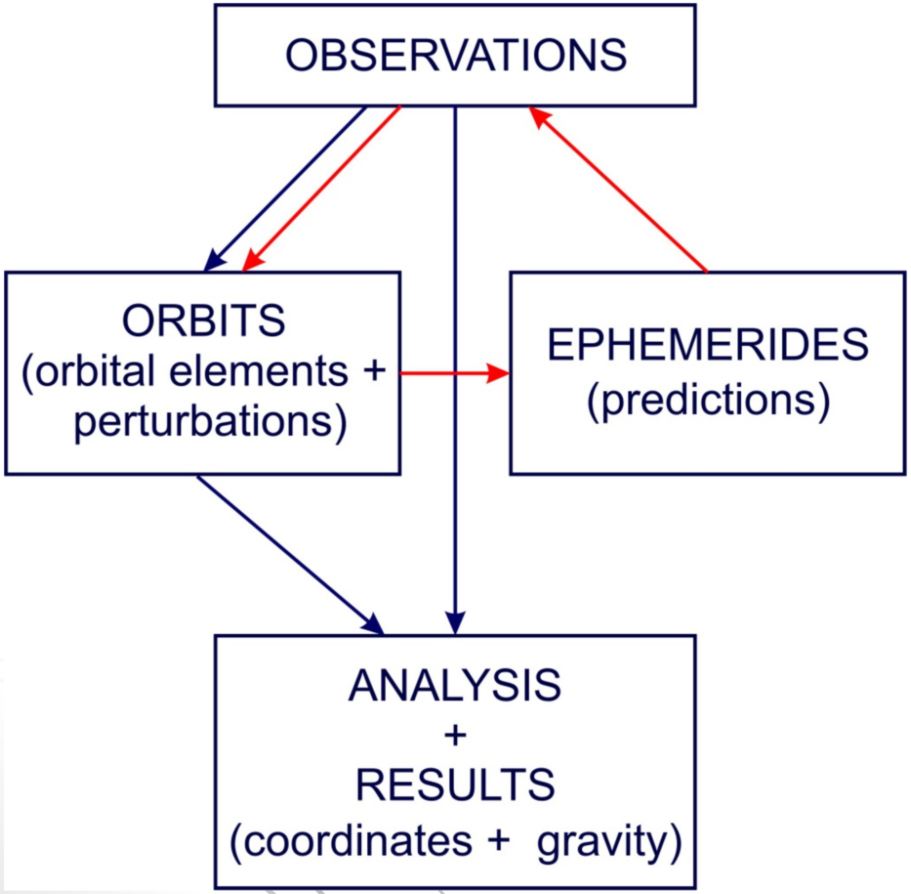
GEOS 1 (1965)



ANNA (1962)

LAGEOS (1966)

ORBITS & EPHEMERIDES



CELESTIAL MECHANICS

(expansion into series)

COMPUTER ALGEBRA

NUMERICAL INTEGRATION

DIFFERENTIAL ORBIT IMPROVENT

(geodetic approach)

tional radius $m = GM/c^2$, eqs. (37) to (40) become

$$y'_{\substack{11\\22}} = -\frac{4m}{r}\left(\frac{\Omega R}{c}\right)^2 \sum_{n=0}^{\infty}\left[\frac{I_n}{2}\left(\frac{R}{r}\right)^n P_n(\sin\phi) \mp \frac{(n-2)!}{(n+2)!}\frac{L_n}{2}\left(\frac{R}{r}\right)^n P_n^2(\sin\phi)\cos 2\theta\right], \tag{41}$$

$$y'_{44} = \frac{4m}{r}\left[1 - \sum_{n=2}^{\infty} J_n\left(\frac{R}{r}\right)^n P_n(\sin\phi)\right], \tag{42}$$

$$g_{12} = y'_{12} = \frac{4m}{r}\left(\frac{\Omega R}{c}\right)^2 \sum_{n=1}^{\infty}\left[\frac{(n-2)!}{(n+2)!}\frac{L_n}{2}\left(\frac{R}{r}\right)^n P_n^2(\sin\phi)\sin 2\theta\right], \tag{43}$$

$$g_{\substack{14\\24}} = y'_{\substack{14\\24}} = \pm i\frac{4m}{r}\left(\frac{\Omega R}{c}\right)\sum_{n=1}^{\infty}\left[\frac{(n-1)!}{(n+1)!}K_n\left(\frac{R}{r}\right)^n P_n^1(\sin\phi)\begin{matrix}\sin\theta\\ \cos\theta\end{matrix}\right], \tag{44}$$

and therefore

$$\sum_{\alpha=1}^{4} y'_{\alpha\alpha} = \frac{4m}{r}\left[1 - \sum_{n=2}^{\infty} J_n\left(\frac{R}{r}\right)^n P_n(\sin\phi) - \left(\frac{\Omega R}{c}\right)^2 \sum_{n=0}^{\infty} I_n\left(\frac{R}{r}\right)^n P_n(\sin\phi)\right].$$

Because

$$g_{kk} = -1 + y'_{kk} - \tfrac{1}{2}\sum_{\alpha=1}^{4} y'_{\alpha\alpha},$$

it follows that

$$g_{\substack{11\\22}} = -1 - \frac{2m}{r}\left[1 - \sum_{n=2}^{\infty} J_n\left(\frac{R}{r}\right)^n P_n(\sin\phi) \mp \left(\frac{\Omega R}{c}\right)^2 \frac{(n-2)!}{(n+2)!} L_n\left(\frac{R}{r}\right)^n P_n^2(\sin\phi)\cos 2\theta\right], \tag{45}$$

$$g_{33} = -1 - \frac{2m}{r}\left[1 - \sum_{n=2}^{\infty} J_n\left(\frac{R}{r}\right)^n P_n(\sin\phi) - \left(\frac{\Omega R}{c}\right)^2 \sum_{n=0}^{\infty} I_n\left(\frac{R}{r}\right)^n P_n(\sin\phi)\right], \tag{46}$$

$$g_{44} = -1 + \frac{2m}{r}\left[1 - \sum_{n=2}^{\infty} J_n\left(\frac{R}{r}\right)^n P_n(\sin\phi) + \left(\frac{\Omega R}{c}\right)^2 \sum_{n=0}^{\infty} I_n\left(\frac{R}{r}\right)^n P_n(\sin\phi)\right]. \tag{47}$$

Taking only the terms up to $n = 2$, the components of the fundamental tensor are

$$g_{\substack{11\\22}} = -1 - \frac{2m}{r}\left[1 - J_2\left(\frac{R}{r}\right)^2 P_2(\sin\phi) \mp \left(\frac{\Omega R}{c}\right)^2 \frac{L_2}{8}\left(\frac{R}{r}\right)^2 \cos^2\phi\cos 2\theta\right], \tag{48}$$

$$g_{33} = -1 - \frac{2m}{r}\left\{1 - J_2\left(\frac{R}{r}\right)^2 P_2(\sin\phi) - \left(\frac{\Omega R}{c}\right)^2\left[\Gamma + \Delta\left(\frac{R}{r}\right)^2 P_2(\sin\phi)\right]\right\}, \tag{49}$$

$$g_{44} = -1 + \frac{2m}{r}\left\{1 - J_2\left(\frac{R}{r}\right)^2 P_2(\sin\phi) + \left(\frac{\Omega R}{c}\right)^2\left[\Gamma + \Delta\left(\frac{R}{r}\right)^2 P_2(\sin\phi)\right]\right\}, \tag{50}$$

$$g_{12} = \frac{4m}{r}\left(\frac{\Omega R}{c}\right)^2 \frac{L_2}{16}\left(\frac{R}{r}\right)^2 \cos^2\phi\sin 2\theta, \tag{51}$$

$$g_{\substack{14\\24}} = \pm i\frac{2m}{r}\left(\frac{\Omega R}{c}\right)\Gamma\left(\frac{R}{r}\right)\cos\phi\begin{matrix}\sin\theta\\ \cos\theta\end{matrix}. \tag{52}$$

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

$$2m^2/r^2 \cdot [1 - 2J_2(R/r)^2 P_2(\sin\phi)]$$

will be added according to de Sitter (eq. 20). The reason why g_{44} is required

EARLY GEODETIC RESULTS

Station		x^1	x^2	x^3		Number of observations
9001	Organ Pass	-1.535713	-5.167030	+3.401099	±15	5 131
9002	Olifantsfontein	+5.056137	+2.716534	-2.775806	10	5 922
9003	Woomera	-3.983618	+3.743212	-3.275642	7	7 257
9004	San Fernando	+5.105602	-0.555230	+3.769708	20	2 715
9005	Tokyo	-3.946563	+3.366400	+3.698878	18	2 459
9006	Naini Tal	+1.018190	+5.471170	+3.109601	30	1 799
9007	Arequipa	+1.942755	-5.804100	-1.796895	15	2 976
9008	Shiraz	+3.376916	+4.404028	+3.136311	20	2 733
9009	Curaçao	+2.251790	-5.816950	+1.327212	10	3 092
9010	Jupiter	+0.976314	-5.601416	+2.880301	12	3 607
9011	Villa Dolores	+2.280624	-4.914540	-3.355451	12	4 514
9012	Maui	-5.466100	-2.404157	+2.242353	22	4 330

Station Coordinates (1961)

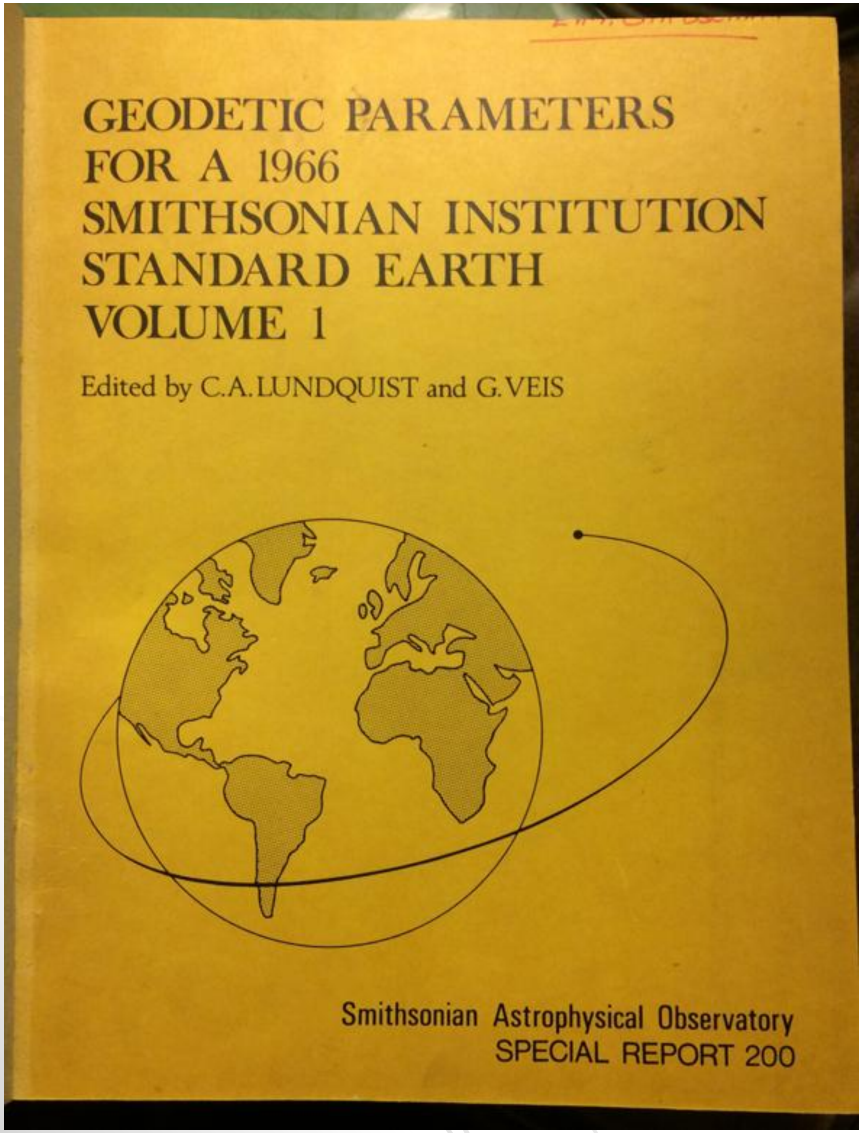
TABLE 5

Numerical results for J_n

Source	$J_2\times10^6$	$J_3\times10^6$	$J_4\times10^6$	$J_5\times10^6$	$J_6\times10^6$	$J_7\times10^6$	$J_9\times10^6$
[6]	1082.79 ±0.15		−1.4 ±0.2		0.9 ±0.8		
[4]	1082.21 ±0.04	−2.29 ±0.03	−2.10 ±0.06	−0.23 ±0.03			
[15]	1082.48 ±0.04	−2.56 ±0.01	−1.84 ±0.09	−0.06 ±0.01	0.39 ±0.09	−0.47 ±0.01	0.12 ±0.01
[17]		−2.42 ±0.10		−0.22 ±0.07		−0.27 ±0.07	
[5]	1082.49 ±0.06	−2.39 ±0.26	−1.70 ±0.06	−0.30 ±0.53			
[11]	1082.61 ±0.05		−1.52 ±0.08		0.73 ±0.10		
[14.18]	1083.15 ±0.20	−2.37 ±0.18	−1.4 ±0.3	−0.05 ±0.15	0.7 ±0.6		
[13]	1083.3 ±0.7	−2 ±3	−4.1 ±0.7				

Gravity field (1962)

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.

SAO STANDARD EARTH (686 pages!)

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 3
(1973)

Laser No 2
(1968)