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12 - 14 DECEMBER 1967

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Volume II

GEOMETRIC AND GRAVIMETRIC INVESTIGATIONS WITH GEOS-I

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LIST OF TECHNICAL PAPERS

FOREWORD

This volume (Volume II) of the proceedings of the GEOS Program Review Meeting held at NASA Headquarters on 12-14 December 1967, presents the technical papers submitted on the geometric and gravimetric investigations conducted with GEOS-I by various investigators.

ANALYSIS OF GEODETIC SATELLITE TRACKING DATA TO DETERMINE TESSERAL HARMONICS OF THE EARTH'S GRAVITATIONAL FIELD

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Prepared For

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Final Report NASA Contract No. NSR 05-007-060

ANALYSIS OF GEODETIC SATELLITE TRACKING DATA TO DETERMINE TESSERAL HARMONICS OF THE EARTH'S GRAVITATIONAL FIELD[1]

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ABSTRACT

Determinations of 88 tesseral harmonic coefficients of the gravitational field were made from camera tracking of seven satellites plus Doppler tracking of five satellites. It was found that addition of Doppler tracking of satellites which also have appreciable camera tracking had relatively little effect on the results. It is felt that not more than 50 of the coefficients are adequately determined. The improvement primarily required is more tracking of high inclination satellites; refinement of the dynamical theory used may also help.

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[1] Publication No. 656, Institute of Geophysics and Planetary Physics, University of California, Los Angeles.

The analyses described in this paper are in continuation of those reported 1½ years ago [Kaula, 1966a]. These investigations are distinguished from other determinations of the earth's gravitational field principally in using an entirely analytic dynamical theory. The principal changes from the previous solution were 1) the incorporation of Doppler tracking data, and 2) an increase in the number of gravitational harmonic coefficients in the solution.

Incorporation of Doppler Data. Tracking by the U.S. Navy "Transit" Network was received in the form of Doppler frequencies, scaled to a reference frequency of about 107 MHz, at intervals of 16 seconds. To utilize these data in the same computer programs as the camera data, and to economize computer time, the following conversion and compression was applied to the Doppler data: 1) the form was converted to range rate in "canonical" units: earth radii/(806.8137 secs.); 2) the time was converted from WWV emitted to A1; 3) observations within 15° of the horizon were omitted, and tropospheric refraction corrections applied; 4) 3 or 4 observations at equal intervals over each pass were selected; 5) for one day at a time, an orbit was fitted to these observations by iterated least squares, taking into account variations of the gravitational field up to ℓ, m = 4,4; 6) from this orbit, the range-rate was calculated for each of the original 16-second interval observations; 7) for each pass, a combination of a polynomial in time and a station position shift was fitted to the residuals of the observed with respect to the computed range rates; 8) at three times within each pass, a range rate was calculated as the sum of the range rate from the orbit fitted for the day plus the polynomial & station shift fitted to the pass. The final information written on a binary tape for use in the subsequent analysis included as one record for each pass: a type number identifying the data as range rate; the tracking station number; the number of observations in the pass; the GST and A1 time (in Modified Julian Days) of the start of the pass; the three aggregated range rates formed by the process described above; and the time after pass start for each of these range rates.

Selection of Spherical Harmonic Coefficients. The zonal harmonics were held fixed at the values given in Table 2 of *Kaula* [1966a]. The tesseral harmonics selected for solution were all those for which a normalized coefficient of magnitude $8 \times 10^{-6}/l^2$ caused a perturbation of at least 10 meters amplitude in one satellite or at least 5 meters amplitude in two satellites, as listed in Table 3 of *Kaula* [1966a]: all coefficients thru 6,6; 7,1 thru 7,5; 8,1 thru 8,6; 9,1 and 9,2; 10,1 and 10,2; 11,1; and and 12,1; plus the small-divisor or near-resonant, harmonics: 9,9; 12,12; 13,12; 14,12; 15,12 thru 15,14; and 17,14.

Thus there were a total of 88 unknowns common to all orbits. With 7 unknowns represented by the Keplerian elements plus an acceleration parameter for each arc, the computer storage capacity for the normal equations as currently dimensioned was equalled. An increase of capacity to at least 145 unknowns could be accomplished with very little difficulty. In the solutions described herein, the positions of 16 Baker-Nunn camera and 33 Transit Doppler tracking stations were held fixed at the values obtained by *Gaposhkin* [1966] and *Anderle & Smith* [1967] respectively. It is intended to modify the programs to increase the capacity for unknowns and to solve for station position shifts when warranted by the accuracy of the solution for gravitational coefficients. So far, this stage has not been reached.

Summary of Satellites. The satellites used are summarized in Table 1. For the five satellites which also were used in the 1966 solution the data are essentially the same (except for 5 more months of Transit 4A), because 1963 was the year of minimum disturbances of atmospheric density by solar activity. There are minor modifications in the arcs actually used, however, because of changes in acceptance criteria for arcs: as well as number of iterations and number of observations (32 for Transit 4A, 40 for Vanguard 2, 60 for the others), a chi-square test was applied.

The significant additions to the data are the tracking of Courier 1B (28.2°), GEOS 1 (59.5°), and Beacon Explorer B (79.7°). It was found that adding a satellite of different orbital inclination made much more difference in the solution than did adding Doppler tracking. Considerable testing was done using different weights of the Doppler tracking relative to the camera tracking of GEOS 1, in particular, with very little variation in the results. While this situation adds to our confidence that the Doppler portions of the program are correct and accurate, it means that the major benefit of adding the capability to analyze Doppler data will not come until it enables analysis of orbits of appreciably different inclination than the set in Table 1: in particular, a polar orbiter.

In addition to Doppler tracking of a polar satellite, it is desirable that the amount of tracking of Beacon Explorer B be increased appreciably and that tracking of all satellites from more overseas stations be added so as to give a better distribution of observations than indicated by Table 2. The poor distribution apparently arises in part from the unavailability for administrative reasons of tracking from some overseas stations. This maldistribution is more severe than that tested by Anderle [1966].

Supplemental Data. Because the station positions were held fixed, of the three types of supplemental equations used in the earlier analyses only the 24-hour satellite orbit accelerations were applied (see Table 4 of Kaula [1966a]). Carrying these equations at unit weight, they have a mild influence on the solutions for the 2,2; 3,1; and 3,3 coefficients. It is planned to add some of the more accurate recent accelerations derived by Wagner [1967].

Manner of Analysis. The method of partitioned normals as described by Kaula [1966a, Eq. (1)-(2)] was utilized, so that there was no limit on the number of orbital arcs which could be analyzed In addition, one reference frequency correction per pass was included as an additional optional unknown to be separated out of the normals in the same manner as the orbital elements. Exercise of this option, however, appeared to make little difference in the results for the gravitational coefficients.

The normal equation blocks generated from the Doppler data were kept separate from the blocks generated from the camera data, in order to facilitate the testing of different relative weights of Doppler vs. camera tracking. However, as mentioned previously, variety of tracking type seems to make much less difference than variety of orbital specifications.

Results. The best solution (by the criterion of minimum discrepancy from terrestrial gravimetry [Kaula, 1966b]) is given in Table 3. This solution utilized a priori standard derivations of $\pm 10^{-5}/\ell^2$ for non-resonating coefficients of degree $\ell \geq 7$. This limitation is disappointing; the variety of inclinations is such that more than a three-fold ambiguity in periodicity of perturbations by tesseral harmonics should be resolvable. Of the two inadequacies which are most likely to cause this result, insufficient amount of data and error in dynamical theory, the former is easier to rectify, and hence is being tested first.

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TABLE 1: SATELLITE SPECIFICATIONS

Satellite	a Earth Radii	e	I Deg.	Days/ Arc	No. Arcs	Total Obs.	Starting Date	Ending Date	Type Tracking
Courier 1B	1.171	0.02	28.2	17	3	193	'65 Jun 11	'65 Oct 9	O
Vanguard 2	1.302	0.16	32.9	18	12	696	'62 Dec 31	'63 Dec 25	O
Transit 4B	1.163	0.01	32.4	9	2	1350	'62 Apr 21	'62 Jun 23	D
Echo 1 Rocket	1.250	0.01	47.2	18	14	1380	'63 Jan 1	'63 Dec 26	O
Anna 1B	1.177	0.01	50.1	18	15	1322	'62 Dec 31	'63 Oct 22	O
				9	2	3930	'63 May 16	'63 Jun 4	D
Geos 1	1.266	0.07	59.5	18	7	1126	'65 Nov 4	'66 Jun 10	O
				10	6	4768	'66 Jul 1	'67 Feb 9	D
Transit 4A	1.147	0.01	66.8	18	14	536	'62 Apr 6	'63 Dec 26	O
				9	2	2556	'62 Jul 19	'62 Aug 7	D
Beacon Expl. B	1.154	0.01	79.7	9	2	2496	'65 Jan 30	'65 May 9	D
Midas 4	1.568	0.01	95.9	30	12	3021	'62 Aug 3	'63 Dec 25	O

TABLE 2: GEOGRAPHIC DISTRIBUTION OF DOPPLER TRACKING

Number of passes observed from stations within each octant

Latitude N \ Longitude E:	25–115	115–205	205–295	295–25
90–0	0	1109	3724	651
0–(-90)	333	352	0	315

TABLE 3: GEOPOTENTIAL FULLY NORMALIZED SPHERICAL HARMONIC COEFFICIENTS x 10^6

Degree ℓ	Order m	$\bar{C}_{\ell m}$	$\bar{S}_{\ell m}$	Degree ℓ	Order m	$\bar{C}_{\ell m}$	$\bar{S}_{\ell m}$	Degree ℓ	Order m	$\bar{C}_{\ell m}$	$\bar{S}_{\ell m}$
2	2	2.45	-1.37	6	3	0.14	0.23	9	1	0.07	-0.06
3	1	1.99	0.13	6	4	-0.16	-0.84	9	2	0.01	0.02
3	2	0.80	-0.71	6	5	-0.24	-0.54	9	9	-0.18	-0.14
3	3	0.47	1.27	6	6	-0.30	-0.80	10	1	0.00	0.00
4	1	-0.58	-0.39	7	1	0.17	0.05	10	2	-0.03	0.05
4	2	0.40	0.68	7	2	0.34	0.04	11	1	-0.03	-0.04
4	3	1.02	0.08	7	3	-0.01	-0.09	12	1	-0.05	-0.03
4	4	-0.36	-0.32	7	4	-0.11	0.06	12	12	-0.11	-0.01
5	1	-0.09	0.02	7	5	0.05	-0.03	13	12	-0.08	0.08
5	2	0.84	-0.14	8	1	-0.02	0.12	14	12	-0.05	-0.04
5	3	-0.50	-0.06	8	2	0.10	-0.10	15	12	-0.08	0.01
5	4	0.36	0.28	8	3	0.08	0.11	15	13	-0.03	-0.07
5	5	-0.22	-0.14	8	4	-0.05	0.02	15	14	-0.00	0.02
6	1	-0.13	0.05	8	5	-0.02	-0.01	17	14	-0.05	0.12
6	2	0.10	-0.40	8	6	-0.03	0.02				

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INVESTIGATIONS IN CONNECTION WITH THE GEOMETRIC ANALYSIS OF GEODETIC SATELLITE DATA

Prof. Ivan I. Mueller
The Ohio State University

GEOS PROGRAM REVIEW MEETING
12-14 December 1967

NASA HEADQUARTERS
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INVESTIGATIONS IN CONNECTION WITH THE GEOMETRIC ANALYSIS OF GEODETIC SATELLITE DATA

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1. Primary Objective

The primary objective of the OSU investigation is the geometric analysis of geodetic satellite data. The analysis is accomplished in three steps:

(1) The establishment of a primary network where station positions are known to an internal consistency of approximately 10 meters or better to serve the following purposes: (a) unify the various geodetic datums in use around the world, (b) connect NASA tracking stations, isolated islands, navigational beacons, and other points of interest to the unified system.

(2) Establishment of a densification network where station positions are known to an internal consistency of approximately 3 meters or better to serve the following purposes: (a) improve the internal quality of existing geodetic system (triangulation, etc.) by establishing "super" control points in sufficient number, (b) to provide control for mapping to scales as large as 1:24,000.

(3) Establishment of a set of scientific reference stations where positions are known to an accuracy of one meter or better with respect to the unified system for advanced applications.

2. Accomplishment During the Report Period

2.1 Planned Geodetic Networks

The original network as proposed to NASA and presented at the 47th annual meeting of the American Geophysical Union in 1966 aimed at (i) the connection of the major geodetic datum blocks shown in Figure 1, (ii) the derivation of a common geocentric-geodetic datum, and (iii) tying the NASA-supported tracking stations (Figure 2) to this world datum. This network is shown in Figure 3. The plan

MAJOR GEODETIC DATUM BLOCKS

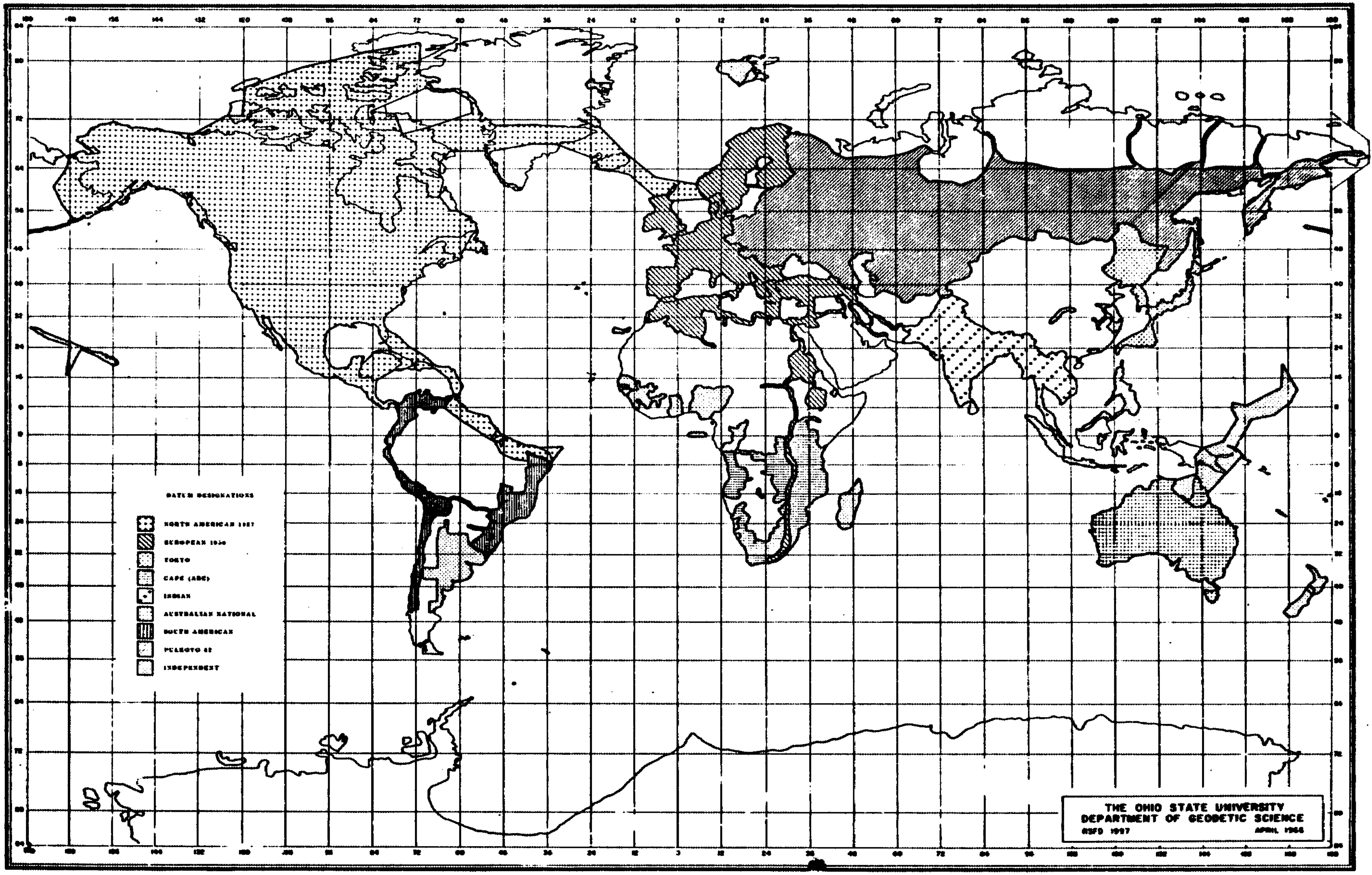


FIGURE I

NASA SUPPORTED STATIONS

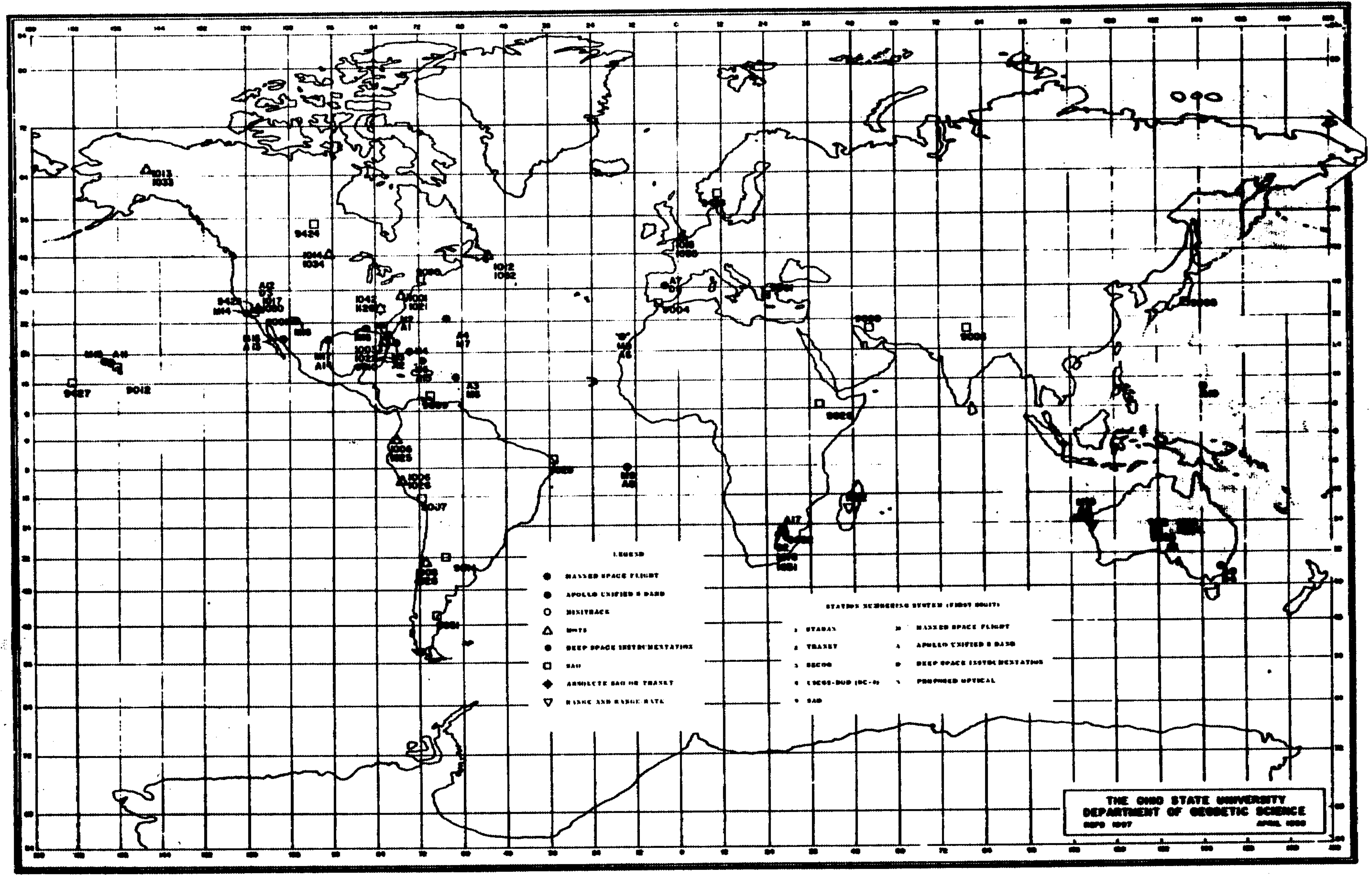


FIGURE 2

PROPOSED OPTICAL NETWORK

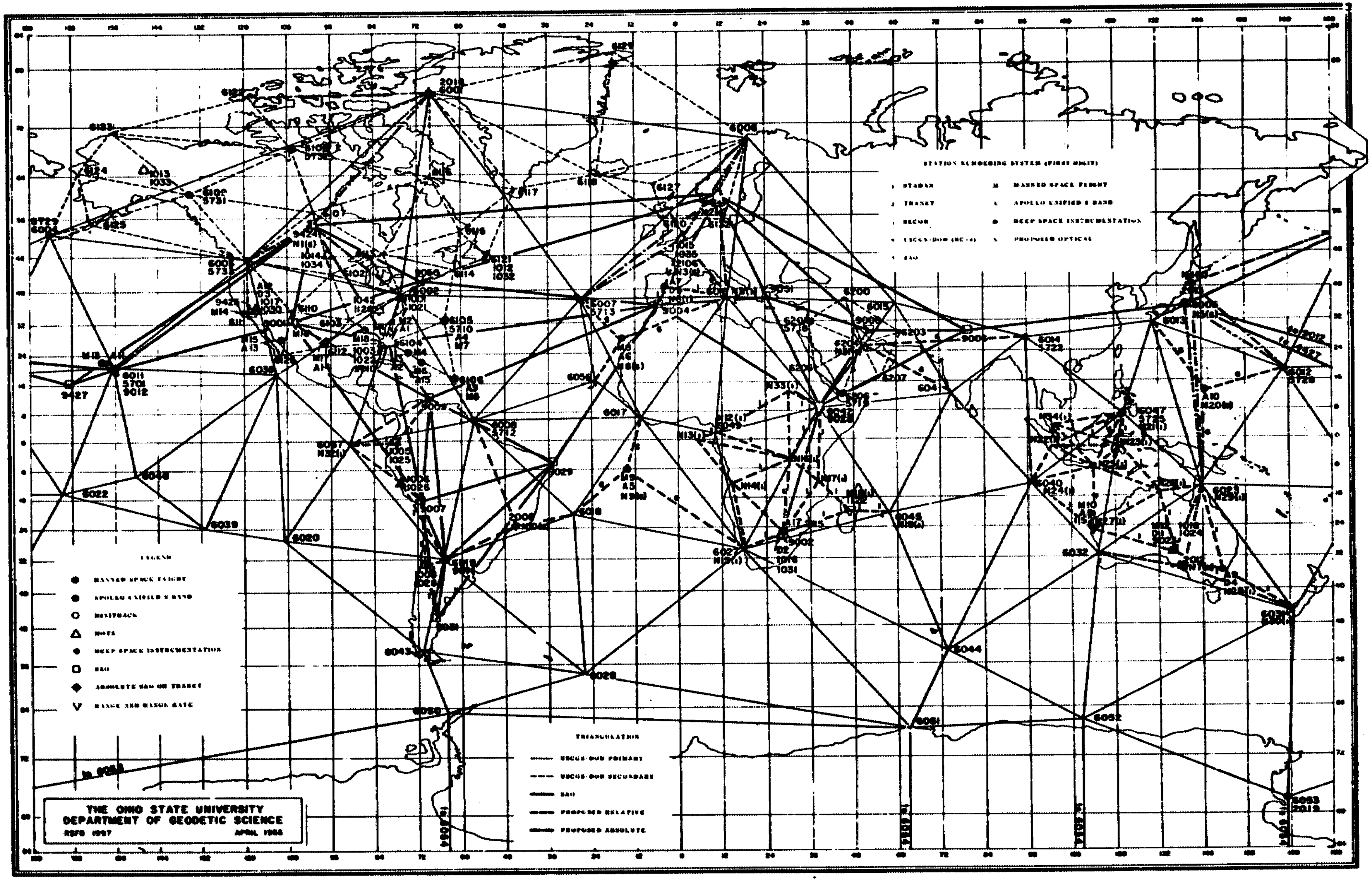


FIGURE 3

Stations selected for planning purposes only.

includes the ESSA-DOD primary geometric world triangulation net with its co-located TRANET and SECOR stations. The underlying philosophy of the proposed network was to tie the supplementary sites to this relative primary geometric world net, and then connect this to a number of "absolute" stations where satellites were observed through an extended period of time. Through this procedure the coordinates of all stations involved could be determined in a geocentric earth-fixed coordinate system. Scaling was to be achieved by available SECOR measurements and by precise terrestrial baselines in Australia, Europe, and in the USA.

During the interim period since April, 1966, certain additional requirements arose, such as the provisional updating of the Mercury datum (derived in 1959) on which most NASA tracking stations are located and the positioning of remote stations with no ties to this datum and of the Loran-C navigational beacons. These requirements necessitate minor changes and additions to the original plan.

2.2 Treatment of the Observation Data

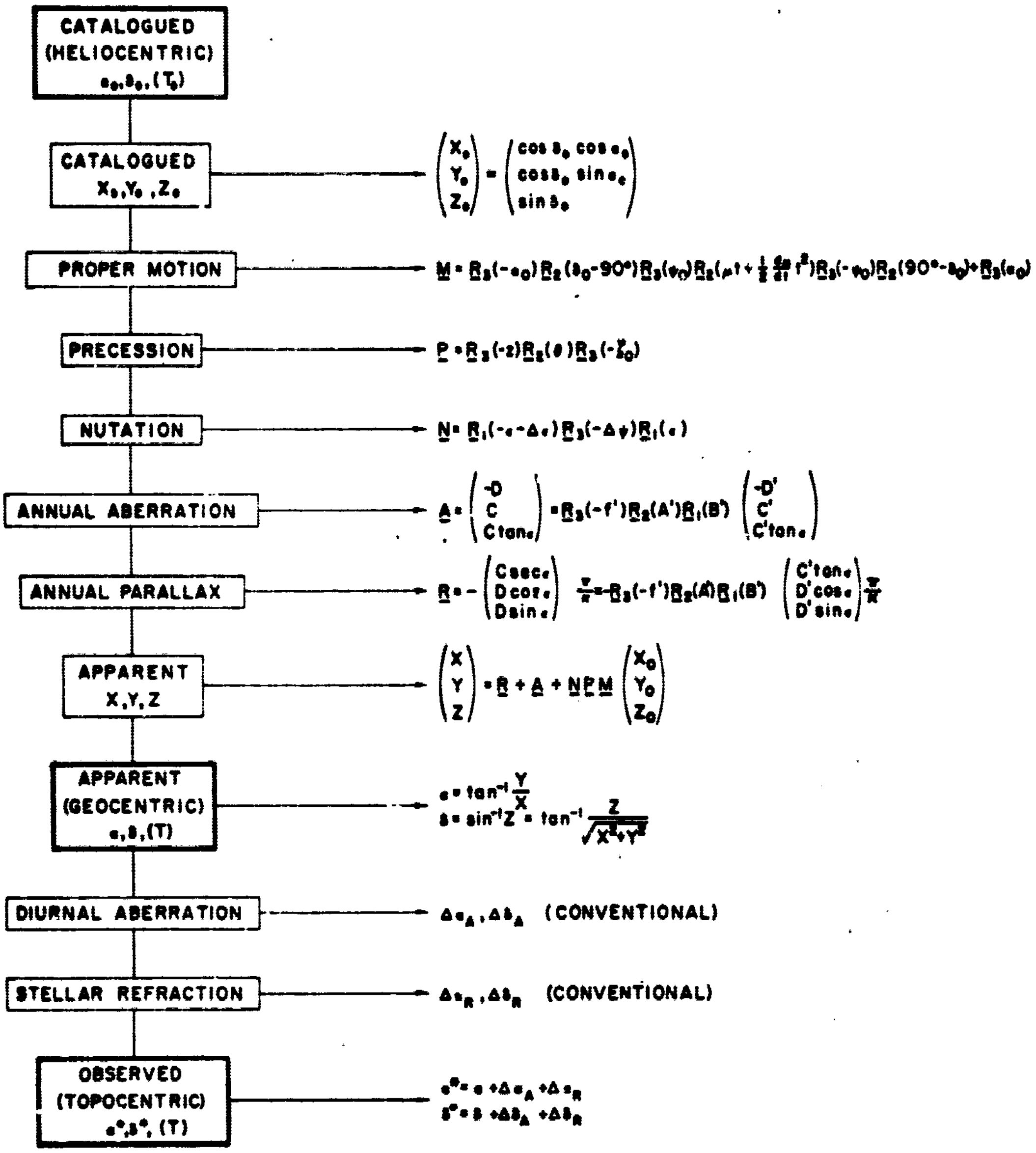
2.2.1 Optical Data

The procedure to obtain the appropriate coordinates of the satellite from its photograph taken with a background of stars, followed to some extent by most observer-groups participating in the program, is the following:

(i) The stars' coordinates, from their "mean" catalogued positions to their "observed" positions, are updated as shown in Figure 4.

In the figure the symbols $\underline{R}_i$ (θ) denote rotation matrices of 3 x 3 dimension. The elements $r_{i\bullet}$ of the matrices satisfy the following rules: $r_{ii}=1$; $r_{ij}=r_{ji}=r_{ki}=0$; $r_{jj}=r_{kk}=+\cos\theta$; $r_{jk}=+\sin\theta$; $r_{kj}=-\sin\theta$; where $j \equiv i$ (modulo 3)+1, $k \equiv j$ (modulo 3)+1. These rules are consistent with a right-handed coordinate system and positive signs for counterclockwise rotation, as viewed looking toward the origin from the positive axis.

STAR UPDATING



$$\begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix} = \begin{pmatrix} \cos\delta_0 \cos\alpha_0 \\ \cos\delta_0 \sin\alpha_0 \\ \sin\delta_0 \end{pmatrix}$$

$$\underline{M} = \underline{R}_3(-\alpha_0)\underline{R}_2(\delta_0 - 90^\circ)\underline{R}_3(\psi_0)\underline{R}_2(\mu t + \tfrac{1}{2}\tfrac{d\mu}{dt}t^2)\underline{R}_3(-\psi_0)\underline{R}_2(90^\circ - \delta_0) + \underline{R}_3(\alpha_0)$$

$$\underline{P} = \underline{R}_3(-z)\underline{R}_2(\theta)\underline{R}_3(-\zeta_0)$$

$$\underline{N} = \underline{R}_1(-\epsilon - \Delta\epsilon)\underline{R}_3(-\Delta\psi)\underline{R}_1(\epsilon)$$

$$\underline{A} = \begin{pmatrix} -D \\ C \\ C\tan\epsilon \end{pmatrix} = \underline{R}_3(-f')\underline{R}_2(A')\underline{R}_1(B') \begin{pmatrix} -D' \\ C' \\ C'\tan\epsilon \end{pmatrix}$$

$$\underline{R} = -\begin{pmatrix} C\sec\epsilon \\ D\cos\epsilon \\ D\sin\epsilon \end{pmatrix} \frac{\varpi}{\kappa} = -\underline{R}_3(-f')\underline{R}_2(A')\underline{R}_1(B') \begin{pmatrix} C'\tan\epsilon \\ D'\cos\epsilon \\ D'\sin\epsilon \end{pmatrix} \frac{\varpi}{\kappa}$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \underline{R} + \underline{A} + \underline{N}\underline{P}\underline{M} \begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix}$$

$$\alpha = \tan^{-1}\frac{Y}{X}$$
$$\delta = \sin^{-1} Z = \tan^{-1}\frac{Z}{\sqrt{X^2+Y^2}}$$

$\Delta\alpha_A, \Delta\delta_A$ (CONVENTIONAL)

$\Delta\alpha_R, \Delta\delta_R$ (CONVENTIONAL)

$$\alpha^* = \alpha + \Delta\alpha_A + \Delta\alpha_R$$
$$\delta^* = \delta + \Delta\delta_A + \Delta\delta_R$$

NOTATION:

ψ_0, μ	DIRECTION AND MAGNITUDE OF PROPER MOTION AT T_0 IN THE MEAN COORD. SYSTEM
$t = T - T_0$	
z, θ, ζ_0	PRECESSIONAL ELEMENTS FOR THE INTERVAL $t = T - T_0$
$\Delta\epsilon, \Delta\psi$	NUTATION IN OBLIQUITY AND LONGITUDE AT T.
ϵ	MEAN OBLIQUITY OF THE ECLIPTIC AT T.
C, D	BESSELIAN DAY NUMBERS AT T IN THE TRUE COORDINATE SYSTEM
A',B',C',D'	BESSELIAN DAY NUMBERS AT THE BEG. OF THE B.Y. NEAREST TO T IN THE MEAN COORDINATE SYSTEM (AS TABULATED IN THE EPHEMERIS)
f'	INDEPENDENT DAY NUMBER AT THE BEGINNING OF THE B.Y. NEAREST TO T IN THE MEAN COORDINATE SYSTEM
ϖ	ANNUAL PARALLAX
κ	CONSTANT OF ABERRATION

FIGURE 4

The symbols $\underline{P}_i$ denote permutation matrices of 3 x 3 dimensions. The elements p_{im} of the matrices are equal to zero except for $p_{ii}=-1$ and $p_{jj}=p_{kk}=1$.

The most advantageous catalogue to use at present is that of SAO (Smithsonian Astrophysical Observatory), which is in the FK4 fundamental system, contains about 259,000 stars having an average distribution of six stars per square degree and an average standard deviation of about $\pm 0\overset{''}{.}5$(at present).

(ii) From the updated stars' positions and their measured plate coordinates, the calibration parameters of the camera system and/or the plate constants are determined utilizing either photogrammetric (Figure 5) or astrometric (Figure 6) techniques.

(iii) Using these parameters and the measured plate coordinates of the satellite images the "observed" position of the satellite is calculated.

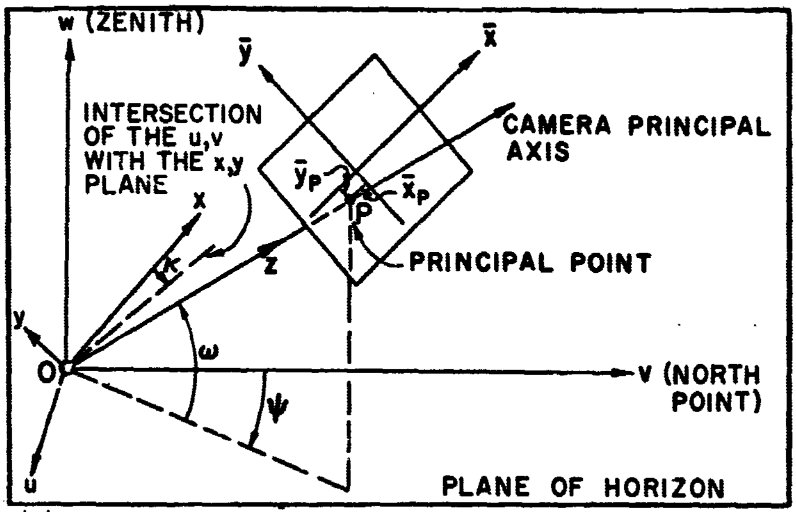
(iv) Appropriate corrections are finally applied to the "observed" satellite position to reduce it to the average terrestrial system (axes toward the IPMS 1900-05 average terrestrial pole, and the meridian of the BIH "mean observatory") as shown in Figure 7, or to any other system in which the adjustment is performed when computing the station coordinates.

Actual procedures followed by the various participating groups may vary with respect to each other in terms of the constants, type, and number of corrections (e.g., the data should be "homogenized" or preprocessed. The procedures of the major U.S. agencies participating in the National Geodetic Satellite Program are shown in Figure 8. The data as deposited in the GSDS in Greenbelt, Maryland, has been treated as shown. If, for example, the desired satellite position is the "true" (see Figure 7), data preprocessing in the areas shaded in Figure 8 is necessary. An example of what this could mean in terms of computational work is shown in Figure 9.

2.2.2 Non-Optical Data

The other tracking systems utilized in the network are the Pulse-laser, the NASA Range/Range Rate, and the SECOR-range. At

PHOTOGRAMMETRIC CALIBRATION



$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \underline{P}_1 \underline{P}_2 \underline{R}_1 (\Phi - \tfrac{\pi}{2}) \underline{P}_1 \underline{R}_3 (-\theta_L) \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{\alpha,\delta \text{ (obs.)}}$$

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \bar{x} - \bar{x}_P \\ \bar{y} - \bar{y}_P \\ c \end{pmatrix} = \bar{\kappa}\, \underline{P}_1 \underline{R}_3 (-\kappa) \underline{P}_2 \underline{R}_1 (\omega - \tfrac{\pi}{2}) \underline{R}_3 (-\psi) \begin{pmatrix} u \\ v \\ w \end{pmatrix}$$

Φ, θ_L STATION LATITUDE, LOCAL SIDEREAL TIME

$\bar{x}_P, \bar{y}_P, c$ ELEMENTS OF INTERIOR ORIENTATION

κ, ω, ψ ELEMENTS OF EXTERIOR ORIENTATION

$$\left.\begin{aligned} \bar{x} &= \bar{x}' + \sum_{i=1}^{n} dx_i \\ \bar{y} &= \bar{y}' + \sum_{i=1}^{n} dy_i \end{aligned}\right\}$$ =MEASURED PLATE COORDINATES ($\bar{x}', \bar{y}'$) CORRECTED FOR COMPARATOR ERROR, LENS DISTORTION, ETC.

i=1 NONPERPENDICULARITY OF COMPARATOR AXIS
2 WEAVE OF GUIDE OF THE COMPARATOR AXIS
3 PERIODIC SCREW ERROR
4 SECULAR SCREW ERROR

} COMPARATOR ERRORS (NOT CANCELLING)

5 SYMMETRICAL RADIAL LENS DISTORTION

$$\left.\begin{matrix} dx_5 \\ dy_5 \end{matrix}\right\} = \left.\begin{matrix} \bar{x} \\ \bar{y} \end{matrix}\right\} (K_1 r^2 + K_2 r^4 + K_3 r^6 + \ldots\ldots)$$

6 TANGENTIAL LENS DISTORTION

$$\left.\begin{matrix} dx_6 \\ dy_6 \end{matrix}\right\} = \left.\begin{matrix} + \\ - \end{matrix}\right\} (J_1 r^2 + J_2 r^4 + \ldots\ldots) \begin{Bmatrix} \sin \hat{\phi} \\ \cos \hat{\phi} \end{Bmatrix}$$

⋮
n

} LENS DISTORTIONS

UNKNOWNS:

$\bar{x}_P, \bar{y}_P, c$
κ, ω, ψ
$K_1, K_2, K_3, J_1, J_2, \hat{\phi}$, etc. (MAY BE PREDETERMINED)
OTHERS: COEFFICIENTS IN THE REFRACTION FORMULA
STAR COORDINATES CONSTRAINED BY ST. ERROR GIVEN IN CATALOG

FIGURE 5

ASTROMETRIC CALIBRATION

$$\left.\begin{aligned}\xi &= \frac{A\bar{x}' + B\bar{y}' + E}{G\bar{x}' + H\bar{y}' + I}\\ \eta &= \frac{C\bar{x}' + D\bar{y}' + F}{G\bar{x}' + H\bar{y}' + I}\end{aligned}\right\}$$ GENERAL TRANSFORMATION BETWEEN THE PLATE COORDINATES AND THE STANDARD COORDINATES

WHERE

$$\left.\begin{matrix}\xi\\ \eta\end{matrix}\right\} = \left.\begin{matrix}\xi\\ \eta\end{matrix}\right\} (\alpha, \delta, \alpha_o, \delta_o) \rightarrow$$ STANDARD COORDINATES FROM

GNOMONIC
CYLINDRIC } PROJECTIONS
OTHER

$\bar{x}', \bar{y}'$ MEASURED PLATE COORDINATES

VARIATIONS

1. $I = 1$
2. $I = 1$ AND $G = H = 0$ (LINEAR METHOD), THEN

$$\left.\begin{aligned}\xi &= A\bar{x}' + B\bar{y}' + E\\ \eta &= C\bar{x}' + D\bar{y}' + F\end{aligned}\right\}$$ AFFINE LINEAR TRANSFORMATION

WHERE

$$\left.\begin{aligned}&\left.\begin{matrix}A\\ C\end{matrix}\right\} = k_\xi \begin{Bmatrix}\cos\gamma\\ \sin\gamma\end{Bmatrix}\\ &\left.\begin{matrix}B\\ D\end{matrix}\right\} = k_\eta \begin{Bmatrix}\sin\gamma\\ -\cos\gamma\end{Bmatrix}\end{aligned}\right\}$$ SCALE AND ROTATION

$$\left.\begin{aligned}E &= \xi_o\\ F &= \eta_o\end{aligned}\right\}$$ STANDARD COORDINATES OF ORIGIN

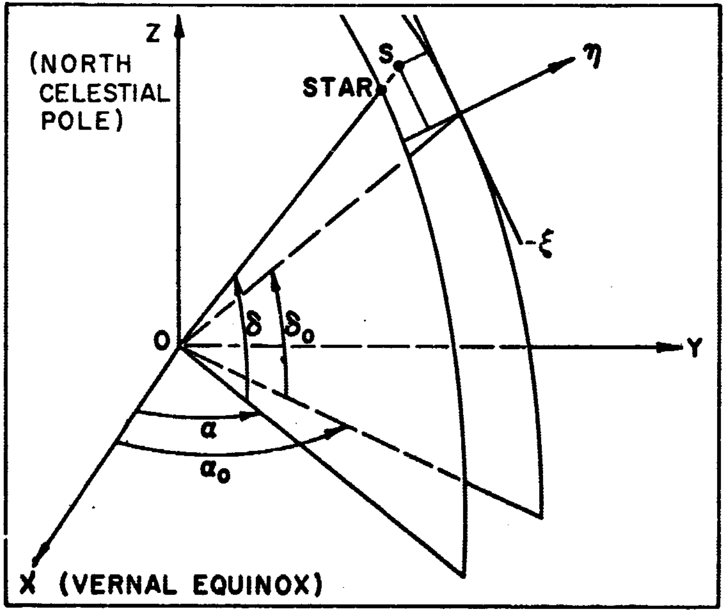
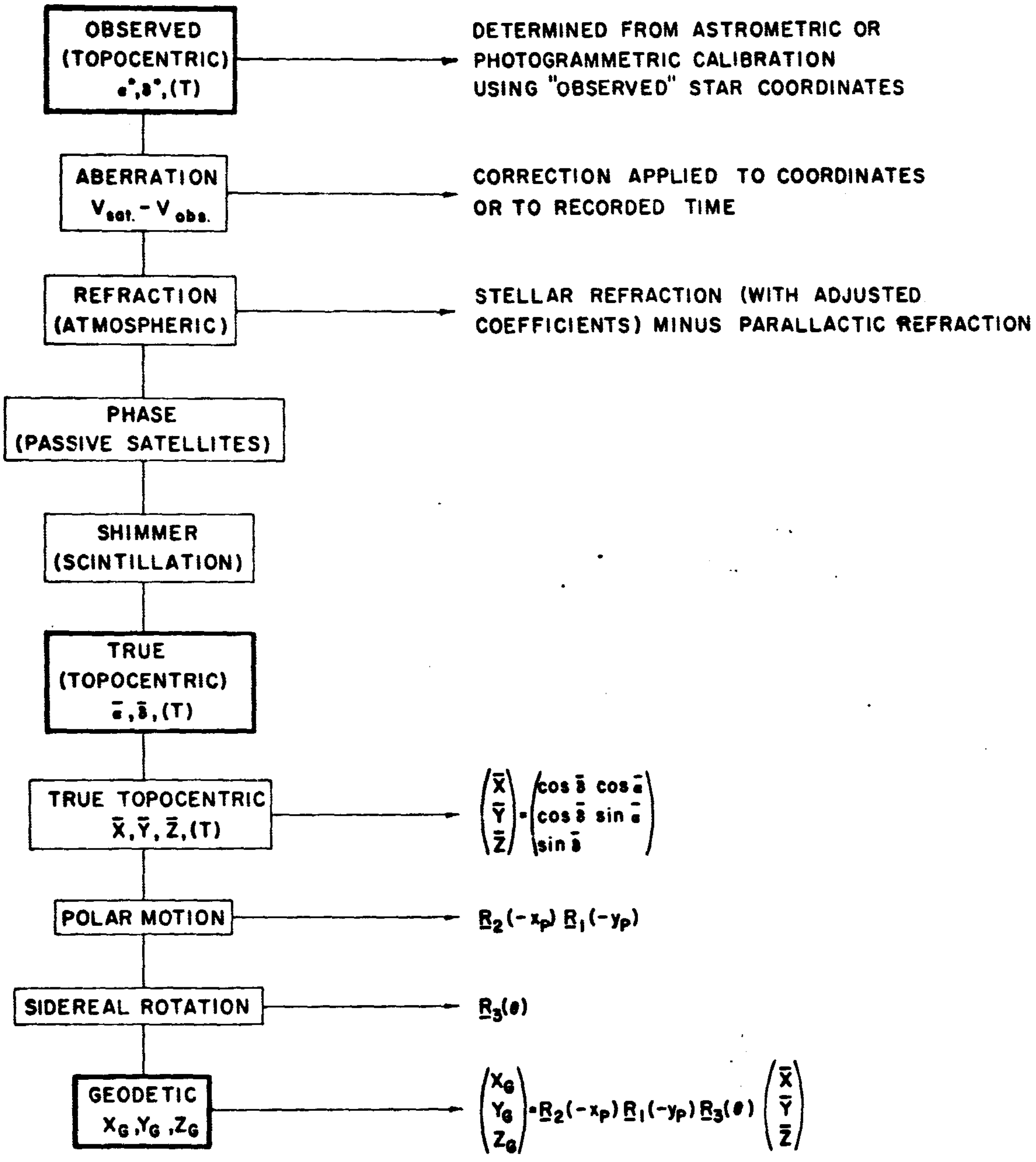


FIGURE 6

SATELLITE IMAGE CORRECTIONS



<u>NOTATION:</u>

x_p, y_p	COORDINATES OF THE INSTANTANEOUS POLE REFERRED TO THE I.P.M.S. 1900-05 AVERAGE TERRESTIAL POLE
θ	APPARENT GREENWICH SIDEREAL TIME AT T.

FIGURE 7

PROCEDURE SUMMARY FOR MAJOR U.S. AGENCIES

		ACIC	ESSA		NASA			SAO	
CAMERA	NAME	PC-1000	BC-4 (ASTRO)	BC-4 (COSMO)	MOTS 24	MOTS 40	PTH 100	BAKER-NUNN	K-50
	FOCAL LENGTH (mm.)	1000	305	450	610	1016	1016	500	1000
	APERTURE (mm.)	200	117		102	203	203	500	250
CATALOGUE		BOSS→SAO	SAO		SAO			SAO	
CALIBRATION	TYPE	PHOTO	PHOTO		PHOTO			ASTRO	
	NO. OF STARS	25-30	120		40-50			8-10	
	NO. OF SAT. IMAGES (PASSIVE)	-	600		-			1	
	NO. OF PARAMETERS	10 (EXT. INT.: 6 REFRACT.: 4)	14-20 (EXT. INT.: 6 DIST.: 6 NON⊥: 1 DIFF. SC.: 1 AVAIL.: 6)		8 (EXT. INT.: 6 REFRACT.: 2)			6	
	LENS DIST. PREDETERMINED	YES	NO		YES			–	
TIME SYNCHRONIZATION		ACTIVE SAT. ONLY *	PORTABLE CLOCK & VLF		ACTIVE SAT. ONLY			PORTABLE CLOCK & VLF	

		ACIC STAR	ACIC SATELLITE	ACIC TIME	ESSA STAR	ESSA SATELLITE	ESSA TIME	NASA STAR	NASA SATELLITE	NASA TIME	SAO STAR	SAO SATELLITE	SAO TIME
STAR UPDATING AND SATELLITE IMAGE CORRECTIONS	PROPER MOTION	C			M			C			C		
	PRECESSION	C			M,C			M				▨	
	NUTATION	C			C			C				▨	
	ANNUAL ABERRATION	C			C			C				▨ C	
	DIURNAL ABERRATION	C			C	▨ C (A.S.O.)		C				▨	
M: MATRIX CORRECTION C: CONVENTIONAL CORR. CP: CONVENTIONAL DURING PLATE PROCESSING P.S.O.: PASSIVE SAT. ONLY A.S.O.: ACTIVE SAT. ONLY	ASTRO. REFRACTION (GARFINKEL)	CP	– CP WITH ADJ. COEF.		CP	– CP		CP	– CP WITH ADJ. COEF.		IMPLICIT IN PLATE REDUCTION		
	PARALL. REFRACTION		▨			▨ C (P.S.O.)			C			▨	
	SAT. ABERRATION (LIGHT TIME)						C (P.S.O.)					▨	C TO.STA (A.S.O.)
	UTC → UT1			▨			C			▨			
	UTC → A.S.												C
	A.S. → UT1												▨
	PHASE (PASSIVE ONLY)					C						▨	

▨ : PRECESSING CORRECTION NEEDED

* SOME CAMERAS ARE BEING EQUIPPED WITH CHOPPING SHUTTERS

FIGURE 8

SAO PREPROCESSING FLOW CHART

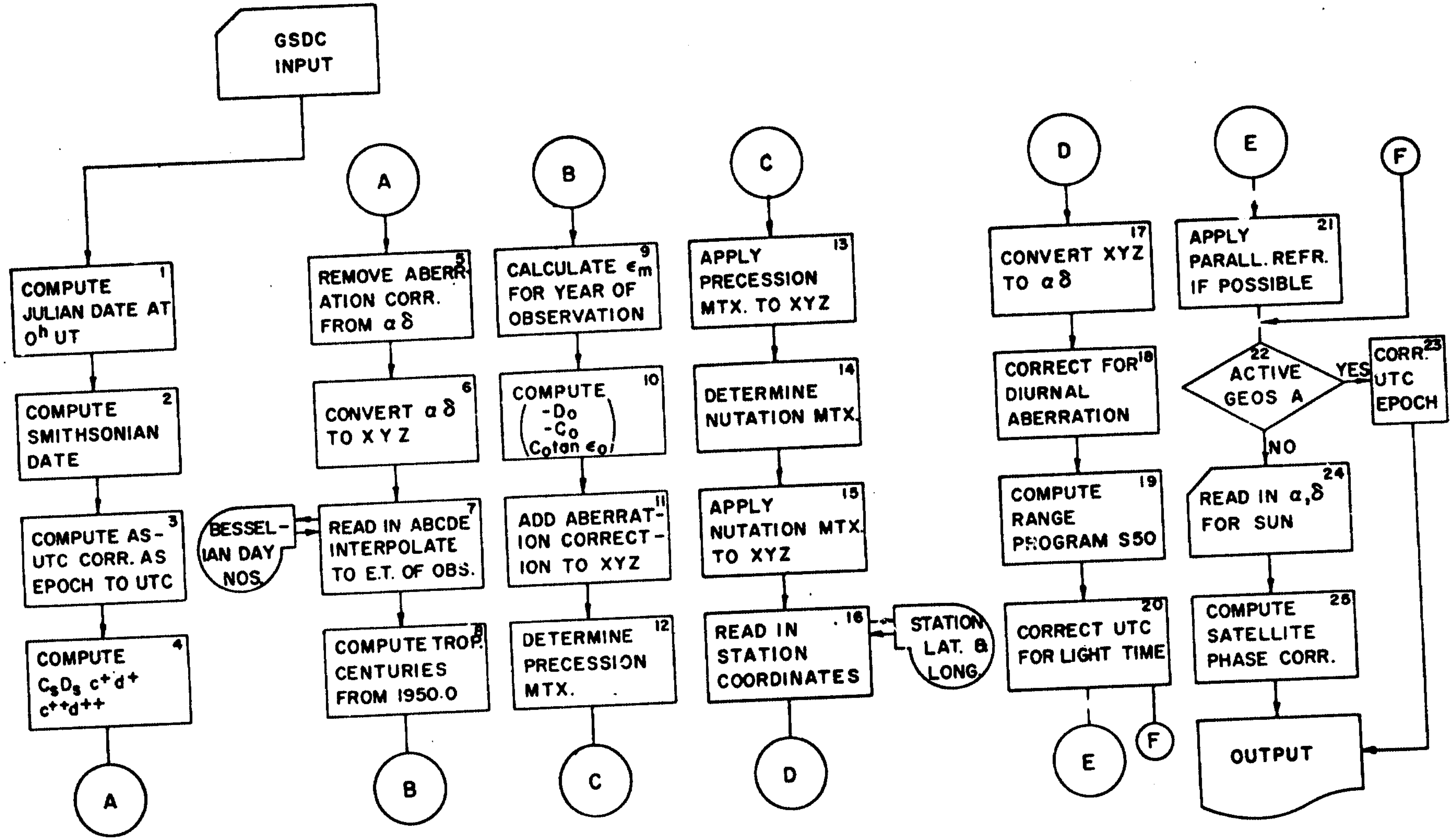


FIGURE 9

present, from the point of view of this program, only SECOR data is available at the GSDS in significant quantities.

SECOR-ranges in the NASA data center (as processed by USAETL) are the results of single pass adjustments. The corrections applied are (i) zero set, (ii) tropospheric correction, (iii) ionospheric correction. The zero set correction removes ambiguities in multiples of 256m. The tropospheric correction (TC) is computed by

$$TC = -\alpha_1/[(\sin E + (\sin^2 E + \ell^2)^{\frac{1}{2}}] \qquad (1)$$

where

$\alpha_1 = 2(n_0 - 1) \cdot H_0$

n_0 = index of refraction (ground level at observer)

H_0 = 7200m (height of troposphere)

E = altitude of satellite

$\ell^2 = 4\, H_0/Y_0$

Y_0 = geocentric distance of the observer

If two-frequency data (good, not noisy data) is available, the following ionospheric correction (IC) is computed:

$$IC = .7125\ [(D_1 - I_c) + BIC - AIC] \qquad (2)$$

where

$(D_1 - I_c)$ = the difference in readings of the two-frequency data

AIC = calibration value for the VF channel (computed from pre- and post-calibration information)

BIC = calibration value for the VFIC channel (also computed from pre- and post-calibration information)

If the two-frequency data is not available, the IC is computed as follows:

$$IC = 2/(\cos Z_1 + \sqrt{\cos^2 Z_1 + B_2 \sin^2 Z_1} \qquad (3)$$

where

$B_2 = 416667/(R + 200{,}000)$

$\sin^2 Z_1 = [(1 - \sin^2 E)R^2]/(R + 200{,}000)^2$

$\cos^2 Z_1 = 1 - \sin^2 Z_1$

R = range in meters

No approximations are needed for any of these corrections. The only approximations that are necessary are the satellite coordinates and velocity components (X, Y, Z, $\dot{X}$, $\dot{Y}$, $\dot{Z}$) at any selected epoch. These are the only parameters in the single pass least squares adjustment (which is essentially an orbit determination).

After the orbit has been determined, the orbital elements are constrained, and a range is computed from each tracking station at every one-second interval (this is a variable option). If the computed ranges agree (within a reasonable limit, which is also a variable option) with the corrected observed ranges, the data is deposited in the GSDS.

2.3 The Adjustment at The Ohio State University

2.3.1 General

The system of the least squares adjustment is shown in Figure 10. After preprocessing, the topocentric right ascensions and declinations are assumed to be free of systematic errors and are referred to the true equator and equinox of the epoch of the observation (UT1). Similarly, the topocentric ranges are also supposed to be free of systematic errors. The adjustment system is composed of three main parts:

(i) Formation of normal equations for optical or range data.

(ii) Addition of different groups of normal equations for optical or range data.

(iii) Solution of normal equations.

Four separate computer programs are involved--two for the formation of the normal equations, and one each for the addition and the

CONCEPT FLOW DIAGRAM OF ADJUSTMENT SYSTEM

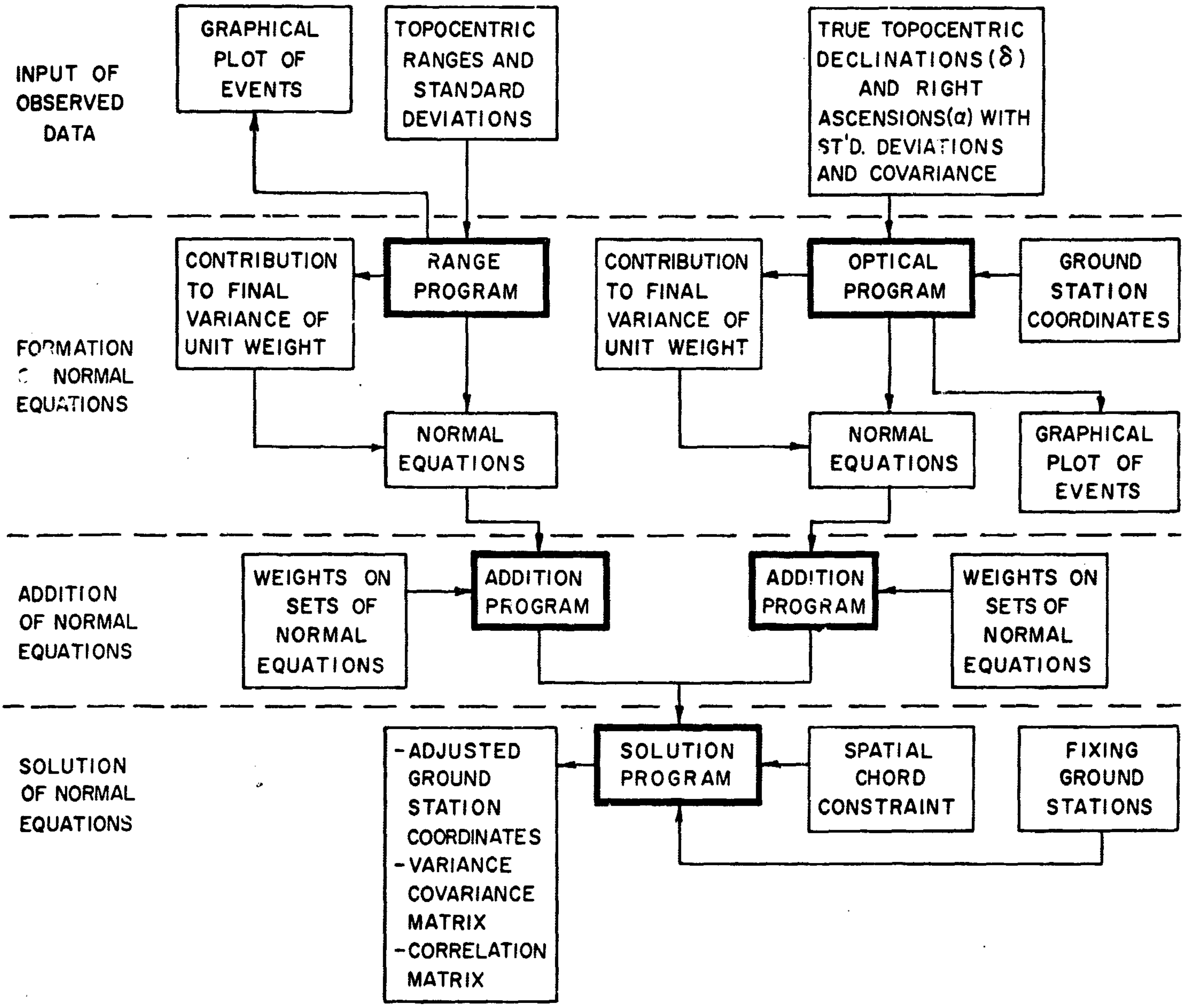


FIGURE 10

solution.

2.3.2 Formation of Normal Equations for Optical Observations

Formulation. The general form of the normal equations is

$$NX_g + U_g = 0$$

where N is the symmetric coefficient matrix whose diagonal is composed of the 3 x 3 matrices,

$$N_{kk} = \sum_j M^{-1}_{kj} + P_k - \sum_j M^{-1}_{kj} \left(\sum_i M^{-1}_{ij}\right)^{-1} M^{-1}_{kj} \qquad (4)$$

while its off-diagonal portion is composed of the 3 x 3 matrices,

$$N_{kl} = \sum_j M^{-1}_{kj} \left(\sum_i M^{-1}_{ij}\right)^{-1} M_{lj} \qquad (5)$$

X_g is the vector of unknown corrections to the preliminary Cartesian station coordinates; U_g is the vector of constant terms which is composed of the 3 x 1 vectors,

$$U_k = -\sum_j M^{-1}_{kj} \left[\overline{X}^o_k - \left(\sum_i M^{-1}_{ij}\right)^{-1} \sum_i M^{-1}_{ij} \overline{X}^o_i\right]. \qquad (6)$$

In the equations above, the subscripts have the following means: k and l denote particular ground stations; j is a particular event; i is any ground station participating in an event j; $\sum_i$ is the summation over all ground stations involved in event j; $\sum_j$ is the summation over all events observed by ground stations k and/or l; also

$$M_{ij} = B_{ij} P^{-1}_{ij} B'_{ij},$$

where P_{ij} is the 3 x 3 weight matrix of any observed direction, and

$$B_{ij} = R_2(-x_p) R_1(-y_p) R_3(\theta) R_3(-\alpha) R_2(-90^\circ + \delta) \begin{bmatrix} 1 & 0 & 0 \\ 0 & -\cos\delta & 0 \\ 0 & 0 & -1 \end{bmatrix},$$

further P_k is the 3 x 3 weight matrix associated with a particular ground station, and $\overline{X}^o_i$ is the preliminary rectangular coordinate vector of any ground station.

The computation of equation (4)-(6) forms the core of the computer program. The addition of independent sets of normal equations is straightforward and has the advantage that batches of optical data can be adjusted separately or as part of an "accumulated" adjustment.

The Computer Program. The input to the program consists of the approximate station coordinates and the observations which are grouped according to simultaneous events. The output consists of a compacted set of normal equations punched on cards. The compacting is such that a diagonal 3 x 3 matrix (referred to station k) is followed immediately in the row only by those non-zero 3 x 3 matrices which are referred to station co-observing with station k.

The capacity of the computer program is limited only by the total number of stations, the maximum being 150. There is no restriction on the number of simultaneous events because of the summation form of the normal equations.

In a study consisting of 40 ground stations (120 unknowns), execution time for the formation of the normal equations on the IBM 7094 was 1.9 minutes.

2.3.3 Formation of Normal Equations for Range Observations

The general form of the normal equations is the same as before,

$$NX_s + U_s = 0$$

where N is the symmetric coefficient matrix whose diagonal is composed of the 3 x 3 matrices,

$$N_{kk} = \sum_j a'_{kj} p_{kj} a_{kj} - \sum_j a'_{kj} p_{kj} a_{kj} \left[\sum_i a'_{ij} p_{ij} a_{ij}\right]^{-1} a'_{kj} p_{kj} a_{kj} ; \quad (7)$$

while its off-diagonal portion is composed of the 3 x 3 matrices,

$$N_{kl} = \sum_j \left[a'_{kj} p_{kj} a_{kj} \left(\sum_i a'_{ij} p_{ij} a_{ij}\right)^{-1} a_{lj} p_{lj} a_{lj}\right]. \quad (8)$$

X_s is the vector of unknown corrections; U_s is the vector of constant terms which is composed of the 3 x 1 vectors,

$$U_k = -\Sigma a'_{kj}\, p_{kj}\, \overline{v}_{kj}\,. \tag{9}$$

The subscripts and symbols in equations (7)-(9) have the same meaning as before except in the following: p_{ij} is the weight of any observed range,

$$a_{ij} = \left[\frac{u^o_j - u^o_i}{r^o_{ij}},\ \frac{v^o_j - v^o_i}{r^o_{ij}},\ \frac{w^o_j\ \ w^o_i}{r^o_{ij}}\right]$$

u^o, v^o, w^o are the approximate Cartesian coordinates in the average terrestrial coordinate system; $\overline{v}_{kj}$ is the residual of any observed range from a particular station (resulting from a preliminary least square adjustment of any simultaneous event with the stations held fixed).

All comments about the computer program made under Section 2.3.2 also apply to the ranging case, except that the maximum number of stations is slightly higher.

2.3.4 Solution of Normal Equations

<u>Formulation</u>. The reduction of N and U is carried out as follows (all quantities are either 3 x 3 matrices or 3 x 1 vectors):

$$\left.\begin{aligned} \overline{n}_{ij} &= \bar{n}_{ij} - \overline{n}'_{ki}\,\overline{n}^{-1}_{kk}\,\overline{n}_{kj} \\ \overline{u}_i &= \overline{u}_i - \overline{n}'_{ki}\,\overline{n}^{-1}_{kk}\,\overline{u}_k \end{aligned}\right\} \qquad \begin{aligned} k &= 1,2,\ldots,n \\ i &= k+1,k+2,\ldots,n \\ j &= i,i+1,\ldots,n \end{aligned}$$

and further

$$\begin{aligned} \bar{\bar{n}}_{ij} &= I & j &= i, \\ \bar{\bar{n}}_{ij} &= \overline{n}^{-1}_{ij}\,\overline{n}_{ij}\,, & j &= i+1,\ i+2,\ldots,n, \\ \bar{\bar{u}}_i &= \overline{n}^{-1}_{ii}\,\overline{u}_i\,, & i &= 1,2,\ldots,n. \end{aligned}$$

The back solution for X_i is

$$X_i = \sum_{k=i+1}^{n} \bar{\bar{n}}_{ik} X_k + \bar{\bar{u}}_i\,.$$

The formation of N^{-1} is

$$n^{ij} = \sum_{k=i+1}^{n} \bar{\bar{n}}_{ik} n^{kj} + \delta_{ij} \bar{n}_{ii}^{-1},$$

where $\delta_{ij} = 0$ for $i \neq j$; $\delta_{ij} = 1$ for $i=j$; and $n^{ij}=(n^{ij})'$.

The reduction, back solution, and the formation of the inverse is the core of this computer program.

The Computer Program. Two features peculiar to the program are:

(i) The coefficient matrix N is broken down into 3 x 3 submatrices, and similarly the U vector is treated as composed of 3 x 1 vectors.

(ii) The coefficient matrix N, its reduced counterpart $\bar{N}$, and N^{-1} are compacted so that 3 x 3 zero submatrices are neither stored nor used in the computation.

The first feature is achieved rather naturally; it is because of the form of expressions (4)-(9) which are used to build up N and U_s. On the other hand, the second feature is achieved through programming logic. Specifically, a first matrix L is used to tag each 3 x 3 non-zero submatrix of N with a row and column number. A second matrix F with a one-to-one correspondence to the first is then employed to tag the storage assigned to the particular 3 x 3 submatrix. The individual elements of the 3 x 3 submatrices are all stored in one large linear array E. For example, consider

$$L = \begin{array}{c} (1) \\ (2) \\ (3) \\ (4) \\ (5) \\ (6) \\ (7) \\ (8) \end{array} \begin{array}{c} \left[\begin{array}{ccccc} 2 & 3 & & & \\ 3 & 5 & 7 & 9 & \\ 4 & 5 & 6 & 7 & 8 \\ 7 & 8 & & & \\ 5 & 7 & 8 & & \\ 7 & 8 & & & \\ 8 & & & & \end{array}\right] \\ \end{array}$$

as depicting eight ground stations (listed along the left-hand side of the matrix) involved in a series of simultaneous events. The information reads as follows: Station (1) has at some time been involved with 3, 5, 7, and 9, and so on. So for L(3,5)=8, the 9 elements beginning with cell E (F(3,5)) are the elements of N_{38}, the 3 x 3 non-zero submatrix on row 3, column 8 of the coefficient matrix N.

The reduced elements of N are stored in the locations previously created for elements in N. During reduction additional 3 x 3 matrices arise in locations where there were none originally in N--thus "drag storage" must be assigned. In doing so, the guide matrix L and the storage tagging matrix F are updated to account for these additional matrices. Similar drag storage is also determined during the formation of the inverse N^{-1}.

Once the drag storage is determined, the reduction, back solution, and inverse determinations are guided by L, the storage located by F, and the elements to be used in the computation found in E.

The capacity of the computer program is determined by two factors--the total number of stations and the amount of drag storage created during reduction and inverse formation. The latter factor may be kept at a minimum by proper ordering of the ground stations in the normal equations. Thus the maximum number of ground stations is also around 150.

In a study consisting of 40 ground stations (120 unknowns) execution time on the IBM 7094 was 1.8 minutes; this included the determination of all correlation coefficients.

DOD GEODETIC SATELLITE EFFORTS WITH GEOS A AND GEOS B

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Department of Defense

Prepared For

GEOS PROGRAM REVIEW MEETING
12-14 December 1967

NASA HEADQUARTERS
400 Maryland Avenue, SW
Washington, D. C.

DOD GEODETIC SATELLITE EFFORTS WITH GEOS A AND GEOS B

Col. J. O'Donnell
Department of Defense

The U.S. (DOD) embarked upon a geodetic satellite observation program with the successful launching of ANNA I B on 31 October 1962. As early as 1961, there had been satellites containing (Navy) doppler transponders and Army SECOR transponders which were included as secondary payloads (piggy-back) aboard vehicles launched for other scientific purposes. However, ANNA and these individual satellites did not provide sufficient data to meet the requirements.

Therefore, a proposed program which specified vehicles, their orbital parameters, and schedules was designed as shown in Figure 1. The satellites launched, or planned, under the NGSP include: Beacon Explorer-B; Beacon Explorer-C; GEOS A, Pageos, and GEOS B. The DOD is utilizing data from four systems as shown in Figure 2, two optical and two electronic, to achieve the necessary objectives. The optical are the BC-4 (450 mm focal length stellar camera) and the PC-1000 (1000 mm focal length stellar camera). Both are equipped with chopping shutters and are capable of observing both passive and active satellites. The electronic systems are SECOR (acronym for Sequential Collation of Range) and the doppler.

A significant portion of the DOD geodetic satellite effort is the participation in the NGSP, the basis of which is the BC-4 or Pageos primary geometric network as shown in Figure 3. Basically, the DOD participation in the NGSP includes any electronic or optical observations of the satellites previously shown, from any of the approximately 42 stations in the primary network. The NGSP data is unclassified and includes observations from each of the DOD systems. Other unclassified DOD geodetic satellite data has been and will continue to be made available to the NASA geodetic satellite data service, even though it is not part of the NGSP.

Since this meeting is primarily concerned with a status report on GEOS A and the intended use of GEOS B, I will confine my remaining remarks primarily to the utilization of these two satellites even though these provide only a part of the observations which are being obtained.

DOPPLER - GEOS-A

The GEOS A doppler subsystem (which continues to be operational) has provided data to the Navy's doppler satellite tracking network (TRANET) since its launch on 6 November 1965. TRANET acquires and processes doppler frequency shift data from several satellites in different inclinations. The GEOS A doppler data along with the data from other satellites are used in determining the earth-centered positions for various locations and to better define the model of the earth's gravity field. The GEOS A inclination, 59°, was chosen specifically to aid in the gravity model solutions.

GEOS A data have been taken by forty-five (45) stations, including the 13 station fixed TRANET network. Thirty-two (32) of the stations were occupied by mobile tracking vans each for a period of approximately six weeks. Eighteen of forty-five stations are part of the Pageos primary geometric network. As shown in Figure 4, plans are to locate at most of the primary network stations in order to provide a means of relating the relative geometric network, obtained from the camera observations, to the center-of-mass of the earth. Approximately three months of doppler observations from GEOS A were combined with data from satellites at six other inclinations for the most recent solution.

GEOS B UTILIZATION-DOPPLER

As was the case with GEOS A, the GEOS B doppler subsystem will be observed by the TRANET. The seventy-four (74°) degree retrograde orbit was selected to provide data at an inclination which is important for the earth gravity model analysis. GEOS B will also provide an additional transponder to aid in positioning the remaining primary network stations.

Also the doppler will participate with the laser systems and SECOR in a GEOS B systems co-observation experiment. The system will observe GEOS B simultaneously from a common location. This should provide valuable information concerning the effect of the ionosphere on the electronic signals.

Another point worth mentioning here is the development of a miniaturized doppler receiver or geoceiver , shown in Figure 5, which weighs less than 80 pounds. The prototype version is scheduled for delivery in January, with 10 operational units scheduled for delivery in late 1968.

SECOR - GEOS-A

The SECOR transponder on GEOS A provided valuable ranging data for SECOR stations during operations to accomplish inter-datum and inter-island ties in addition to being the primary tool for the intercomparison test. GEOS A was observed from the quad (Hunter AFB, Georgia; Homestead AFB, Florida; Greenville, Mississippi; and Herndon, Virginia) during the period of 29 December 1965 through 1 May 1966 for the purpose of systems intercomparison. (The test will later be discussed in detail by Mr. Anderle, NWL.) GEOS A was also observed from 24 May 1966 through 8 February 1967, to aid in the completion of the tie from Tokyo to Hawaii, Figure 6, and the first phase of the SECOR equatorial belt. A total of fourteen (14) SECOR stations acquired GEOS A data during the latter operations. SECOR ranging data acquired in these operations is being transformed into the format requested by NASA and will be furnished to the NASA Data Center upon completion.

I would like to mention at this point that some noise difficulty was encountered in the GEOS A SECOR transponder during the observations. It was first thought that this interference was the result of the doppler transponder. About 11 March 1966, TRANET was turned off for a period of one week so that tests could be made to determine if in fact the doppler transponder was the culprit. The test indicated that even with the TRANET turned off an interference still existed although at a somewhat diminished rate. The situation later improved and the GEOS A SECOR transponder proved very valuable in the S.W. Pacific operations and in the initial phase of the equatorial belt.

SECOR - GEOS-B

Immediately following the launch of GEOS B, now scheduled for mid January 1968, a SECOR station will be deployed to Wallops Island, to participate in an intercomparison test with NASA laser. The tests are presently scheduled for April 1968. Army, however, will occupy the test site earlier in order to eliminate any problems that may develop prior to observation.

Army and NASA representatives are working out the details for the intercomparison tests. It is believed that this test will furnish very valuable information concerning ray path and calibration data. As agreed upon, Army will expedite the reduction and publishing of test data.

After completion of the current SECOR equatorial network now scheduled for September, 1968, plans are to utilize the SECOR systems for accomplishing densification programs (Figure 7) in the areas such as Africa to support mapping and charting efforts. At this time, the 800 n. mi. GEOS-B will be used in the Army operational SECOR program. Another satellite scheduled to be launched in this time frame with a SECOR transponder aboard will be the NIMBUS, now planned for late March 1968. GEOS-B and the NIMBUS SECOR satellite will both be used in the densification program.

BC-4 - GEOS A

Under arrangements between C&GS and NASA, the C&GS BC-4 cameras observed GEOS-A on a non-interference basis (see Figure 3). The Army BC-4 cameras were primarily concerned with observation of Pageos and the ECHO satellites.

BC-4 - GEOS-B

The use of GEOS-B in the BC-4 camera program, both by Army and C&GS, will be increased as a result of the requirement for co-observation with the Air Force PC-1000 cameras in South America. Also, we expect that the BC-4's will co-observe with the SAO Baker-Nunn and the NASA MOTS cameras to tie these to the basic network. It is expected that the increasing degradation of the ECHO I satellite will result in an increased use of the GEOS-B satellite for the shorter lines of the Pageos network. Parenthetically, the demise of ECHO I is predicted for mid-summer of 1968 during the height of the solar storms.

GEOS-A PC-1000

The PC-1000 cameras have been engaged in satellite observations for geodetic position determinations since the launch of ANNA 1-B. In October 1964 they were deployed to the southeast U.S. along with other systems to "provide comparative information necessary for integration of data obtained" from the geodetic systems participating in the geodetic satellite program. Later in the same year, this project was expanded to include stations on the Eastern Test Range (ETR) to satisfy certain geodetic requirements of the Air Force Systems Command. The tie extended from Cape Kennedy to Trinidad. These two projects were completed by observing ANNA 1-B and GEOS-A. The latter permitted an accelerated completion in early 1966; 92 percent of the ETR-1 data was GEOS-A. PC-1000 cameras observed 75 GEOS-A events in the final positioning of Trinidad. Utilizing this data an 8.4 meter (spherical standard error) accuracy was achieved in positioning Trinidad relative to the Florida triangulation.

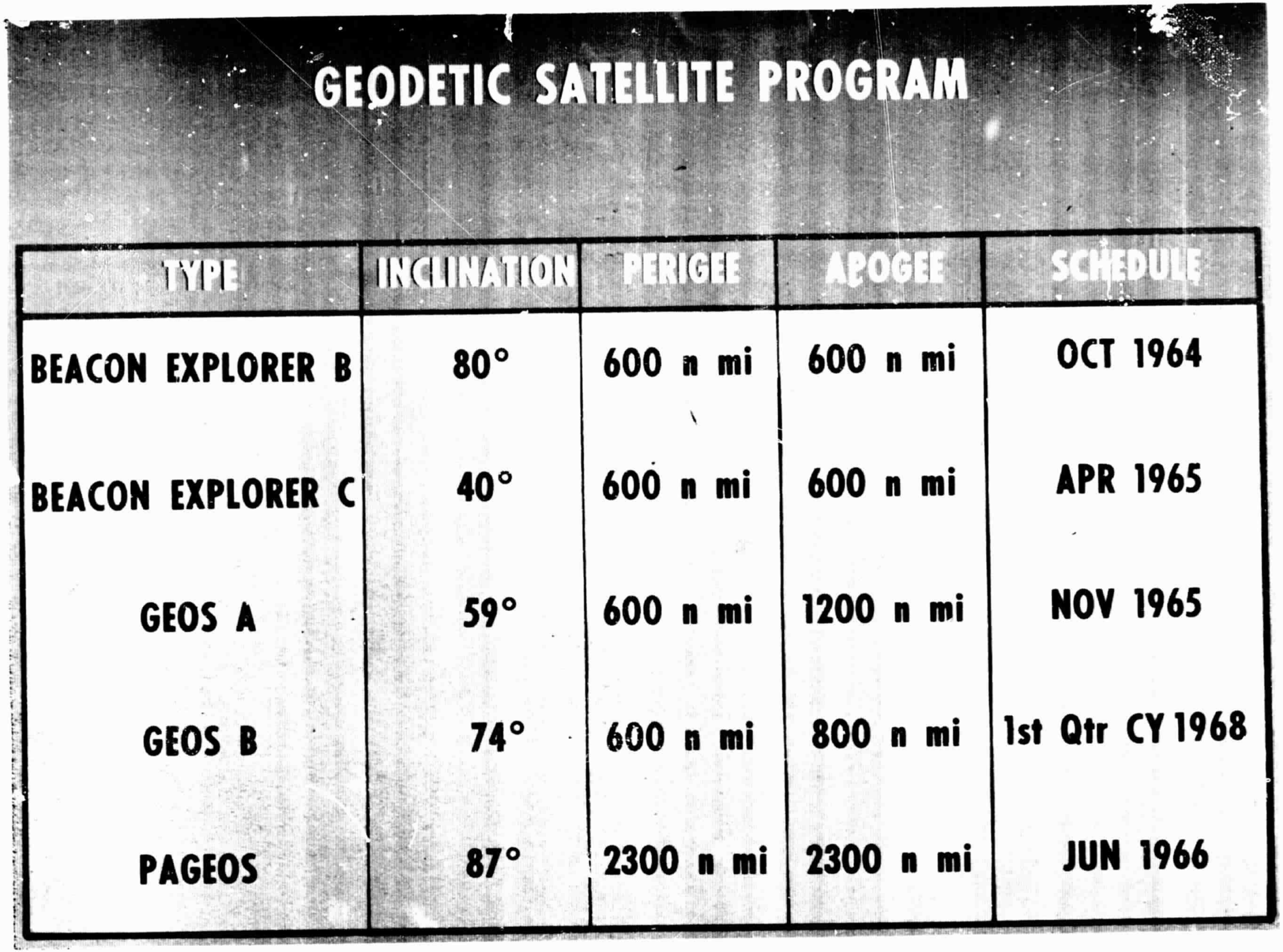
GEOS-B PC-1000 (Figure 9)

The PC-1000 cameras will continue to be used by the USAF to satisfy various DOD requirements. The cameras are now equipped with chopping shutters so that observations of both passive and active satellites are possible. Data obtained by observing GEOS-B in addition to the passive satellites will be used to:

A. Accomplish control densification in such areas as South America to support mapping and charting programs. The densification network(s) will be tied to the Pageos primary network by co-observing with the BC-4 sites. Air Force teams and PC-1000's are presently located in South America at Bogota, Curacao, Trinidad, and Paramaribo. It is our intention to extend the network to complete a control densification of South America.

B. PC-1000 cameras will also observe GEOS-B to improve the accuracy of space tracking sites. Again these will be tied into the primary network by co-observation.

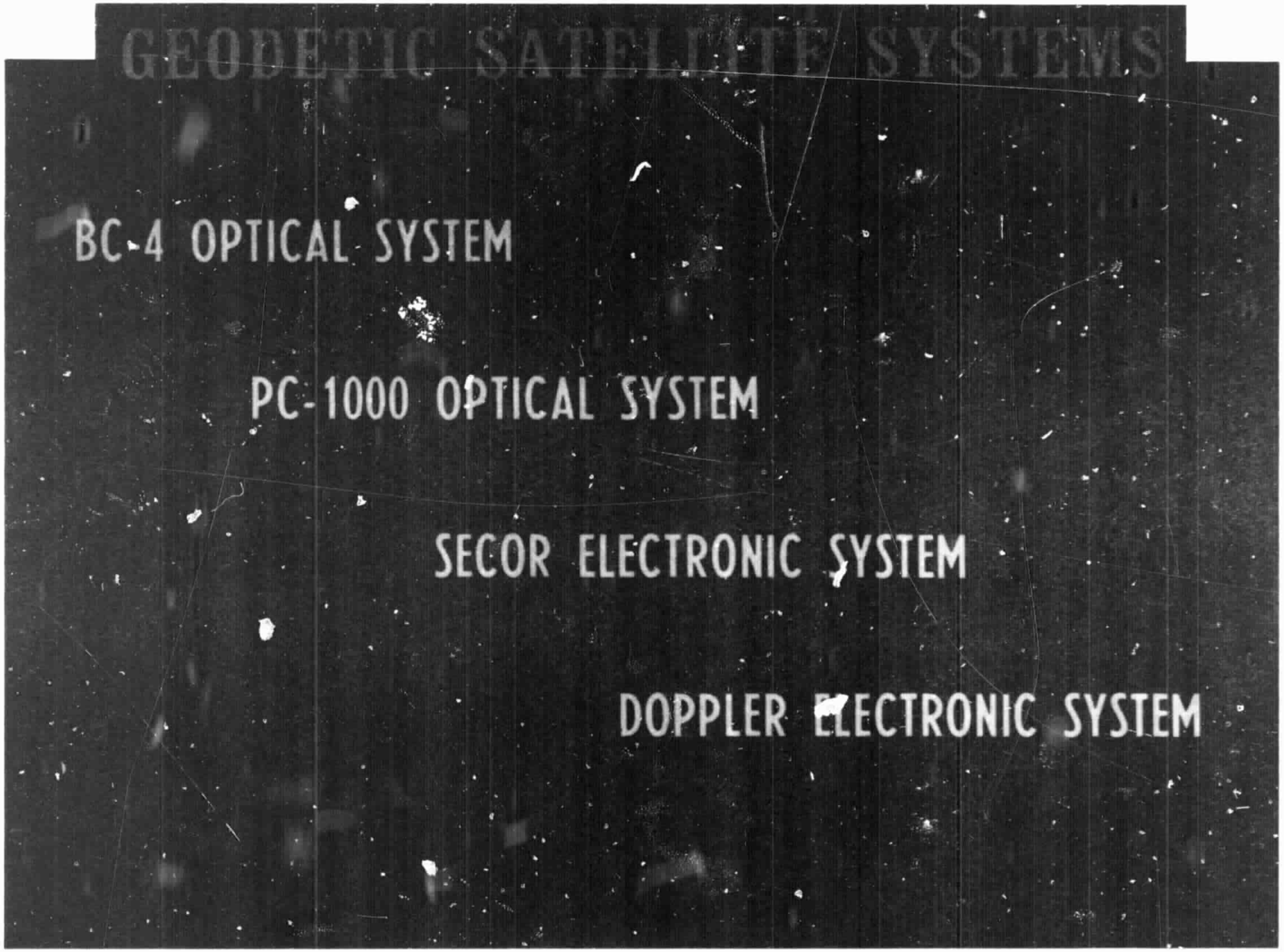
C. Calibration of tracking radars.



GEODETIC SATELLITE PROGRAM

TYPE	INCLINATION	PERIGEE	APOGEE	SCHEDULE
BEACON EXPLORER B	80°	600 n mi	600 n mi	OCT 1964
BEACON EXPLORER C	40°	600 n mi	600 n mi	APR 1965
GEOS A	59°	600 n mi	1200 n mi	NOV 1965
GEOS B	74°	600 n mi	800 n mi	1st Qtr CY 1968
PAGEOS	87°	2300 n mi	2300 n mi	JUN 1966

Figure 1



GEODETIC SATELLITE SYSTEMS

BC-4 OPTICAL SYSTEM

PC-1000 OPTICAL SYSTEM

SECOR ELECTRONIC SYSTEM

DOPPLER ELECTRONIC SYSTEM

Figure 2

AMS-C&GS SATELLITE OBSERVATION PROGRAM

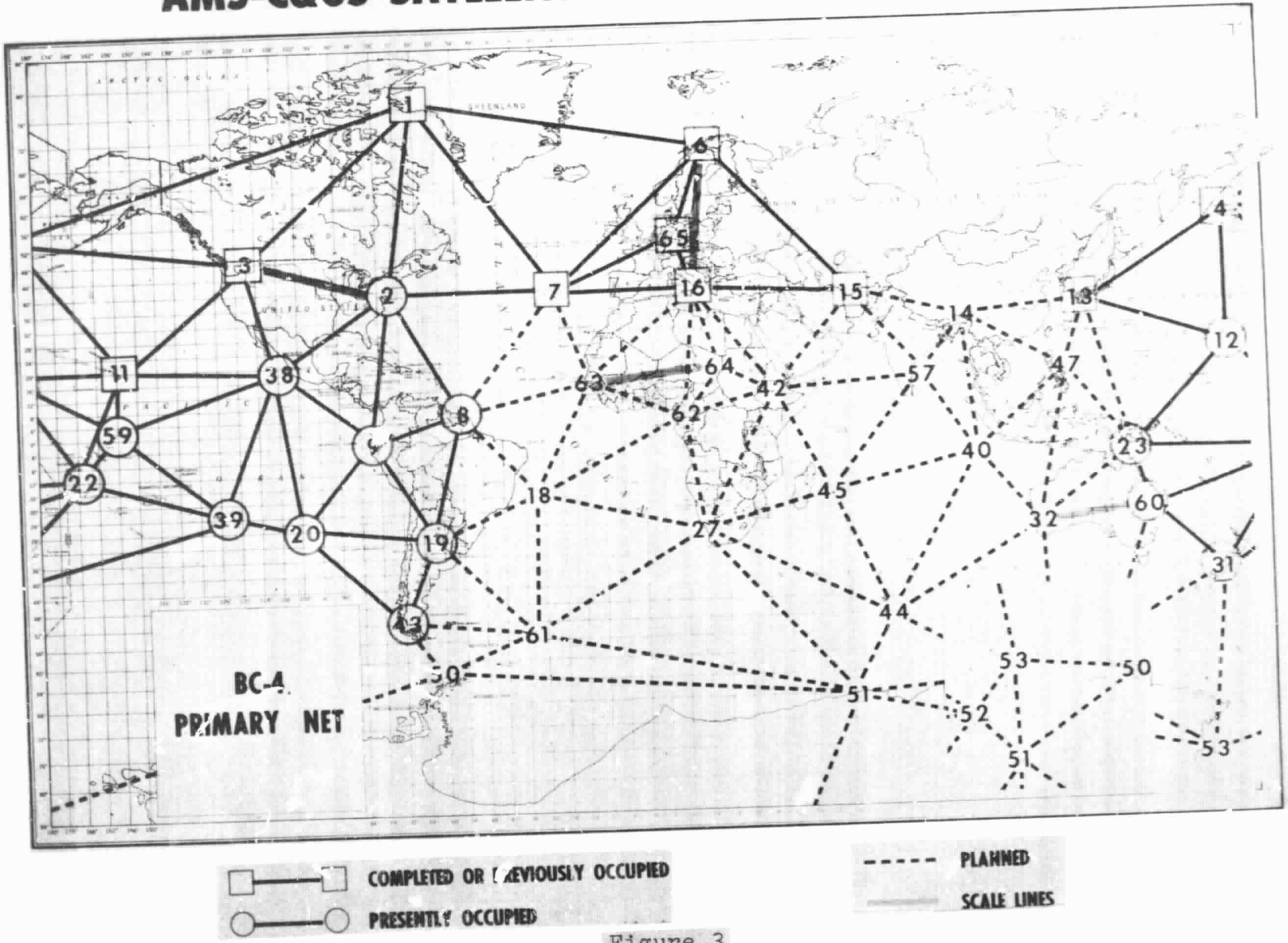
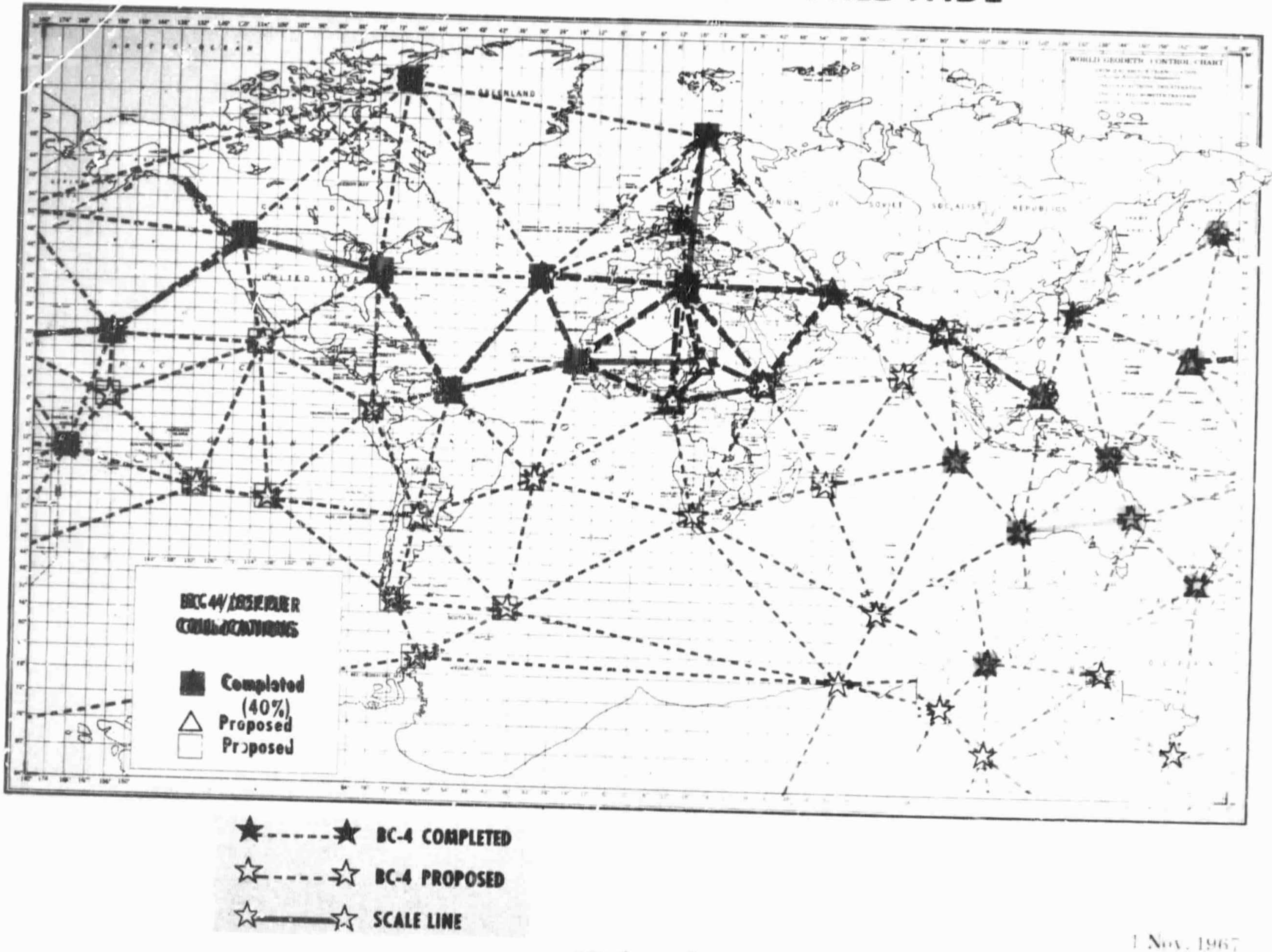


Figure 3

COLLOCATED SYSTEMS WORLDWIDE



1 Nov. 1967

Figure 4

GEOCEIVER SYSTEM

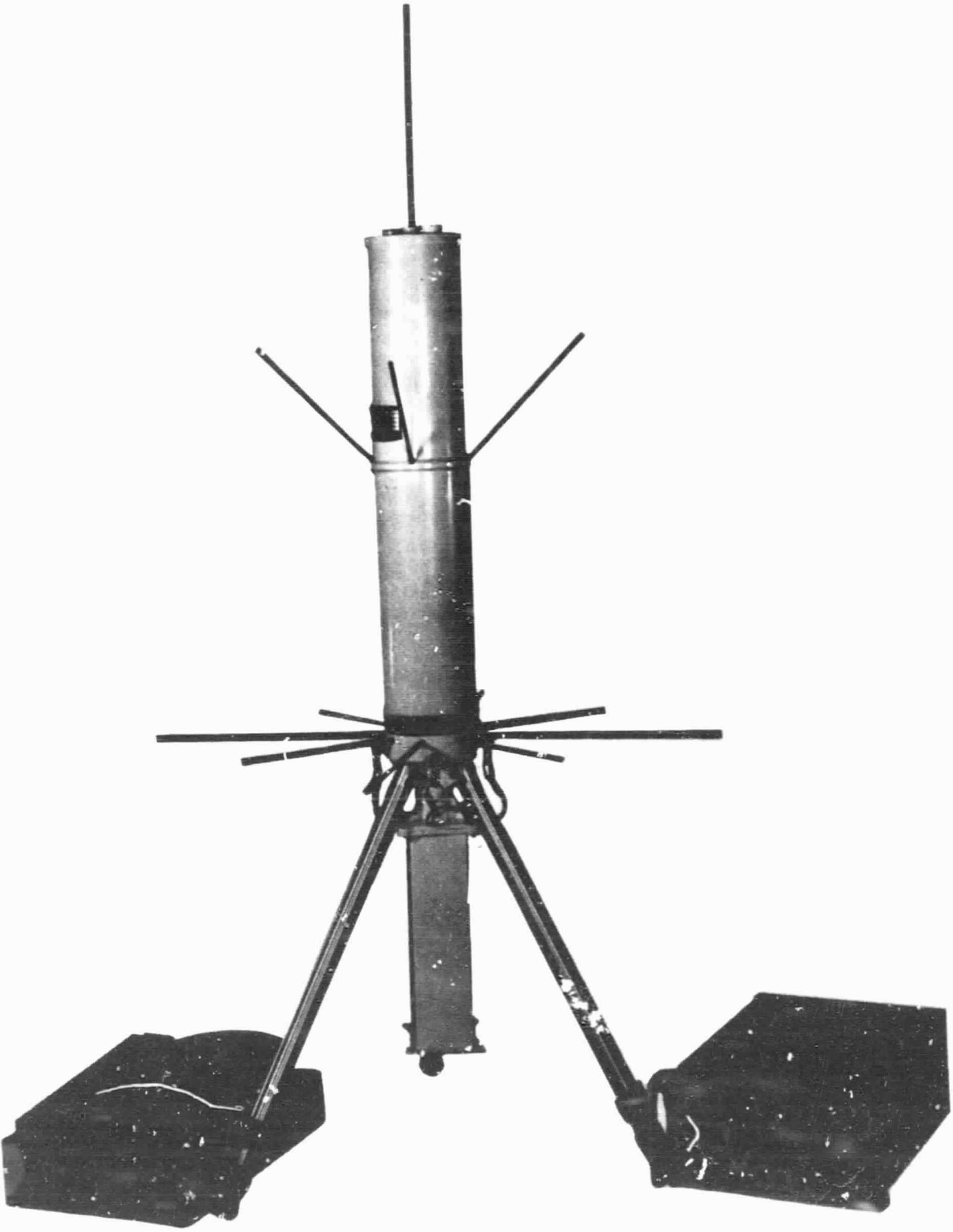


Figure 5

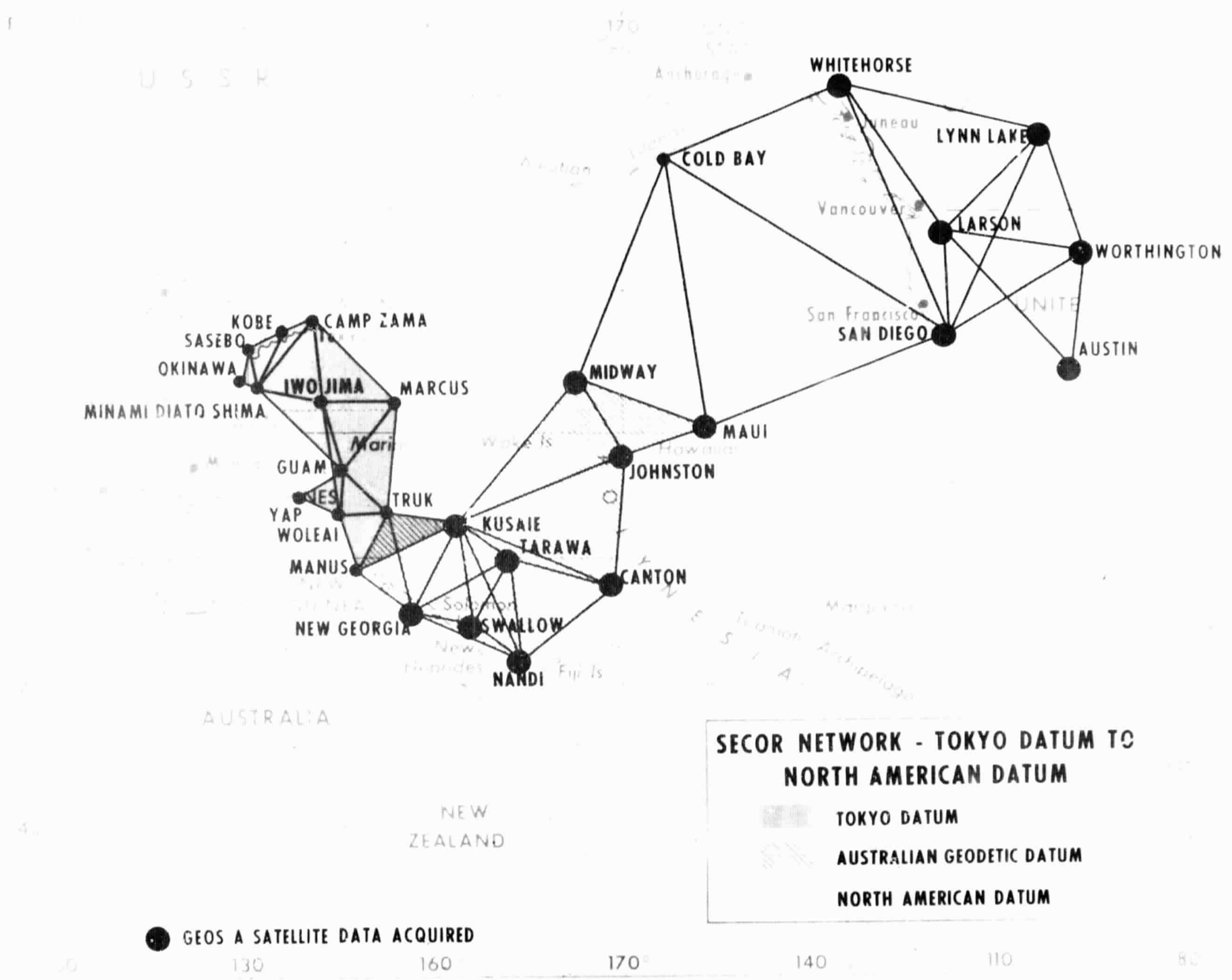
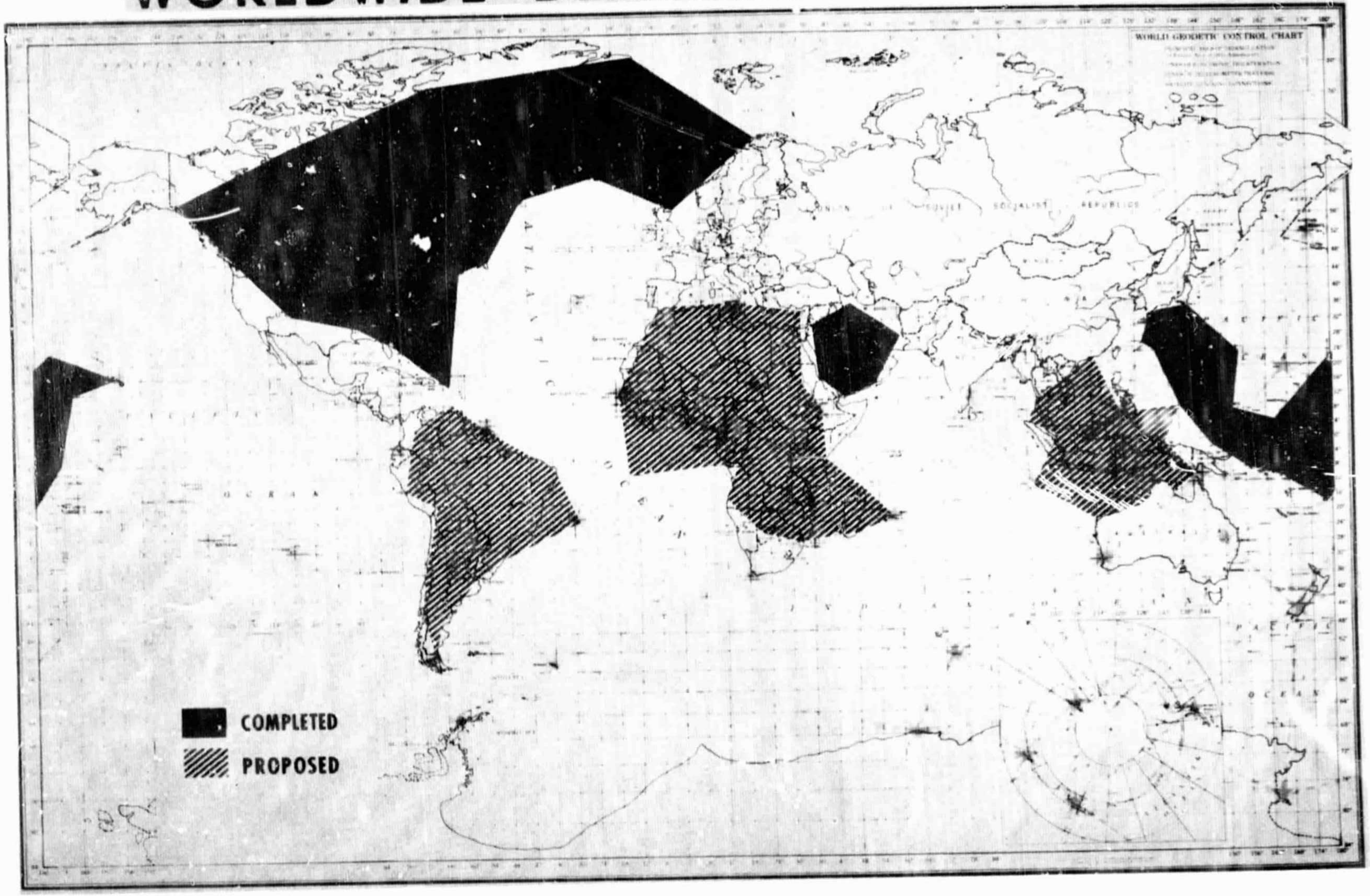

WHITEHORSE
LYNN LAKE
COLD BAY
LARSON
WORTHINGTON
SAN DIEGO
AUSTIN
MIDWAY
MAUI
JOHNSTON
KOBE
CAMP ZAMA
SASEBO
OKINAWA
IWO JIMA
MARCUS
MINAMI DIATO SHIMA
GUAM
YAP
TRUK
WOLEAI
KUSAIE
TARAWA
MANUS
CANTON
NEW GEORGIA
SWALLOW
NANDI
U S S R
Anchorage
Juneau
Vancouver
San Francisco
Hawaii
Wake Is
Fiji Is
AUSTRALIA
NEW ZEALAND
SECOR NETWORK - TOKYO DATUM TO NORTH AMERICAN DATUM
TOKYO DATUM
AUSTRALIAN GEODETIC DATUM
NORTH AMERICAN DATUM
GEOS A SATELLITE DATA ACQUIRED
130
160
170
170°
140
110
80

Figure 6

WORLDWIDE DENSIFICATION AREAS



1 Nov. 1967

Figure 7

GEODETIC POSITIONING
AF 65-WGS-2 & ETR 1

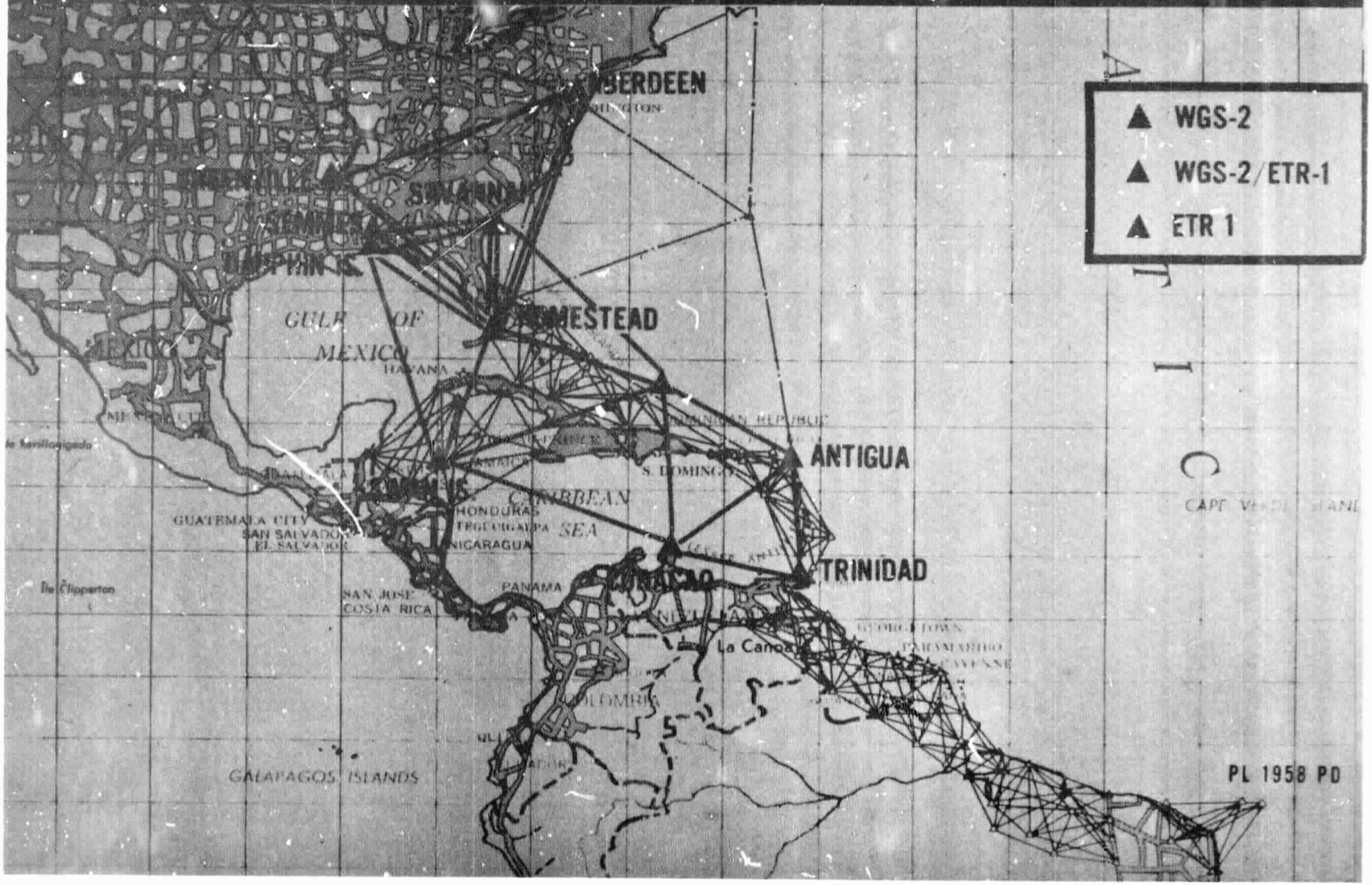


Figure 8

PROJECT: AF67-27
SOUTH AMERICA DENSIFICATION

Figure 9

DEPARTMENT OF DEFENSE GEOS-A
COMPARISON TESTS

R. J. Anderle

U. S. Naval Weapons Laboratory

Dahlgren, Virginia

November, 1967

The Army SECOR (Sequential Collation of Range), the Navy Doppler, and the Air Force PC-1000 camera systems are engaged in operational missions with the objective of bringing the various geodetic datums and isolated sites into an improved world geodetic system. Each of the systems has undergone evaluations at one time or another. However, the start of the construction of precision base lines in Southeastern United States by Coast and Geodetic Survey with the use of geodimeters provided an improved terrestrial standard for tests of the accuracy of the satellite systems. The Department of Defense therefore requested the services to position their equipment on the base lines and to execute new tests. With the subsequent launch of the GEOS-A satellite, the geodetic community was provided with the means of making more direct comparisons of satellite measurements by diverse observing equipment. Since it then became more important to coordinate the efforts of the three services, a Tri-Service committee was established under the chairmanship of John McCall, Office of the Chief of Engineers, to direct the tests. A subgroup of this committee was then organized to analyze and report the results of the experiment. The subgroup had the following membership:

<u>NAVY</u>

R. J. Anderle, NWL (Chairman)

ARMY

L. A. Gambino, GIMRADA

A. Mancini, GIMRADA (Alternate)

G. Dudley, AMS

E. H. Rutscheidt, AMS (Alternate)

AIR FORCE

G. Hadgigeorge, AFCRL

D. Huber, ACIC

This report is a summary of the findings of this committee based principally on agency reports prepared by members of the committee and by:

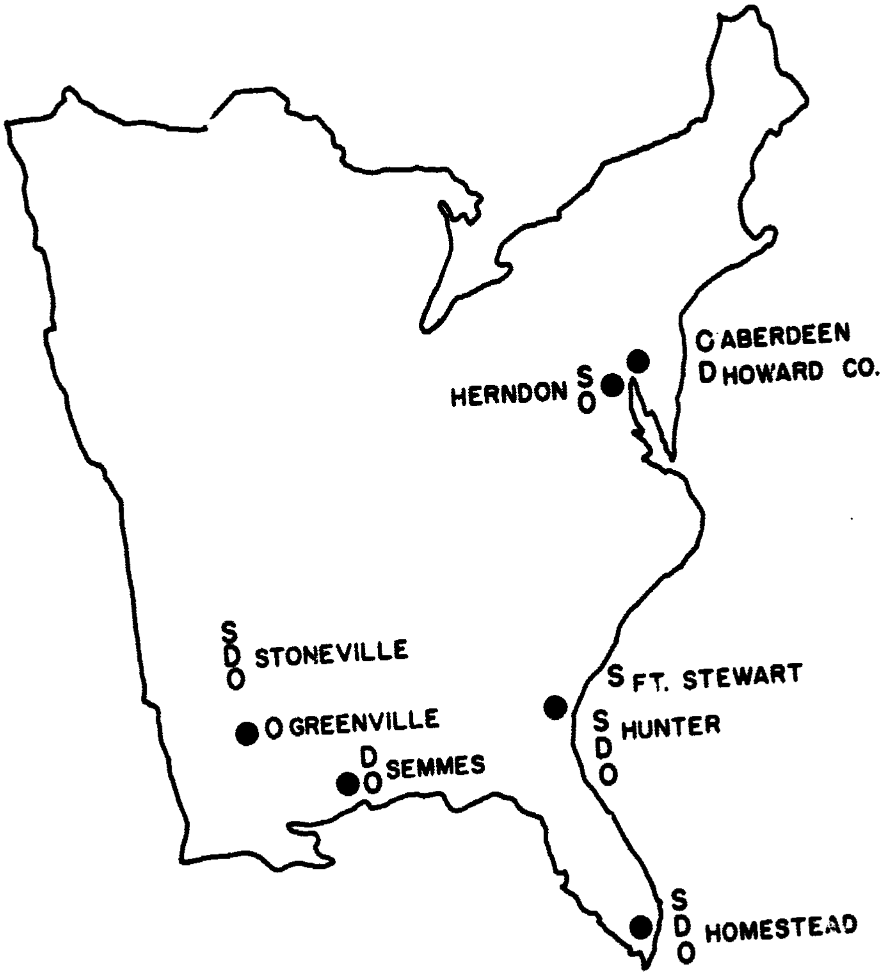
Marvel A. Warden, AMS

Robert W. Hill, NWL

William L. Gleiber and Charles Weiss, ACIC

The SECOR, Doppler and optical equipment were deployed on the Southeastern United States geodimeter base line at the locations shown in figure 1. The geodimeter coordinates of the sites on the Cape Canaveral Datum and the time periods of occupation are shown in table 1. The changes of the SECOR equipment from Ft. Stewart to Hunter and of the optical equipment from Greenville to Stoneville were made following the launch of the GEOS-A satellite in order that simultaneous measurements could be made on the satellite by different equipment from the same site. Since the Doppler equipment had completed the tests planned initially at Hunter, Homestead and Semmes

STATION SITES EMPLOYED IN INTERCOMPARISON TESTS



INSTRUMENTATION SYSTEMS:
S – SECOR
D – DOPPLER
O – OPTICAL

FIGURE 1

TABLE 1

CAPE CANAVERAL DATUM COORDINATES AND TIME PERIOD OF OCCUPATION OF SITES USED IN COMPARISON TESTS

Site	Equipment	Station Number	Latitude	Longitude	Height (msℓ)	Geoid Height Used	Period of Occupation
Jupiter, Fla.	Optical		27° 01' 13.16"N	80° 06' 47.31"W	14.9 m	- 1.3 m.CCD	
Homestead, Fla.	Doppler	734	25° 30' 25.83"N	80° 2[illegible]' 16.82"W	7.5 m	5.0 m.NAD	9 Apr 65-25 May 65
	Optical	3861	25° 30' 24.78"N	80° 23' 17.33"W	2.4 m	5.6 m.CCD	9 Apr 65- 7 Feb 66
	SECOR	--	25° 29' 21.27"N	80° 22' 20.65"W	2.7 m	10.0 m.NAD	8 Nov 65- 1 May 66
Ft. Stewart, Ga.	SECOR	--	31° 55' 18.53"N	81° 33' 59.87"W	23.9 m	.5 m	8 Nov 65-11 Mar 66
Hunter, Ga.	Doppler	735	32° 0' 3.90"N	81° 09' 17.14"W	18.5 m	+ 2.0 m.NAD	9 Apr 65- 6 June 65
	Optical	3648	32° 0' 6.01"N	81° 09' 13.79"W	12.7 m	- [illegible] m.CCD	9 Apr 65- 7 Feb 66
	SECOR	--	32° 0' 4.18"N	81° 09' 16.98"W	14.0 m	0.5 m.NAD	20 Mar 65- 1 May 66
Semmes, Ala.	Doppler	736	30° 46' 49.80"N	88° 15' 7.95"W	78.6 m	3.0 m.NAD	9 Apr 65-25 May 65
	Optical	3402	30° 46' 49.23"N	88° 15' 7.69"W	72.7 m	4.0 m.NAD	9 Apr 65- 7 Feb 66
Stoneville, Miss.	Doppler	745	33° 25' 31.46"N	90° 54' 49.45"W	43.9 m	+ 3.0 m.NAD	12 Jan 66-15 Mar 66
	Optical	333A	33° 25' 31.84"N	90° 54' 48.80"W	38.5 m	6.3 m.NAD	Jan 66- June 66
	SECOR	--	33° 25' 32.23"N	90° 54' 49.36"W	38.6 m	6.3 m.NAD	8 Nov 65- 1 May 66
Greenville, Miss.	Optical	333	33° 28' 48.86"N	91° 0' 10.98"W	40.3 m	6.3 m.NAD	May 65- Dec 65
Herndon, Va.	Optical	--	--	--	--	--	Mar 66- June 66
	SECOR	--	38° 59' 38.04"N	77° 19' 43.43"W	118.4 m	- 1.5 m.NAD	Permanent
Howard Co., Md.	Doppler	111	39° 09' 48.17"N	76° 53' 49.08"W	145.0 m	- 2.0 m.NAD	Permanent

prior to the launch of the GEOS-A satellite, the only Doppler data taken simultaneously with SECOR or optical data were observed at Stoneville and Howard County. Three types of solutions for station and satellite positions were used during the course of the analysis: geometric, short local arc, and short worldwide arc. The geometric method uses the satellite as a reference point simultaneously observed by at least two optical stations or at least three SECOR stations to establish equations of condition for the solution of each satellite position observed and for the station positions. No attempt was made to analyze Doppler observations by this procedure since simulations conducted in the past indicated that the solution would be statistically weak. In the short arc procedure, a set of orbit parameters for each passage of the satellite across the station net and the coordinates of the stations are the unknowns of the solution, while the dynamic equations of motion are used to permit independent observations of the satellite to be made by each station during the satellite crossing of the net. Doppler and SECOR short local arc solutions were made using data from the stations listed in table 1. Doppler short worldwide arcs were also made using data from additional stations not shown in the table. SECOR and optical solutions were normally made in a reference frame defined by the Cape Canaveral Datum since the terrestrial coordinates were given in that frame. Since tests showed that differences between coordinates on the Cape Canaveral Datum and corresponding

TABLE 2

OBSERVATIONAL MATERIAL USED

IN SOLUTION FOR HUNTER, GEORGIA

Equipment	Sites	Number of Passes	Time Period Of Observation
SECOR	Homestead, Fla.	47	20 Mar 66- 1 May 66
	Hunter, Ga.	47	"
	Stoneville, Miss.	47	"
	Herndon, Va.	47	"
Doppler	Homestead, Fla.	148	20 Apr 65-17 May 65
	Hunter, Ga.	148	"
	Semmes, Ala.	148	"
	Howard County, Md.	148	"
Optical	Homestead, Fla.	11	9 Apr 65- 7 Feb 66
	Hunter, Ga.	19	"
	Semmes, Ala.	10	"

coordinates on the Mercury Datum would produce irreconcilable results in Doppler short arc solutions, the Doppler analyses made use of transformations between the Cape Canaveral and the Mercury system (for short local arcs) or between the Cape Canaveral and the NWL-8D system (for short worldwide arcs). (While a similar bias could result for SECOR short arcs, the time spans used in the tests discussed here were sufficiently short so that the effect was negligible.)

Since very few simultaneous observations were made on the satellite by the three systems, it was necessary to compare solutions for station coordinates made using non-simultaneous data taken by each system. The observational material used in each solution is summarized in table 3. The data taken by each system at the sites listed in the table were used to determine the position of Hunter, Georgia, on the basis of the geodimeter measurements of the positions of the other sites. The differences between the geodimeter coordinates for Hunter and the coordinates determined in SECOR geometric, Doppler short arc and optical geometric solutions are shown in table 3. The estimated errors in the body of the table correspond to the residuals of observation and are based on the assumption that the coordinates of the other sites used in the solution are known perfectly. The corresponding Doppler solution considering uncertainties in the coordinates of the other sites is given in the footnote. The SECOR and Doppler differences in the

TABLE 3

COMPARISON OF DETERMINATIONS OF POSITION OF HUNTER WITH GEODIMETER SURVEY

(SURVEY MINUS INTERVISIBLE SATELLITE)*

Latitude: Positive North
Longitude: Positive East

Equipment	Latitude (Meters)	Longitude (Meters)	Height (Meters)
SECOR	- 3.7 ± 0.4	+ 5.0 ± 0.4	+ 1.5 ± 0.3
Doppler**	- 0.6 ± 0.4	- 1.4 ± 0.6	- 5.6 ± 0.5
Optical	+ 3.1 ± 1.7	+ 1.8 ± 1.6	+ 0.4 ± 3.1

*Standard deviations indicate the error corresponding to the residuals of the intervisible satellite solution

**The Doppler solution including the effects of assumed uncertainties in the Cape Canaveral Datum coordinates of Semmes and Howard Co. of $\frac{1}{500,000}$ of the distances from Homestead to the sites is as follows:

- 1.5 ± 0.9	- 1.0 ± 1.1	- 4.6 ± 1.2

body of the table are significant compared to the standard deviations corresponding to perfect station coordinates; the more realistic comparison given for Doppler solution in the footnote is fairly reasonable. Consideration of station coordinate uncertainties would also improve the SECOR comparison, while the optical comparison is satisfactory as given. In all three instances the differences are within the accuracies desired for operational use.

Comparisons of satellite positions determined by SECOR and Doppler equipment were not made because the SECOR equipment was experiencing electrical interference problems during the time period the Doppler equipment was deployed at Stoneville. Comparisons of SECOR and optical positions determined geometrically are shown in table 4 on the Cape Canaveral datum, where possible, and on the North American Datum, when observations from more distant optical stations were used. The standard deviation of the optical solution corresponds to the residuals of observations, or one second arc, whichever was greater. The 5 meters used for the standard deviation for the SECOR positions was selected arbitrarily. The final column of numbers is the ratio of the difference in satellite position divided by the estimated accuracy of the measurement of the difference. These position differences, accuracies of measurement and ratio are summarized in table 5. The differences appear to be significantly large, but there was insufficient information to trace the source of

TABLE 4

INDIVIDUAL COMPARISONS OF SATELLITE POSITIONS
DERIVED FROM OPTICAL AND SECOR OBSERVATIONS

	Time				Position Difference(m)				Random Error(m)			Ratio	
Orbit	Hr	Min	Sec	Date	ΔX	ΔY	ΔZ	Total	Optical	Range	rms	Diff/Error	
1874	8	16	00	12 Apr '66	- 41.	- 7.	- 40.	58.	13.	5.	14.	4.	NAD
	8	16	04		- 12.	- 47.	4.	49.	41.	5.	41.	1.	
	8	16	08		- 18.	- 32.	- 94.	101.	27.	5.	27.	4.	
	8	16	12		- 3.	- 66.	- 23.	70	46.	5.	46.	2.	
	8	16	16		- 11.	-114.	- 24.	117.	56.	5.	56.	2.	
	8	16	20		10.	- 59.	43.	74.	22.	5.	23.	3.	
	8	16	24		- 31.	- 56.	- 44.	78.	15.	5.	16.	5.	
MEAN			7					78.			32.	3.	
STD DEV								22.			15.	1.	
1907	1	57	12	15 Apr '66	10.	13.	15.	22.	16.	5.	17.	1.	NAD
	1	57	20		- 1.	- 17.	13.	21.	36.	5.	36.	1.	
MEAN			2					22.			27.	1.	
STD DEV								0			10.	0	
1993	6	51	00	22 Apr '66	35.	- 35.	15.	52.	56.	5.	56.	1.	NAD
	6	51	04		26.	- 22.	- 47.	58.	41.	5.	41.	1.	
	6	51	08		20.	- 19.	25.	37.	28.	5.	28.	1.	
	6	51	12		1.	- 2.	-103.	103.	68.	5.	68.	2.	
	6	51	16		27.	- 37.	- 44.	64.	17.	5.	18.	4.	
	6	51	20		30.	- 8.	-115.	119.	73.	5.	73.	2.	
	6	51	24		13.	- 20.	- 30.	38.	22.	5.	23.	2.	
MEAN			7					67.			44.	2.	
STD DEV								29.			21.	1.	
1993	6	56	04	22 Apr '66	17.	19.	- 45.	52.	21.	5.	22.	2.	CCD
	6	56	20		13.	- 7.	- 83.	84.	29.	5.	29.	3.	
	6	56	24		45.	- 31.	- 29.	62.	19.	5.	20.	3.	
MEAN			3					66.			23.	3.	
STD DEV								14.			4.	0	
1993	7	01	04	22 Apr '66	128.	- 60.	- 4.	141.	30.	5.	30.	5.	NAD
	7	01	08		67.	- 16.	- 27.	74.	14.	5.	15.	5.	
	7	01	12		- 13.	35.	- 44.	58.	13.	5.	14.	4.	
	7	01	24		- 16.	- 2.	- 38.	41.	31.	5.	31.	1.	
MEAN			4					79.			23.	4.	
STD DEV								38.			8.	1.	
2006	9	06	16	23 Apr '66	-104.	-100.	- 59.	156.	42.	5.	42.	4.	CCD
MEAN			1					156.			42.	4.	
STD DEV								0			0	0	

TABLE 5

SUMMARY OF COMPARISON OF SATELLITE POSITIONS DERIVED FROM OPTICAL AND SECOR OBSERVATIONS

	Flash Sequence					Mean	Mean	Mean Ratio	
		Time			No.	Position	Std. Dev. of	of Difference	
Orbit	Date	Hr	Min	Sec	Flashes	Difference (m)	Difference (m)	to Std. Dev.	Datum
1874	12 Apr 66	08	16	00	7	78	32	3.0	NAD
1907	15 Apr 66	01	57	12	2	22	27	1.0	NAD
1993	22 Apr 66	05	51	00	7	67	44	1.7	NAD
1993	22 Apr 66	06	56	04	3	66	23	2.8	CCD
1993	22 Apr 66	07	01	04	4	79	23	3.8	NAD
2006	23 Apr 66	09	06	16	1	156	42	3.7	CCD
		Mean by Flash Sequence				78	31	2.7	

the discrepancy.

Comparisons of geometric solutions based on optical data and short local arc solutions for satellite positions based on data taken at two Doppler stations are shown in table 6. Comparisons are only shown for one flash on each pass. The random errors correspond to the residuals of observations while the estimated accuracy of the difference is the rss of the Doppler and optical random errors. While the ratio of the difference to estimated accuracy of difference is somewhat large, the comparison is not especially useful because of the large size of estimated accuracy of the difference. As shown in the table, the principal component of the difference is the large Doppler random error which resulted from the fact that data from only two Doppler stations were used in the calculations. In order to permit a more useful comparison to be made, data from additional Doppler stations were used in the short arc solution. It then became necessary to replace Cape Canaveral station coordinates by NWL-8D station coordinates in order to have a consistent set of coordinates for the additional stations. Since errors of about 5 meters have been noted in transforming from the NWL-8D system to the Cape Canaveral system, the estimated accuracy of the difference given in table 7 is the rss of two random errors and a 5 meter estimated error in coordinate transformation. The estimated error is now small enough to permit useful comparisons to be made. While the overall ratio of difference to accuracy is again somewhat

"REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR"

TABLE 6

COMPARISON OF SATELLITE POSITIONS DERIVED FROM OPTICAL AND TWO-STATION DOPPLER OBSERVATIONS

Day	Coordinate	Difference (m)	Doppler Random Error(m)	Optical Random Error(m)	Est. Acc. of Diff(m)	Ratio Diff/Acc
17	x	- 60	38	7	39	1.5
	y	-168	57	3	57	2.9
	z	141	77	16	80	1.8
18	x	23	24	11	26	.9
	y	17	32	5	32	.5
	z	-153	69	19	71	2.2
19	x	- 10	9	2	9	1.1
	y	54	22	6	23	2.3
	z	157	48	15	50	3.1
28	x	37	33	48	58	.6
	y	27	69	56	88	3.1
	z	- 49	81	15	82	.6
38	x	- 28	54	30	62	.5
	y	67	64	13	65	1.0
	z	88	26	29	39	2.3
Mean	x		31	20	39	.9
	y		49	17	53	2.0
	z		60	19	64	2.0

"REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR"

TABLE 7

COMPARISON OF SATELLITE POSITIONS DERIVED FROM OPTICAL AND WORLDWIDE DOPPLER OBSERVATIONS

Day	Coordinate	Difference (m)	Doppler Random Error(m)	Optical Random Error(m)	Est. Acc. of Diff(m)	Ratio Diff/Acc
17	x	- 18	11	7	14	1.3
	y	- 21	6	3	8	2.6
	z	- 17	5	16	17	1.0
18	x	10	9	11	15	.7
	y	- 40	5	5	9	4.4
	z	- 90	5	19	20	4.5
19	x	- 21	7	2	9	2.3
	y	61	3	6	8	7.6
	z	145	5	15	17	8.5
28	x	11	5	48	48	.2
	y	- 11	1	56	56	.2
	z	- 5	3	15	16	.3
38	x	32	8	30	31	1.0
	y	4	5	13	15	.3
	z	30	5	29	30	1.0
Mean	x		8	20	23	1.0
	y		4	17	19	3.0
	z		5	19	20	3.1

large, the extreme variations are a more obvious indication of an inconsistency between the actual and estimated accuracies. While a firm conclusion about the source of the discrepancy cannot be drawn, it seems probable that the variations result from the limited quantities of optical data. The predicted and actual accuracy of the Doppler positions would not be expected to vary from day to day since there is a fair amount of redundancy in the observations. On the other hand, the minimum two sight lines to the satellite were obtained by the optical system on the first three days, and the intersection of the lines was very poor (18°-26°).

To summarize, solutions for station positions based on SECOR, Doppler and optical satellite observations each agreed with the results of geodimeter surveys to about 3 meters. No serious discrepancies were noted in the estimated accuracies of the solutions if the expected error in the survey is considered in the estimates. Comparisons of SECOR with optical determinations of satellite position and Doppler with optical determinations of satellite position resulted in discrepancies which exceeded the expected accuracy of the comparison. In the latter case the discrepancy appears to be associated with poor geometry in the optical solution for some of the times of observation.

RESULTS OF GEOS I OBSERVATIONS BY THE COAST AND GEODETIC SURVEY

J. Austin Yeager
Coast and Geodetic Survey

Prepared For

GEOS PROGRAM REVIEW MEETING
12-14 December 1967

NASA HEADQUARTERS
400 Maryland Avenue, SW
Washington, D. C.

RESULTS OF GEOS I OBSERVATIONS BY THE COAST AND GEODETIC SURVEY

by

J. Austin Yeager

Basically the Coast and Geodetic Survey's participation in the National Geodetic Satellite Program is directed toward establishing a global 43-station network of satellite triangulation. Execution of this fundamental network is a cooperative effort with NASA and DOD. Our participation also includes co-observing with the SAO Baker-Nunn and NASA optical networks on both GEOS and balloon satellites.

The network is geometric in nature and scale will be introduced by precisely measured base lines between several stations in the network. Accuracy goals are within the NGSP guidelines of ±10 meters in position.

Data acquisition is being accomplished utilizing BC-4 cameras with 450 mm and 300 mm focal lengths. All 300 mm lenses are currently being replaced with 450 mm focal lengths. The PAGEOS and Echo balloon satellites are utilized as the observing targets.

GEOS I PROGRAM

Participation in the GEOS I observational program began in November 1965 at a time when the Coast and Geodetic Survey was engaged in densification work on the North American Continent utilizing the passive Echo satellites. Eight mobile field teams were actively involved in operations.

A cooperative agreement was completed with NASA to serve as a basis for C&GS participation in the GEOS I program.

Flash schedules were prepared by NASA and all possible observations were provided to the C&GS.

C&GS field teams were then scheduled for GEOS observations on a non-interference basis with the existing program.

Raw field data for the successful observations were forwarded to NASA and particular observations requested by NASA were measured and processed by C&GS before forwarding. This data reduction was also completed on a non-interference basis with our existing program.

Figures I & II show the statistics of C&GS participation and results.

The six reduced plates simultaneous with the NASA MOTS network were distributed as follows:

	C&GS - BC-4	NASA - MOTS
1.	Timmins, Canada (3)	Columbia, Mo. (7)
2.	Timmins, Canada (5)	Goddard, Md. (7) Blossom Pt.,Md. (7)
3.	Timmins, Canada (7)	Columbia, Mo. (14)
4.	Timmins, Canada (7)	Goddard, Md. (21) Rosman, N.C. (21)
5.	Timmins, Canada (7)	Puerto Rico (7)
6.	Lynn Lake, Canada (7)	Ft. Myer, Fla. (21)

() Number of GEOS I images positively identified on the photographic plates.

GEOS I OBSERVATION SUMMARY

Coast and Geodetic Survey

SCHEDULE		PLATES TAKEN				PLATES CANCELLED		
OBSERVATION PERIOD	TOTAL OBSERV. SCHEDULED	TOTAL	NO IMAGES	IMAGES FOUND	PROCESSED	WEATHER	CAMERA OR OPERATOR ERROR	SATELLITE FAILURE
1/ 11/24/65 thru 1/25/66	365	95	84	11	5	214	7	49
2/ 4/13/66 thru 6/23/66	89	33	26	7	5	53	1	2
3/ 7/6/66 thru 11/30/66	129	54	35	19	12	69	4	2
TOTALS	583	182	145	37	22	336	12	53

1/ Observations scheduled when expected image size was > 30μ : 103F emulsion
2/ Observations scheduled when expected image size was > 30μ : Royal X Pan emulsion
3/ Observations scheduled when expected image size was > 40μ : Royal X Pan emulsion

FIGURE I

DISTRIBUTION OF SUCCESSFUL OBSERVATIONS

	Beltsville	Halifax	Timmins	Goose Bay	Lynn Lake	Moses Lake
PROCESSED **	5 0	1 0	5 5	1 0	1 1	9 0
NOT PROCESSED	2	0	2	1	1	1

	Cambridge Bay	Frobisher Bay	Sicily	Hawaii	Japan	TOTAL
PROCESSED **	0 0	0 0	0 0	0 0	0 0	22 6
NOT PROCESSED	1	2	1	2	2	15

** Simultaneous with NASA MOTS Network

FIGURE II

GEOS I PLATE PROCESSING

The reduced GEOS I plates were processed through the same C&GS programs as routine Echo I, Echo II and PAGEOS plates, although some modifications were incorporated to reduce individual flashes on a single plate. Each GEOS flash was treated as an unknown star image and reduced to apparent place at the epoch flash time. This time was UTC, WWV emitted. The standard deviation of the Right Ascension and Declination was computed by assigning (to all flashes of a specific plate) an average variance for the precision of the comparator setting as obtained for multiple measurements of the individual flash images. The given standard deviations have, in addition, rigorously taken into account the influence of the plate orientation process; however, no allowance was made for the uncertainty caused by scintillation. The final Right Ascensions and Declinations were corrected for astronomic refraction and diurnal aberration, but no corrections for parallactic refraction were made because the spatial positions of the flashes relative to the observing station were not known.

The punched cards containing the information needed for additional processing have been prepared in the format given in the NASA, GEOS A Mission plan booklet.

PLANS FOR GEOS B PROGRAM

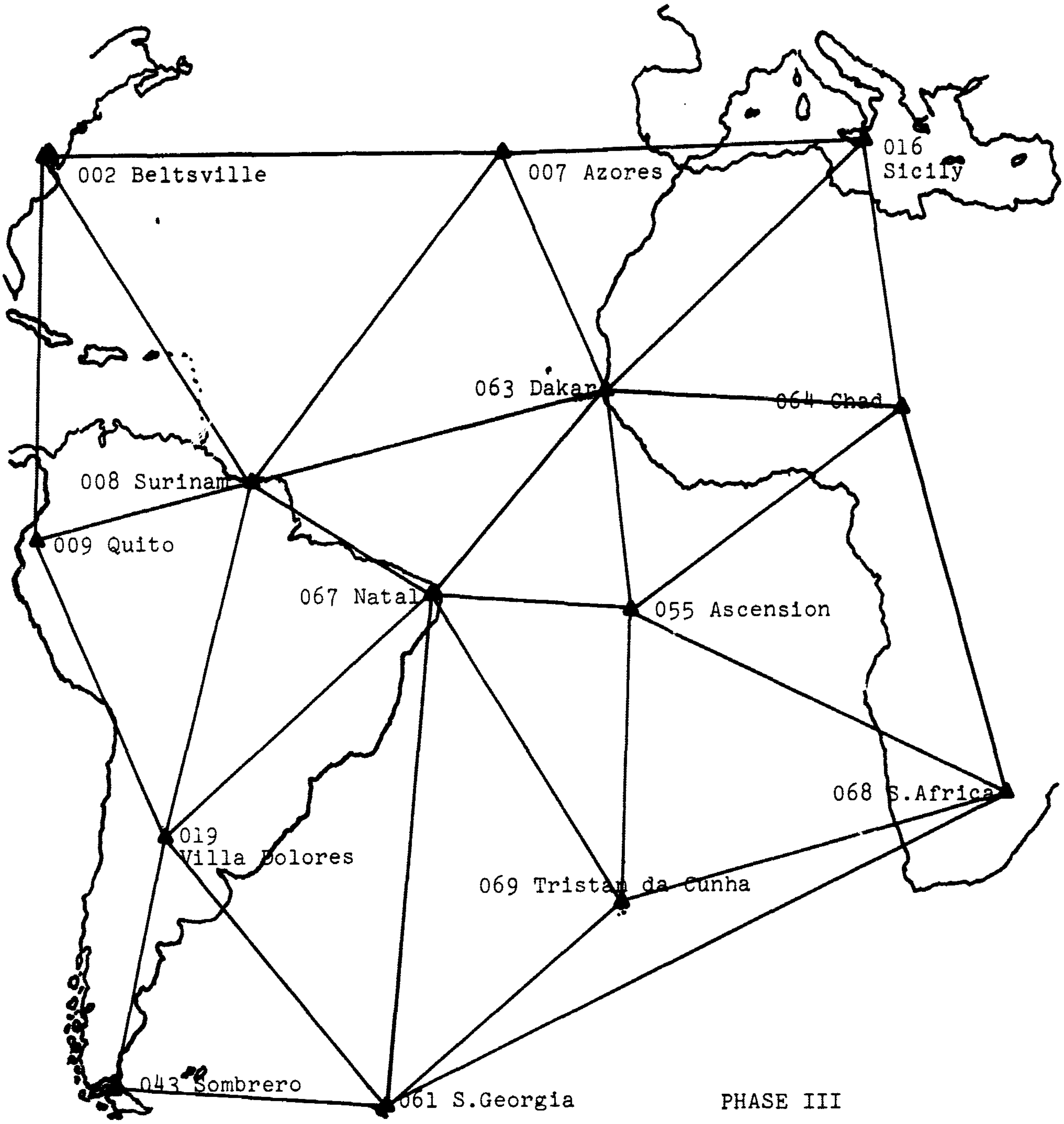
The C&GS intends at this time to participate in the GEOS B mission basically as it did in the GEOS I program.

We will accept flash predictions and schedule observations for the 13 BC-4 systems involved in the 43-station worldwide PAGEOS network. Eight C&GS, 4 AMS and 1 West German systems.

GEOS B schedules forwarded to the field teams will be on a non-interference basis with PAGEOS-Echo observations. However, in view of the troubles we are experiencing with the orbit of Echo I and its further expected degradation, the C&GS will probably want to request flashes over certain lines in the network where distances permit. The southern Chile-South Georgia Island line is one where GEOS B observations would be possible.

Figure III illustrates Phase III of BC-4 program which will begin late this month (December 1967). We expect to be operational on these sites until July 1968.

The C&GS will reduce GEOS plates that are simultaneous between the 13 BC-4 stations and single plates from stations in the network as requested by NASA.



PHASE III

Coast and Geodetic Survey

BC-4 Network

FIGURE III

Following, by Hellmut H. Schmid (page 1 of 2 pages)
Director, Geodetic Research Laboratory, ESSA

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CONTRIBUTIONS OF GEOS-1 TO GEODETIC OBJECTIVES

Charles A. Lundquist

To be presented at GEOS Program Review Meeting
NASA, Washington, D.C.
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CONTRIBUTIONS OF GEOS-1 TO GEODETIC OBJECTIVES[1]

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THE ROLE OF GEOS-1

The contributions of Geos-1 to geodetic science must be viewed first as part of a continuing geodetic activity utilizing observations of many satellites. This is true particularly at the Smithsonian Astrophysical Observatory (SAO), where satellite geodesy now spans ten years (Whipple, 1967; Whipple and Lundquist, 1967). The role of any satellite is incremental in the senses that observations of it supplement a bulk of previous data and that the augmented observations allow improvement of geodetic results.

Because of the specialized design of Geos-1, its incremental contribution far exceeds that of any other single satellite. Thus, Geos-1 has had a dominant influence in the recent results reviewed below, although it was by no means the sole contributor.

The immediate foundations above which Geos-1 results rise are the Geodetic Parameters for a 1966 Smithsonian Institution Standard Earth (Lundquist and Veis, 1966), which in turn was based on earlier work (e.g., Izsak, 1966; Veis, 1965). The investigations reported here and in subsequent papers presented at this meeting are of 1967 vintage. They are preliminary to a comprehensive solution for geodetic parameters planned at SAO for 1968, which will use digital computer programs (Gaposchkin, 1967a) greatly improved in precision over those employed in 1966. It will also use a substantially enlarged and diversified data base. While the role of Geos-1 will be

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[1] This work was supported in part by grants NsG 87-60 and NSR 09-015-018 from the National Aeronautics and Space Administration.

important in the 1968 analysis, it will not dominate as it did in 1967. In summary, the geodetic results derived at SAO during 1967 can justly be associated with Geos-1, and this is the point of view adopted below.

OBSERVATIONS

SAO scientific investigations based on satellite observations begin from several distinct collections of data. One data class contains precisely reduced observations of any convenient satellite made simultaneously from two or more ground stations. A second contains numerous observations of individual satellites during intervals of several weeks, months, or years. A third comprises coordinated observations between various tracking systems and networks with the objective of establishing compatibility of various data types. Observations of Geos-1 contribute significantly to each of these classes.

To be seen simultaneously from two or more stations, a satellite must be high enough so that it is above the horizon of each station. The mean altitude of Geos-1 is such that it may be visible simultaneously from stations separated by no more than about 4000 km. Hence, observations of Geos-1 and particularly of its flashing lights are most useful in regional programs, for example, in Europe. (The separations of the 12 Baker-Nunn sites in the primary SAO network are mostly greater than 4000 km.) Thus, many Baker-Nunn photographs of Geos-1 flashes were scheduled for potential simultaneity with other camera systems in the region of an SAO station. With this objective, the Baker-Nunn cameras obtained the vast number of successful photographs listed in Table 1.

Typically, only a fraction of these photographs are matched by like photographs from other sites. Where the successful simultaneous observations are useful for active programs of investigation, SAO has precisely reduced the data from the Baker-Nunn photographs. The distribution of these reductions is listed in Table 2. If additional useful simultaneous observations are later recognized, these too can be reduced. Laser range observations simultaneous with Baker-Nunn photographs are listed in Table 2a.

For determination of the orbit of a particular satellite, observations well distributed in time and around the orbit are preferable. In the case of Geos-1, the great multiplicity of tracking systems generated a greater volume of data from more geographical sites than obtained for any previous satellite. The number of Baker-Nunn observations increased substantially because flash sequences could be scheduled throughout the night during periods when photography with reflected sunlight was impossible. In fact, the number of successful photographs far exceeded the number that could be justified for precise measurement either on economic or on scientific grounds. This circumstance required adoption of criteria for the selection of films for precise reduction.

The reduced simultaneous observations were equally useful for orbit determination, so these data were included in both the first and second data classes. Two requirements guided the selection of further films for orbits determination. First was the need for orbits in a contiguous sequence of many months duration and based on about 100 reasonably distributed observations per month. This density of observations could usually be obtained by reduction of one good photographic frame out of each set of several adjacent frames obtained by a Baker-Nunn camera, either by reflected light or of a flash sequence. However, when two or three sets of adjacent frames came from different areas of the sky during an individual pass over a station, one set from each pass was reduced. Because this was the conventional mode of reduction at SAO for several years, the result is called a "normal file" of data, which yields a "normal orbit." In practice, the normal Geos-1 files were composed chiefly of observations by reflected sunlight supplemented with flash observations selected for simultaneity or for distribution around the orbit. The SAO normal files also include the laser ranges from Organ Pass, and, when appropriate, data from the several other tracking systems contribute to the normal orbits.

There is also a requirement for a few files of data having the maximum practical observation density for about a month per file. During these periods, typically five adjacent frames are reduced from each set and all of the flashes of each sequence are measured. The intervals for such treatment were selected after success statistics reported from the field stations permitted the identification of periods of optimum observation distribution and density. For this reason, these are called "select files" of data, and from them result "select orbits."

Figure 1 shows the periods during the electronic life of Geos-1 for which normal or select orbits exist. The figure also shows an additional select interval in spring 1967 that will be reduced by January 1968. This is one of several such intervals of observations made in the spring of 1967 of the five then-existing satellites with retroreflectors for laser tracking. These satellites were observed by the Baker-Nunn network and by a cooperating network of five laser stations. The latter encompassed three French stations at Haute Provence, France, Hammaguir, Algeria, and Stephanion, Greece; a NASA station at Greenbelt, Maryland; and the SAO station at Organ Pass, New Mexico.

The third class of data from Geos-1 is distinctly separated from the previous two not by its content, but rather by the unique opportunity provided by Geos-1 observations for investigating compatibility of virtually all important tracking systems and techniques. In their most direct form, these data arise from periods during which two or more tracking instruments were collocated at a station. For example, several camera systems were present in juxtaposition at the SAO Jupiter site from December 1965 through May 1966 (Berbert, 1967; Berbert et al., 1967). During this time they photographed the same Geos-1 flash sequences. As a second example, a laser system was operated adjacent to the Baker-Nunn at the Organ Pass station (Lehr et al., 1967). Next in directness are Geos-1 passes over continental United States, which were intensively observed by many camera and electronic systems (Berbert, 1967; Berbert et al., 1967). Finally, there is the opportunity to blend several data types into determination of normal or select orbits. SAO observing systems have participated extensively in these programs and appropriate data reductions have been accomplished. A subsequent paper in this program (Gaposchkin, 1967b) discusses the results of analyses based on diverse data.

STATION POSITIONS

Accurate coordinates for observing instruments are important results in satellite geodesy. From them follow geometrical relations, such as ties between survey datums. Accurate instrument coordinates are necessary also for productive analyses of satellite orbits.

Two independent methods and one combination method for refining station coordinates are employed in the treatment of Geos-1 data at SAO. Substantial agreement between the methods is the strongest factor supporting confidence in the final results.

The first method uses the simultaneous observations to derive interstation directions or the directions interconnecting a group of stations. Geos-1 data contributed to such investigations in several regions of the globe, particularly in the continental United States and in Europe. In these regions, coordinates of a number of additional sites have been determined in a common coordinate system derived from the global distribution of Baker-Nunn sites. The Geos-1 simultaneous observations indicated in Table 2 fit into the larger framework of previous simultaneous observations from the Baker-Nunn network. These are tabulated in Table 3, but the tabulation does not include a block of observations currently being prepared for reduction in early 1968. The multiplicity of sites in the North American and European datums provides information for statistically significant relations between the individual survey datums and a single well-defined global coordinate system. This topic is the subject of detailed consideration in a subsequent paper (Rolff, 1967).

The second method for deriving station positions depends on accurate orbits for the Geos-1 satellite. As a first step in an iterative process, the coordinates of the basic SAO Baker-Nunn network are held constant, so that the geometry of the orbit is fixed by the Baker-Nunn positions. A later paper gives details of the normal and select orbits obtained for Geos-1 (Gaposchkin, 1967b). Given such orbits as well as observations from a site whose position is desired, a differential improvement scheme yields the station coordinates that minimize the residuals between the observations and the orbit derived essentially from the Baker-Nunn data. The observations from the new site can be made by any instrument having accuracy sufficient for geodetic objectives. This procedure for locating stations can be applied to an isolated site – for example, an island. Of course, it can also be applied to stations in local or global networks. The use of Geos-1 data in this way is discussed in a paper to follow (Gaposchkin, 1967b).

Previous analyses have established for Baker-Nunn observations that the two methods just discussed have comparable accuracies (Köhnlein, 1966). This justifies use of a method that combines both methods to obtain a still stronger solution. This combination step can be taken for cases where the requisite Geos-1 data are available.

In analyses planned for 1968, coordinates of the primary Baker-Nunn sites and those of other instruments will be refined with the use of data from many satellites, including Geos-1. Uncertainties no greater than 10 meters are anticipated.

ORBITS AND THE GEOPOTENTIAL

The normal or select orbits for Geos-1 are based primarily upon the geopotential representation (Gaposchkin, 1966) in the Geodetic Parameters for a 1966 Smithsonian Institution Standard Earth. However, before accurate orbits are forthcoming, coefficients must be determined for the spherical harmonics with which the Geos-1 orbit is resonant. These coefficients were reported earlier (Gaposchkin and Veis, 1967).

The refined Geos-1 orbits by themselves are not a sufficient supplement to those used in the 1966 geopotential solution to justify a new solution for the full geopotential representation. Nevertheless, the select Geos-1 orbits are significant in the collection of orbits prepared for the solution scheduled at SAO during 1968. Also significant are the orbits of the other two United States satellites with laser retroreflectors, particularly during the periods of concentrated laser tracking (see Table 4). The same is true for the French satellites with retroreflectors (see Table 4) (Kovalevsky, 1967), and for several other satellites chosen because the inclinations of their orbits differed from those used in previous solutions.

The contiguous run of Geos-1 orbits, normal and select, during 1965 and 1966, in conjunction with similar long orbit sequences for other satellites, is useful for refining coefficients of the zonal harmonics in the geopotential. Through J_{20}, this was done during 1967 (Kozai, 1967) and a further refinement will probably follow in 1968.

INTERPRETATIONS

Station positions and geopotential coefficients are direct products of satellite geodesy, but both are also intermediate results because they are prerequisite to other research. These further investigations and interpretations often involve information from other branches of science. It is at this stage that satellite geodesy must demonstrate its compatibility with neighboring fields.

In this vein, the representation of the gravitational potential of the earth derived from satellite dynamics should be compatible with measurements of gravity by earth-based instruments. Indeed, that this is the case was again demonstrated, but with greater satisfaction, during 1967 (Köhnlein, 1967). Köhnlein began, on one hand, with a set of tesseral harmonic coefficients from the 1966 Smithsonian Standard Earth, augmented by more recent "resonant" coefficients, and the 1967 Kozai zonal coefficients. On the other hand, he began his study with published sets of surface gravity values averaged over 300 nautical-mile squares. From these he derived a geopotential representation through (15, 15) that preserves the essential features of both the satellite and the surface information. Figure 2 illustrates the role that Geos-1 played in the chain of events culminating in this representation. This representation will in turn be an initial input to the major geopotential solution scheduled at SAO during 1968.

An equipotential surface obtained from a spherical harmonic representation of the earth's potential field should agree also with astrogeodetic geoids where they are known from surface surveys. This correspondence between satellite and surface information was examined by Veis during 1967 (Veis, 1967). The correspondence involves a consistent set of fundamental geodetic parameters (see Table 5). For values of these constants determined by Veis, the agreement is quite satisfactory between satellite-derived and astrogeodetic geoids.

This agreement is only one of several results lending confidence to the values given by Veis for a consistent set of fundamental geodetic parameters. Another result comes from an analysis of the simultaneous observations between the Baker-Nunn in Jupiter, Florida, and the Baker-Nunn and laser in Organ Pass, New Mexico. While these simultaneous observations are few in number, they do, nevertheless, give for the geocentric coordinate system a distance scale that is in substantial agreement with scale factors derived from other arguments (Veis, 1967). Veis concludes that GM and hence the scale are known with an accuracy of about 2 parts-per-million.

Figure 3 illustrates the process by which Veis arrives at a consistent set of fundamental geodetic constants. The role of Geos-1 in these procedures shows also. These constants should be refined further as a consequence of the comprehensive solution for geodetic parameters scheduled at SAO during 1968.

In the final analysis, the geodetic knowledge resulting from the Geos-1 activity establishes the outstanding success of its mission as a vehicle for geodetic research.

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TABLE 1. GEOS-1 PHOTOGRAPHS

Month	Number of flash photographs	Number of flash photographs precisely reduced	Number of passive photographs precisely reduced
Nov. 1965	757	757	402
Dec. 1965	1636		191
Jan. 1966	2457	119	87
Feb. 1966	2445		75
Mar. 1966	4167		187
Apr. 1966	4297		231
May 1966	5506		70
June 1966	5041		29
July 1966	4653	3090	125
Aug. 1966	4050	857	301
Sep. 1966	4482	1127	74
Oct. 1966	3223	2530	186
Nov. 1966	1595		
Total	44309	8480	1958

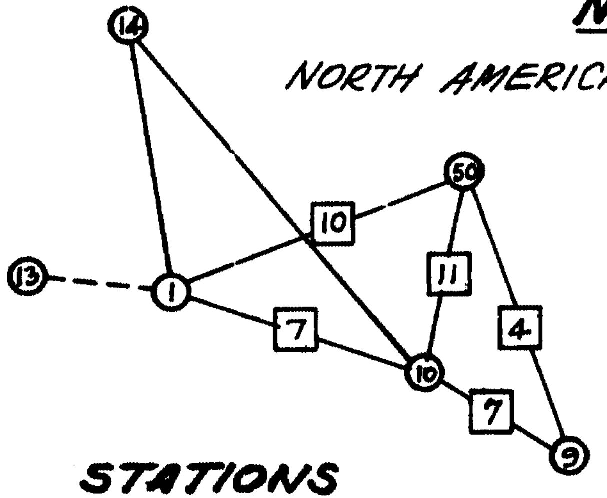
TABLE 2

FLASH SYNTHETIC SIMULTANEOUS OBS.

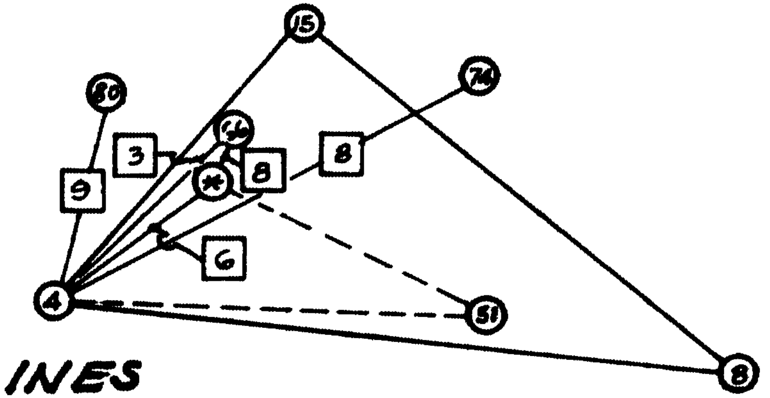
NOV. 1, 1967

NETWORKS

NORTH AMERICAN



EUROPEAN



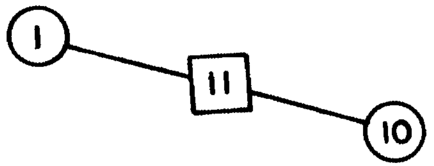
STATIONS

CODE	NUMBER	NAME
1	9001	N. MEXICO
4	9004	S. FERNANDO
8	9008	SHIRAZ
9	9009	CURAÇAO
10	9010	JUPITER
13	9113	ROSAMOND
14	9114	COLD LAKE
15	9115	HARESTUA
50	9050	AGASSIZ
51	9051	ZOGRAPHOU
66	9066	ZIMMERWALD
74	9074	RIGA
80	9080	MALVERN
*	8015	HAUTE PROVENCE

LINES

LINES	NUMBER OF		SATELLITES
	SEQUENCES	FLASHES	
* → 4	6	41	GEOS A
* → 66	8	55	GEOS A
1 → 10	7	23	ANNA
1 → 50	10	58	GEOS A
4 → 66	3	20	GEOS A
4 → 74	8	48	GEOS A
4 → 80	9	54	GEOS A
9 → 10	7	25	ANNA
9 → 50	4	21	GEOS A
10 → 50	11	56	GEOS A

TABLE 2a. LASER SYNTHETIC SIMULTANEOUS OBSERVATIONS NOVEMBER 1, 1967



Stations

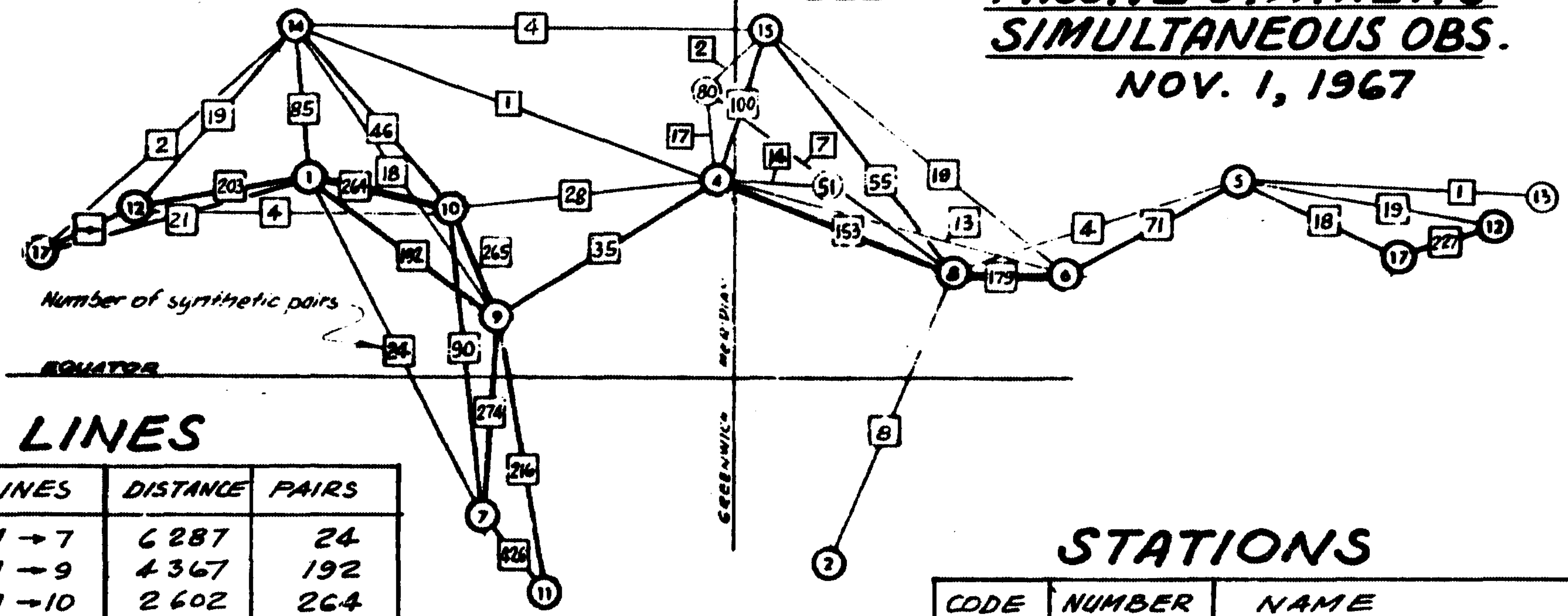
Station	Name
10	New Mexico — Laser/Baker-Nunn
1	Jupiter — Baker-Nunn

Number of returns	Satellites
5	GEOS-A
4	D1-D
1	BE-B
1	D1-C

TABLE 3

PASSIVE SYNTHETIC SIMULTANEOUS OBS.

NOV. 1, 1967



LINES

LINES	DISTANCE	PAIRS
1 → 7	6 287	24
1 → 9	4 367	192
1 → 10	2 602	264
1 → 12	4 942	203
1 → 14	2 479	85
1 → 17	6 238	21
2 → 8	6 373	8
4 → 6	7 312	13
4 → 8	5 290	153
4 → 9	6 465	35
4 → 10	6 581	28
4 → 14	7 146	1
4 → 15	2 880	100
4 → 80	1 768	17
5 → 6	5 424	71
5 → 8	7 418	4
5 → 12	6 142	19
5 → 13	8 130	1
5 → 17	5 275	18
6 → 8	2 589	179
6 → 15	5 831	19

LINES	DISTANCE	PAIRS
7 → 9	3 139	274
7 → 10	4 780	90
7 → 11	1 826	426
8 → 15	4 499	55
8 → 80	4 941	7
9 → 10	2 021	265
9 → 11	4 769	216
9 → 14	5725	18
10 → 12	7220	4
10 → 14	3859	46
12 → 14	5238	19
12 → 17	1461	227
14 → 15	5985	4
14 → 17	6271	2
80 → 15	4941	2
4 → 51	2636	14

STATIONS

CODE	NUMBER	NAME
1	9001	N. MEXICO
2	9002	OLIFANTSFONTEIN
4	9004	SAN FERNANDO
5	9005	TOKYO
6	9006	NAINI TAL
7	9007	AREQUIPA
8	9008	SHIRAZ
9	9009	CURAÇAO
10	9010	JUPITER
11	9011	VILLA DOLORES
12	9012	MAUI
13	9113	ROSAMOND
14	9114	COLD LAKE
15	9115	HARVESTUA
17	9117	JOHNSTON ISLAND
80	9080	MALVERN
51	9051	ZOGRAPHOU

TABLE 4. LASER TRACKING INTERVALS

No.	Satellite	Period
D1-D	1967-14A	April 30-June 3, 1967
D1-C	1967-11A	April 16-May 20, 1967
GEOS 1	1965-89A	February 26-March 25, 1967
D1-C	1967-11A	February 19-March 25, 1967
D1-D	1967-14A	February 19-March 25, 1967
BE-B	1964-64A	February 26-March 25, 1967
BE-C	1965-32A	March 12-April 29, 1967
BE-B	1964-64A	May 7-June 3, 1967

TABLE 5. FUNDAMENTAL GEODETIC CONSTANTS

$a = 6,378,142 \pm 6$ m

$1/f = 298.255 \pm 0.005$

$GM = 398,600.9 \pm 0.7 \text{ km}^3 \text{ sec}^{-2}$

$g_e = 978,031.1 \pm 3.2$ mgal

Based on a definition of the meter as

$1 \text{ m} = 3.33564048 \times 10^{-9}$ light-sec

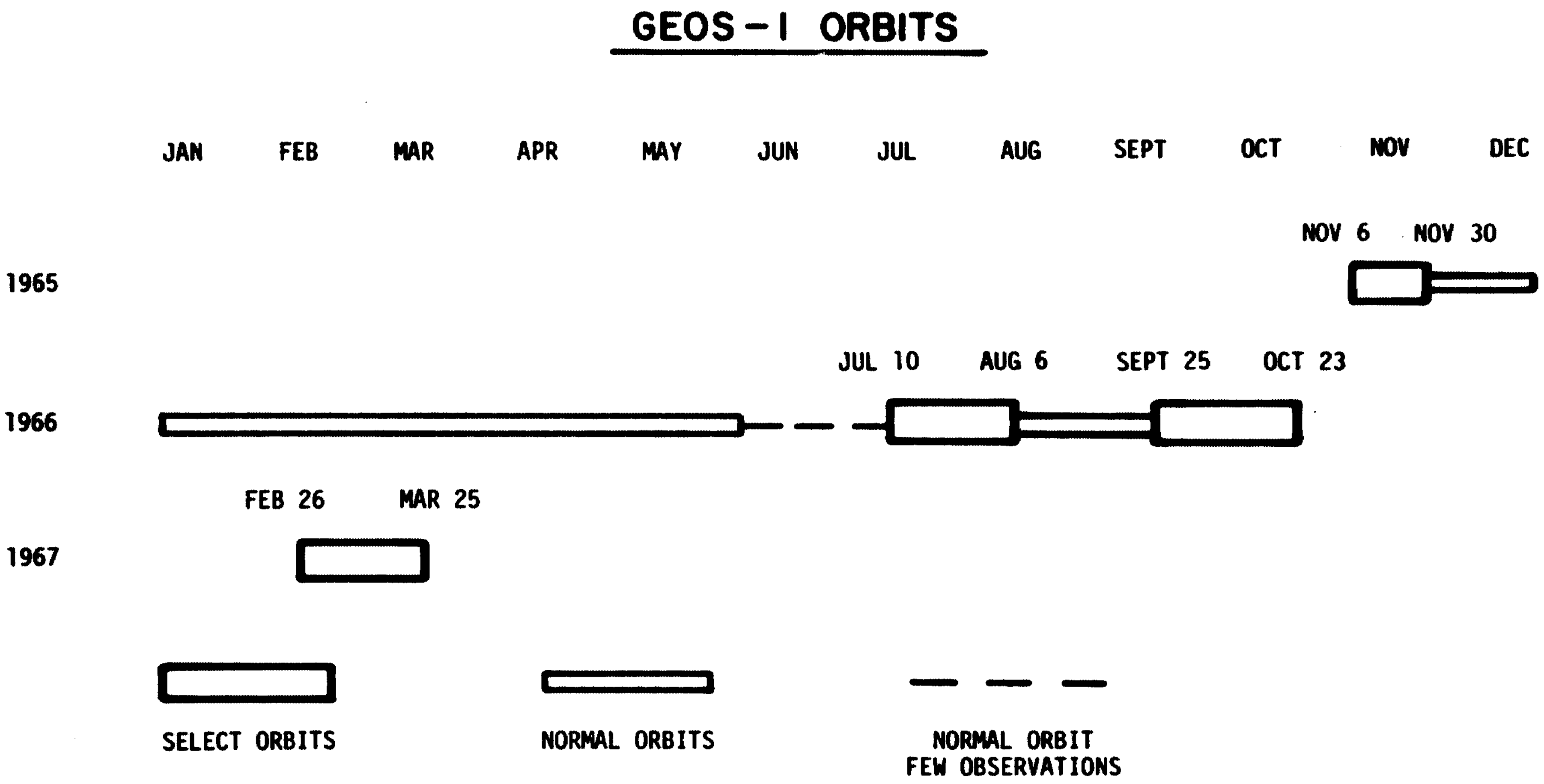

GEOS-I ORBITS
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEPT
OCT
NOV
DEC
NOV 6
NOV 30
1965
JUL 10
AUG 6
SEPT 25
OCT 23
1966
FEB 26
MAR 25
1967
SELECT ORBITS
NORMAL ORBITS
NORMAL ORBIT
FEW OBSERVATIONS

Figure 1.

GEOS-I CONTRIBUTION TO GEOPOTENTIAL

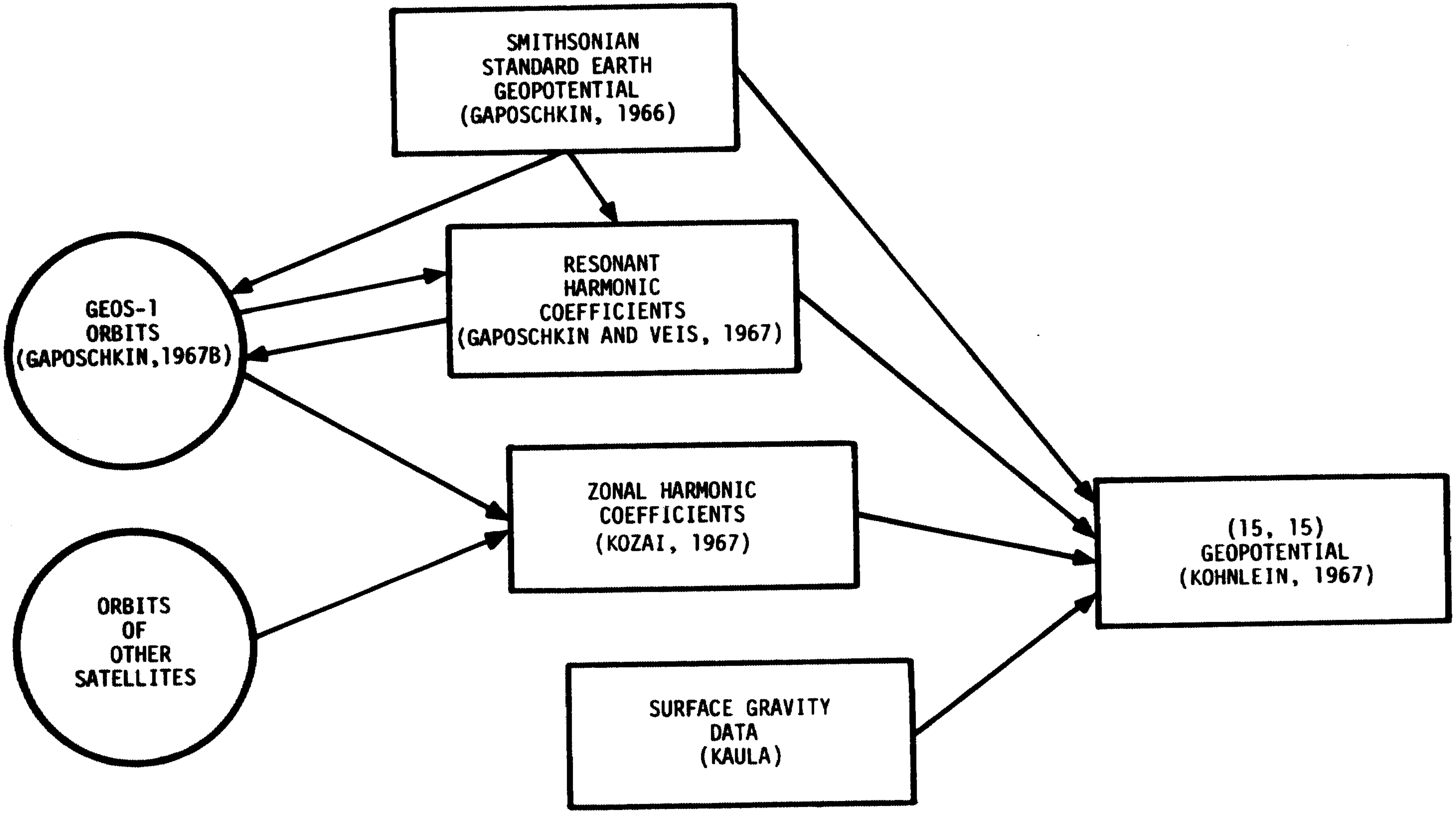


Figure 2.

GEOS-I CONTRIBUTION TO GEODETIC CONSTANTS

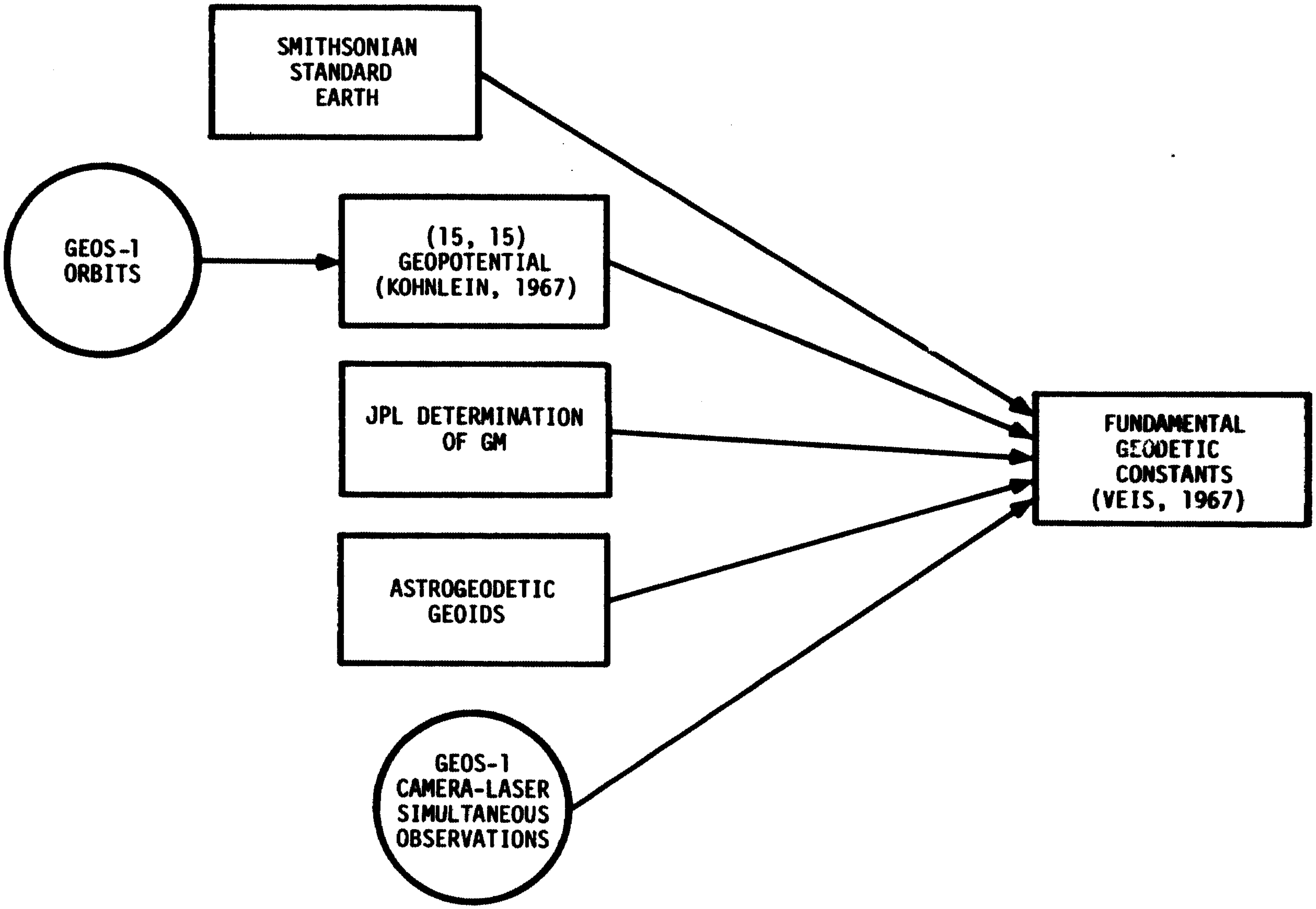


Figure 3.

INTERSTATION CONNECTIONS FROM GEOS-1 BEACON OBSERVATIONS

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INTERSTATION CONNECTIONS FROM GEOS-1 BEACON OBSERVATIONS

Jan Rolff

In his report, Dr. Lundquist stated that scientific investigations at SAO are based upon three collections of data.

The third class, consisting of coordinated observations between various tracking systems, is a very challenging one from a scientific point of view. First, it leads to the intercomparison and consequently to the evaluation of each tracking system. Second, the use of stations with different types of tracking systems may lead to a higher concentration and a better distribution of observing sites in a certain area. Generally speaking, this can not be provided by one tracking system alone.

As far as optical observations of GEOS flashes are concerned, such comparison and net improvement have occurred in two specific regions: the North American and the European continents.

Some background and results will be given on the intercomparison between SAO Baker-Nunn stations and stations of other agencies in these two areas.

Europe

At the end of 1965, no fewer than 14 stations were listed by NASA as the so-called international participants, all of them located in Western Europe. These stations had responded positively to NASA's invitation to participate in the NGSP.

During the first few months after the launch of GEOS-A, however, some of these stations had problems in obtaining useful photographs of the GEOS flashes. This was not surprising, since most of these 14 stations had no previous experience in satellite photography.

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It was suspected that the problems encountered could only be solved by establishing more direct contact with an organization experienced in satellite tracking. For this purpose SAO obtained a special contract from NASA to establish this contact, mainly on an operational level.

By visits, correspondence, and even telephone calls, we found a great variety of reasons for these station failures, and mention the following:

inadequate photographic material
inadequate optics
inadequate sidereal drive
inadequate shutters
no observing staff
no time for satellite observations
inadequate reduction facilities
lack of interest.

Only a few stations performed well: Delft, Haute Provence, Malvern, and Zimmerwald.

One of the scientific objectives at SAO is the location of the European Datum with respect to the SAO world net. The stations are concentrated on the western side of the origin of the European Datum. Some stations east of Potsdam would be very helpful. Hence SAO had to find some participants in the East European zone and at the origin of the European Datum itself. These additions would give the much better distribution of stations needed to connect the European Datum to the world system.

Through the full cooperation of the USSR Astronomical Council, three stations, Potsdam, Riga, and Zvenigorod, undertook the necessary observations of the GEOS flashes. However, only Riga succeeded in its efforts and produced useful observations.

Altogether five international participants successfully photographed GEOS-1 flashes: Delft, Haute Provence, Malvern, Riga, and Zimmerwald.

The next step was to study the reduction techniques applied at each of these stations.

From past experience, we knew that complete information on reduction methods could only be obtained by visiting the stations. This resulted in a clear picture of the reduction methods used at the five successful international stations. With this information SAO was able to put the observations of these five stations into the same format as that of the Baker-Nunn observations.

Unfortunately, Delft had problems with its measuring machine. Therefore, only the following totals of reduced observations have been received from the international participants by SAO:

115	Haute Provence, France
137	Zimmerwald, Switzerland
21	Riga, USSR
20	Malvern, UK.

The majority of these observations could be incorporated in SAO's most recent determinations of station coordinates, as well as in GEOS-1 orbit determinations.

There were a few simultaneous observations between the SAO astrophysical observing station in Spain and these four international stations. Preliminary investigations indicate an agreement between results obtained from the dynamic method based on orbit determination and those obtained by the geometric method based on simultaneous observations.

North America

The SAO station in Agassiz, Massachusetts, equipped with a K-50 camera, successfully observed GEOS flashes. Station coordinates could be determined by the dynamic method. The same was true for the USAF Baker-Nunn stations at Rosamund, California; Johnston Island, Pacific; and Cold Lake, Canada.

Synchronous observations between Agassiz and the SAO astrophysical observing stations in Las Cruces, New Mexico, Jupiter, Florida, and Curaçao, Netherlands Antilles, were in very good agreement with the results obtained from the dynamic method.

As in the European group of stations, however, the number of synchronous observations was still far too small for the derivation of precise results.

No attempts could be made to achieve interstation connections between the SAO sites and MOTS or PC-1000 camera sites. This will be done in the very near future.

Conclusions

It has been clearly demonstrated that only complete information on camera techniques and reduction methods will lead to correct interpretation of interstation connections.

The results obtained from the GEOS-1 optical beacon have been very promising.

Proper scientific investigations on interstation connections will require many more observations of this kind. Hence the launch of GEOS-B is eagerly awaited.

DYNAMICAL DETERMINATION OF STATION LOCATIONS USING GEOS 1 DATA

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April 1968

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DYNAMICAL DETERMINATION OF STATION LOCATIONS USING GEOS 1 DATA

E. M. Gaposchkin

1. INTRODUCTION

The Smithsonian Astrophysical Observatory (SAO) has for some years been actively engaged in a geodesy program. This field of study is in the process of expansion through the acquisition of new sources of data, new methods of data analysis, and the combination of satellite geodesy with classical techniques. The general background, basic concepts, and broad context of this program will be discussed in separate papers by Lundquist and Rolff.

Our most recent significant achievement was the publication in 1966 of the Smithsonian Institution Standard Earth (Lundquist and Veis, 1966), which was based entirely on Baker-Nunn camera observations. Before this work was accomplished, we had already recognized that a wider distribution of data and a greater variety of data types would improve geodetic results.

We are encouraged in the expansion of our program by the investigations currently pursued by the Applied Physics Laboratory of Johns Hopkins University (APL) and by the Naval Weapons Laboratory (NWL) with the use of electronic TRANET doppler data. It is reassuring that the geodetic results obtained by SAO, APL, and NWL are in reasonably good agreement. The combination of the data from these sources is a logical advance in geodetic studies. Moreover, additional sources of data are becoming available. Smaller observatories and geodetic institutes can participate in global geodetic investigations with an illuminated satellite. Newer electronic systems such as the Goddard Range and Range Rate (GRARR) and the SECOR systems are beginning to acquire data in fairly large amounts, and the development of laser tracking provides greater accuracy.

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The first step in combining different kinds of data to solve the geodetic problem involves selection of additional data types, establishment of suitable variances, reduction to a uniform time and spatial reference system, and, as part of the last item, adoption of an initial set of station locations. A geodetic satellite such as Geos 1 is ideal for these tasks. Each of the cooperating agencies has acquired data from this satellite, and its orbital characteristics are such that we can be reasonably confident in using a dynamical theory.

2. SCOPE AND GOALS OF THIS STUDY

First, and most important, we have used data from a variety of tracking systems (optical directions, range, and range rate) to determine station locations in a geocentric Cartesian coordinate system. Second, having performed this adjustment, we have obtained some measure of the validity, accuracy, and potential usefulness of these data-acquisition systems for future work.

Our approach to the problem is the so-called dynamical method, which is discussed in detail in the Smithsonian Institution Standard Earth. Some use will be made of simultaneous optical observations to ascertain the validity of the positions of the optical stations determined in our reference system.

I assert that the results given here are only an indication of the accuracy of the system, and in the final analysis, a dynamical theory cannot be used to calibrate an observing system with an accuracy greater than 100 m. Such a calibration can be performed only by intercomparison.

3. REFERENCE SYSTEMS AND ORBITAL ACCURACIES

The 1966 Smithsonian Institution Standard Earth forms the basis for this analysis. The coordinate systems are briefly as follows. The inertial reference frame is referred to the equinox of 1950.0 and the equator of date.

The terrestrial reference frame is referred to the mean pole of 1900.0 to 1905.0 and the longitude of the mean observatory at Greenwich. The coordinates of the SAO Baker-Nunn cameras expressed in this terrestrial system are the C6 coordinates of the Standard Earth. The relation between these two frames of reference is given by the measured values of the time UT1 and the position of the pole.

The usefulness of the dynamical method hinges exclusively upon the accuracy of the orbital ephemeris. This, in turn, depends on the accuracy of the orbit theory itself, which includes uncertainties in the earth gravity-field model adopted, and on the accuracy with which the orbital elements of the satellite can be determined. Unfortunately, Geos 1 was in an orbit that is resonant with some of the 12th-order tesseral harmonics. Therefore, before any attempt can be made to use the dynamical method, these harmonics must be determined quite accurately.

The important harmonics with which Geos 1 is resonant are ℓ, m = 12, 12; 13, 12; 14, 12; and 15, 12. One satellite is not adequate for the determination of the eight numerical parameters. Fortunately, we have observations of another satellite, 1960 ι2, resonant with the same harmonics and of essentially different orbital characteristics. The required harmonics can be determined by the combined use of these two satellites.

Table 1 gives the orbital characteristics of Geos 1 and 1960 ι2, with other relevant information. The first step, then, is to determine the resonant gravity-field harmonics from optical observations of these two satellites. The harmonic coefficients determined in this way are shown, with additional geodetic information, in Table 2.

The question of the accuracy of the reference orbits can be answered, in part, by the range observations acquired by the SAO laser tracking system collocated with the SAO Baker-Nunn camera at Organ Pass, New Mexico (station 9001). The collocation eliminates any problem of possible timing-system differences or errors in the station coordinates. If we use the reference orbits computed without the laser observations and compare the computed ranges with the laser observations, we get a measure of the accuracy in an absolute sense of the orbit theory. The mean value of 20 m agrees quite well with previous estimates of the orbital accuracy and must be taken to be the accuracy we can expect.

Table 1. Characteristics of Geos 1 and 1960 ι2

		Geos 1	1960 ι2
a		8.073861 Mm	7.971380 Mm
e		0.070941	0.0114367
I		$59\overset{\circ}{.}38020$	$47\overset{\circ}{.}231275$
n		11.967616 rev day^{-1}	12.197092 rev day^{-1}
$\sqrt{\bar{C}_{\ell,m}^2 + \bar{S}_{\ell,m}^2}$ (maximum amplitude)			
ℓ	m		
12	12	60 meters	7 meters
13	12	490 meters	360 meters
14	12	90 meters	26 meters
15	12	310 meters	630 meters
Period of perturbation:		7.1 days	14.5 days

Table 2. Geodetic constants

Velocity of light	c	2.997925×10^{10} cm sec^{-1}
Gravitational constant times earth mass	GM	3.986013×10^{20} cm^3 sec^{-2}
Semimajor axis of the earth	a_e	6.378155×10^6 m
Zonal harmonics	J_n	Kozai solution to J_{14}*
Tesseral harmonics	$\overline{C}_{\ell,m}\overline{S}_{\ell,m}$	M1 solution* with the following changes: $\overline{C}_{13,12} = -6.848 \times 10^{-8}$ $\overline{S}_{13,12} = 6.57 \times 10^{-8}$ $\overline{C}_{14,12} = 0.261 \times 10^{-8}$ $\overline{S}_{14,12} = -2.457 \times 10^{-8}$ $\overline{C}_{15,12} = -7.473 \times 10^{-8}$ $\overline{S}_{15,12} = -1.026 \times 10^{-8}$

*From Lundquist and Veis (1966).

The mean elements of these reference orbits are plotted in Figure 1. We note that the semimajor axis has a consistent variation of not more than 10 m. The eccentricity and inclination show the long-period effect of the earth's oblateness; this effect has a period of 550 days. Including the laser observations in the orbit determination does not change the values of the elements to any significant extent, and the mean value of the range residuals computed with respect to these orbits is 10 m.

As stated in Lundquist and Veis (1966), the internal consistency of the fundamental Baker-Nunn coordinates is 15 m. The orbital ephemeris is computed for 1-month arcs and has an accuracy of 20 m. Therefore, we cannot hope to determine the station positions to an accuracy better than 15 to 20 m.

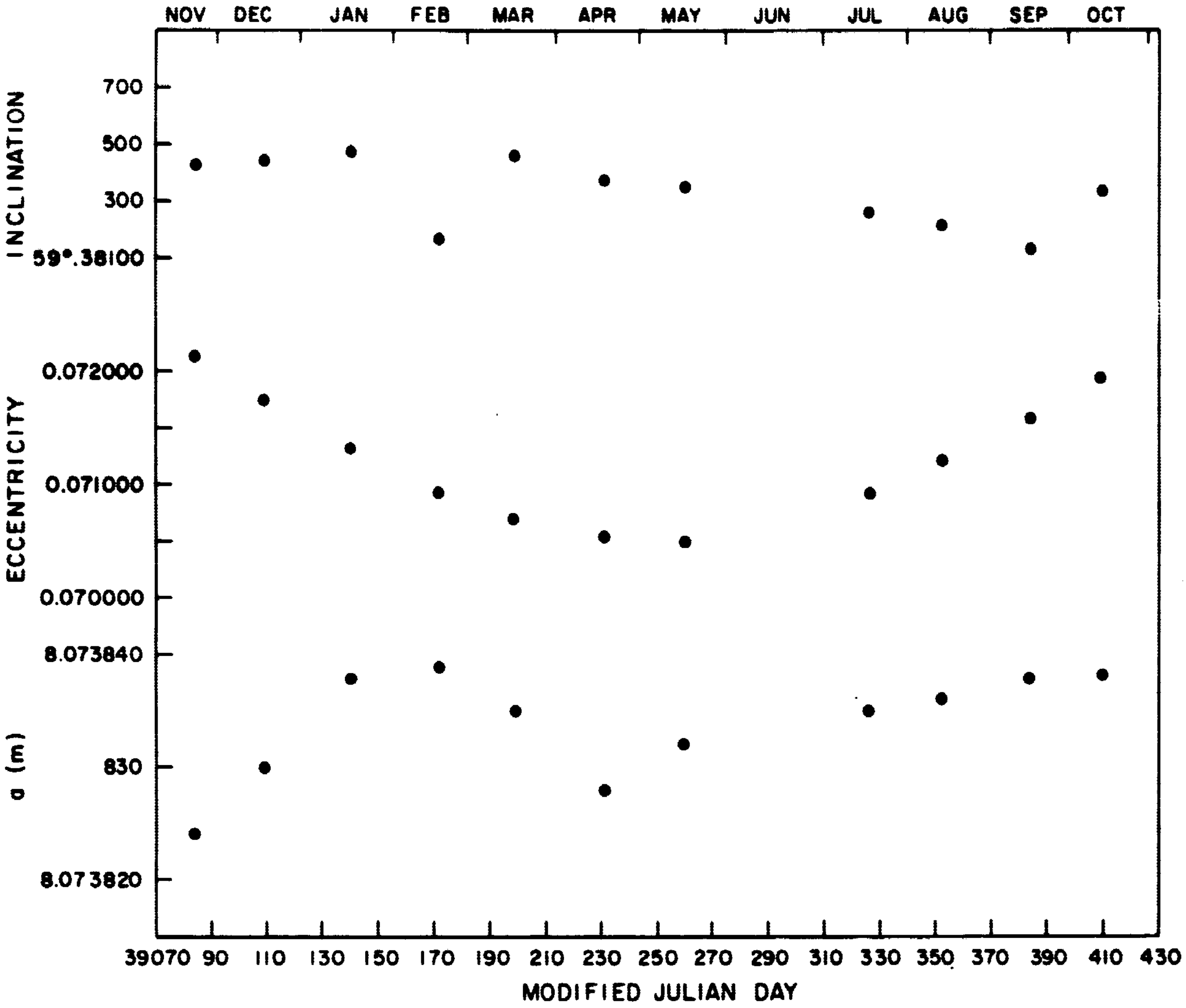

Figure 1. Mean inclination, eccentricity, and semimajor axis of Geos 1 for November 1965 to October 1966.

4. DETERMINATION OF THE LOCATIONS OF NINE MISCELLANEOUS OPTICAL SITES

The flashing light of Geos 1 was observed by several observatories. The coordination of the flashes removed the problems of mixed time systems. The observation of a flash sequence provided a set of points. We reduced each flash sequence to a synthetic observation for use in the dynamical determination of the station coordinates. These observations seemed to have an accuracy of nearly 1 arcsec.

The essential results are given in Table 3. The initial coordinates, the corrections, and the resulting coordinates are shown in the columns labeled X, Y, and Z. The numbers of synthetic observations are also given. For all stations except 9113, a direction to this previously unknown station from an SAO station had been determined by the use of simultaneous observations. In general, these directions are determined from other satellites as well. If the distance between the stations is known, this direction would suffice to determine the station coordinates uniquely. If we adopt the dynamically determined position to compute the distance, we can compute the location. The equivalent corrections from this method are also given in Table 3. This calculation is merely a consistency check.

In general, the agreement is good when there are sufficient observations. The coordinates for Rosamund seem well determined. The three stations at Cold Lake, Harvestua, and Johnston Island were determined in the Standard Earth. In each case the data were few and were acquired from geodetically less useful satellites. Since Geos 1 is essentially a better satellite, more orbital arcs are used here, and the agreement with the directions is good, the coordinates determined from Geos 1 for Cold Lake and Harvestua are preferable to the earlier results. Nevertheless, the number of observations is marginal, and these coordinates can be considered only provisional. Since

Table 3. Dynamical determination of station coordinates (optical observations of Geos 1)

Station	X (Mm)	Y (Mm)	Z (Mm)	Correction from the direction between stations dx (m)	 dy (m)	 dz (m)	Stations	Number of synthetic observations
9113 Rosamund California	-2. 450064 +28 -2. 450036	-4. 624412 -24 -4. 624388	3. 635023 11 3. 635034					243
9114 Cold Lake Canada	-1. 264346 -13 -1. 264859	-3. 466880 27 -3. 466853	5. 185464 -8 5. 185456	-5	46	-3	9001, 9009, 9010, 9012	28
9115 Harvestua Norway	3. 121265 1 3. 121266	0. 592600 20 0. 592620	5. 512684 18 5. 512702	7	17	13	9004	34
9117 Johnston Island Pacific	-6. 007395 72 -6. 007323	-1. 111893 80 -1. 111813	1. 825725 -10 1. 825715	-22	39	-14	9012	17
9050 Agassiz Massachusetts	1. 489724 23 1. 489747	-4. 467505 13 -4. 467492	4. 287291 -21 4. 287270	12	12	-8	9001, 9009, 9010	41
9066 Zimmerwald Switzerland	4. 331312 10 4. 331322	0. 567475 15 0. 567490	4. 633124 15 4. 633139	11	25	-2	9004	109
9074 Riga Latvia	3. 183913 -161 3. 183752	1. 421510 -51 1. 421459	5. 322773 -13 5. 322760	-53	3	53	9004	15
9080 Malvern England	3. 920160 34 3. 920194	-0. 134757 -2 -0. 134759	5. 021706 42 5. 012748	25	14	30	9004	20
8015 Haute Provence France	4. 578321 4 4. 578325	0. 457957 2 0. 457959	4. 403167 63 4. 403230	13	13	52	9004	77

for Johnston Island the agreement between the direction and the dynamical determination is poor, and since there are so few observations, this determination must be considered unreliable. The remaining stations are all new. Haute Provence and Zimmerwald are clearly well determined. Because of the small number of observations at Agassiz and Malvern, the determination would have to be provisional, but the good agreement between the direction and the dynamical determination is very encouraging. Riga is a first attempt.

5. DETERMINATION OF THE SECOR RANGE STATIONS

The Goddard Data Bank provided us with more than 20,000 observations from four stations. These data were obtained from as many as 17 passes from each station. In our opinion, much of this large volume of data was redundant. We therefore removed 9 of every 10 observed points, rather than fitting polynomials to the 10 points to compute a synthetic observation, because the data from each pass were extremely coherent. The noise level from the mean was 5 m or less. Nothing would have been gained by the use of synthetic points.

SECOR data have a range ambiguity of 256 m. This is because the equipment is so constructed that the range is determined from the properties of an electromagnetic wave with a 256-m wavelength. The analysis must provide the range to within that accuracy. Therefore, in the determination of station locations, we used the residuals modulo 256 m. Hence, we never computed a residual greater than 128 m. We rejected residuals greater than 100 m.

Table 4 summarizes the data available. It details the standard errors (σ) and the corrections to the station locations computed. Because of the small number of passes available and the standard error relative to the rejection criterion, we consider this determination unacceptable. In Table 4 the corrections are resolved into the height component because this sometimes provides an insight into possible problems with an ionospheric or elevation correction. This is not the case here. Table 5 gives the initial coordinates used for these stations.

Table 4. Dynamical determination of station coordinates (SECOR)

	Station			
	5001 Herndon Virginia	5333 Greenville Mississippi	5648 Ft. Stewart Georgia	5861 Homestead Florida
January '66 passes	4	5	5	4
February '66 passes	1	1	1	1
March '66 passes	6	5	3	5
April '66 passes	6	6	–	5
Total passes	17	16	9	15
Number of observations	742	641	219	550
σ (m)	48	53	54	54
Corrections (m)				
dx	10	-9	8	-10
dy	5	4	-31	20
dz	29	12	-48	27
dh	18	3	11	-7

Range ambiguity of 256 m removed

Maximum residual accepted = ±100 m

The small number of passes would not allow a very good determination of the station locations. However, the size of the standard error comes from the data set itself. Either difficulties in converting the time systems or systematic errors in the data seem the most likely reasons for the large standard error.

Table 5. Initial coordinates for SECOR stations (Mm)

Station	X	Y	Z
5001 Herndon, Virginia	1.088856	-4.842927	3.991836
5333 Greenville, Mississippi	-0.085002	-5.327944	3.493472
5648 Ft. Stewart, Georgia	0.794688	-5.360041	3.353082
5861 Homestead, Florida	0.963463	-5.679723	2.728118

6. DETERMINATION OF THE GRARR STATIONS

The GRARR system provides both distance and velocity measurements. Geos 1 was observed from three stations during the interval of our precise orbits. By far the largest amount of data came from the station at Rosman, North Carolina.

It was found that careful data selection was necessary. We obtained the raw data directly from Goddard and developed our own reduction methods and rejection criteria. During that phase of the analysis we were in close contact with the Goddard Intercomparison Effort, and we were fortunate to be able to incorporate their findings into our analysis. We found polynomial fitting to short intervals (e.g., 20 sec) valuable for two reasons: First, the smoothed or synthetic points provided significantly better results for station-coordinate determination than did the raw data points used "en masse." Second, the standard error of the curve fit proved to be an excellent rejection criterion. For the range rate data we used virtually all the data available. For the range data, a rejection criterion of 8 m in the curve fit satisfactorily discriminated good from bad passes. The 8-m criterion should not be interpreted as the accuracy of the data; it is only a measure of the internal consistency of the data for a short interval.

Table 6 details the results of the determination of three stations. Five points per pass were used. Clearly, the combination solution depends on the adopted uncertainties of the two kinds of data, and these were taken at 30 m for range and 15 cm sec^{-1} for range rate. In addition, the relative number of data points is important. We rejected residuals at 100 m for range and 45 cm sec^{-1} for range rate. Since the correction for station 4714 was larger than the rejection criterion, we performed a second iteration to verify convergence.

The results for station 4713 are quite reasonable; the data set was good. The initial coordinates were given in the North American datum. In addition, the effective correction of 16 m in height agrees with the determination by Brown (1967) from short-arc studies. The Madagascar and Australian coordinates must be considered preliminary at this stage. The small amount of data, the lack of a comparison, the high rejection rate of the data, and the lack of timing records all support this conclusion.

7. DETERMINATION OF THE TRANET DOPPLER STATIONS

The TRANET network provided data from 10 stations, generally 30 points per pass. The data were available through the entire period of precise orbits. The ionospheric correction had, of course, been removed. In addition, a preliminary frequency correction had been applied. These doppler data were treated in the same way as the Goddard range rate data.

Table 7 gives the corrections computed for the 10 sites. The initial coordinates were heterogeneous. As designated in Table 7, six stations were initially taken from an APL solution (H. Black, 1968, private communication); the remaining were taken from the Goddard directory. However, some comparisons are possible. Any solution for station coordinates computed solely with electronic data is indeterminate by one longitude. If the longitude of one station is fixed, a unique solution is possible. Therefore, for solutions to be compared, this rotation must be removed.

Table 6. Dynamical determination of station coordinates (GRARR)

Station	dX (Mm)	dY (Mm)	dZ (Mm)	dh (m)	Number of range observations	Number of range-rate observations	σ unit weight
4713 Rosman North Carolina	16	-3	19	15	4485	9764	0.90
Final coordinates	0.647192	-5.178336	3.365152				
4714 Madagascar	40	-95	-107	-6	124	1056	1.08
Final coordinates	4.091419	4.434122	-2.066035				
4715 Carnarvon Australia	-59	-34	-4	-5	225	1358	1.11
Final coordinates	-2.328264	5.299679	-2.669395				

	Range	Range Rate
Assumed accuracy	30 m	0.15 cm $\sec^{-1}$
Rejection criterion	100 m	0.45 cm $\sec^{-1}$

Table 7. Dynamical determination of station coordinates (TRANET)

Station	σ	Number of obs.	dX	dY	dZ
7014* Anchorage, Alaska	0.93	9014	-50	5	-17
7017 Tafuna, American Samoa	1.07	6108	-55	342	109
7019* McMurdo Sound, Antartica	0.96	3263	-42	66	-102
7100* South Point, Hawaii	0.97	18088	-25	15	54
7103* Las Cruces, New Mexico	0.91	19890	-25	16	74
7106* Lasham, England	0.99	23615	-54	-38	42
7111* Johns Hopkins University Baltimore, Maryland	0.85	24595	-34	-76	-21
7739 Shemya, Alaska	0.71	4986	31	226	7
7742 Beltsville, Maryland	0.85	3533	-41	-42	-23
7745 Stoneville, Mississippi	0.89	4279	-66	-35	-27

Assumed accuracy = 15 cm sec^{-1}; rejection criterion = 45 cm sec^{-1}.

*Initial coordinates APL 3.5 solution.

With several points given in two coordinate systems that differ by a rotation, this rotation can be determined. If we introduce the infinitesimal rotation (Goldstein, 1950, p. 124) $\mathcal{R}(d\Omega_1, d\Omega_2, d\Omega_3)$ such that

$$\mathcal{R}(d\Omega_1, d\Omega_2, d\Omega_3) = \begin{bmatrix} 1 & d\Omega_3 & -d\Omega_2 \\ -d\Omega_3 & 1 & d\Omega_1 \\ d\Omega_2 & -d\Omega_1 & 1 \end{bmatrix} ,$$

we want to find $d\Omega_i$ such that

$$\bar{X}_j^{SAO} = \mathcal{R}(d\Omega_i)\, \bar{X}_j^{APL} .$$

We have three candidates for such a computation and comparison: the APL 3.5 coordinates, a set of coordinates given by Anderle and Smith (1967), and a set attributed to Guier and Yionoulis (Anderle and Smith, 1967). These three sets of coordinates will be designated as X_j^{APL}, X_j^A, and X_j^{GY}, respectively. In each case, the subset of stations is different. During the comparison, the determinations of X_{7017}^{SAO} and X_{7019}^{SAO} showed large disagreement and were therefore not included in the determination of the relative positions of the reference systems. Table 8 gives the relative rotations of the reference systems in seconds of arc and the standard error of the determination in meters. The rotation in terms of meters at the surface of the earth is also included.

The physical significance of the $d\Omega_3$ is a rotation in longitude and corresponds to the difference in the adopted longitude of the TRANET solutions and the longitude of the mean observatory; $d\Omega_1$ and $d\Omega_2$ would correspond to the differences in the adopted pole of the difference solutions. While SAO used observed values of the polar motion in its analysis, none of these data were used for the TRANET solutions (Black, 1968, private communication); hence, the resulting pole is defined by a mean of the data arcs used. The computed values are consistent in sign and magnitude with this interpretation.

The differences in the values of GM used in the solutions are small, as evidenced by the values adopted (Lundquist and Veis, 1966; Black, 1968, private communication):

$$\bar{X}_j^{A} \quad GM = 3.986010 \times 10^8 \ \mathrm{Mm}^3 \ \mathrm{sec}^{-2}$$

$$\bar{X}_j^{SAO} \quad GM = 3.986013 \times 10^8 \ \mathrm{Mm}^3 \ \mathrm{sec}^{-2}$$

$$\bar{X}_j^{GY} \quad GM = 3.986015 \times 10^8 \ \mathrm{Mm}^3 \ \mathrm{sec}^{-2} \ .$$

Table 8. Relation between the various reference systems: SAO C6 coordinates (SAO); APL 3.5 coordinates (APL); Anderle coordinates (A); Guier and Yionoulis coordinates (GY).

	$d\Omega_1$ (arcsec)	$d\Omega_2$ (arcsec)	$d\Omega_3$ (arcsec)	$a_e d\Omega_1$ (m)	$a_e d\Omega_2$ (m)	$a_e d\Omega_3$ (m)	σ (m)
SAO-APL	-0.02	0.42	1.24	0	13	41	41
SAO-GY	-0.93	0.35	2.11	-28	10	65	35
SAO-A	-0.85	0.36	0.91	-26	11	28	18
A-GY	-0.08	-0.03	0.94	-2	-1	29	13

The standard errors of 18 m for the Anderle solution relative to the SAO solution and of 35 m for the Guier and Yionoulis solution relative to the SAO solution are quite satisfactory in view of the 13-m agreement between the A and the GY (Table 8). Considering that both the TRANET solutions also used other satellites and involved a further improvement of the frequency and tropospheric correction, their reliability is much enhanced. This is especially true for station 7019, which is at -77° latitude. Since Geos 1 is of 59° inclination, all the data used in our analysis were low passes to the north, which resulted in very poor geometry. The poor results from station 7017 cannot be attributed to its latitude. Table 9 provides the final coordinates determined from GEOS 1.

Table 9. Final coordinates of the TRANET stations

		X_j^{SAO}			$X_j^{SAO} - X_j^{A}$	
Station	X (Mm)	Y (Mm)	Z (Mm)	dx (m)	dy (m)	dz (m)
7014 Anchorage Alaska	-2.656183	-1.544326	5.570618	22	25	-23
7017 Tafuna American Samoa	-6.100005	-0.997366	-1.568560	19	-244	-73
7019 McMurdo Sound Antartica	-1.310712	0.310531	-6.213456	-11	25	-83
7100 South Point Hawaii	-5.504199	-2.224095	2.325278	-20	-3	-7
7103 Las Cruces New Mexico	-1.556251	-5.169461	3.387239	19	-23	10
7106 Lasham, England	4.005469	-0.071800	4.946720			
7111 Johns Hopkins Univers Baltimore, Maryland	1.122608	-4.823073	4.006486	11	-1	29
7739 Shemya, Alaska	-3.851550	0.397301	5.051523	-16	15	63
7742 Beltsville, Maryland	1.130731	-4.830861	3.994701	-4	-13	-8
7745 Stoneville, Mississippi	-0.085070	-5.327989	3.493425	-17	-14	-10

8. SUMMARY AND CONCLUSIONS

The geodetic satellite Geos 1 has been immensely successful in the determination of the locations of many new stations in the SAO C6 system. In some cases these coordinates are preliminary, in the sense that the determination is thought to be significantly worse than the 20-m accuracy that could be desired. Where stations had previously been determined by earlier and more comprehensive analysis, these results can be viewed as a confirmation of our technique, and an adjustment or average may provide somewhat more realistic results. The values determined for the relation between the SAO and the TRANET systems are considerably more reliable than any of the individual determinations. In any case, the station coordinates determined here are suitable for an initial set to be used in future large-scale solutions. It is quite clear that it is desirable and feasible to combine the SAO Baker-Nunn observations, other optical observations of good quality, and GRARR, TRANET, and laser observations in a comprehensive global solution for station coordinates and the gravity field with the use of a wide variety of satellites.

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