TRACKING STATION POSITIONING FROM ARTIFICIAL SATELLITE OBSERVATIONS

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Abstract. The paper first reviews the various methods of tracking station positioning from artificial Earth satellite observations, namely the general and partial dynamic solutions, the methods of short arc, point positioning, translocation, and the purely geometric constructions. The description of recent results from both global and local networks is followed by a comparison of the various solutions and examples of geodetic and geodynamic applications.

1. Introduction

The scientific purpose of satellite observations falls into either dynamic or geometric categories. The dynamic purpose of satellite tracking is to observe positions and motions of satellites as a function of time, with sufficient accuracy for developing a theory of motion capable of predicting future positions at least as accurately as they can be observed. In order to make these predictions an extensive theory of the motion, the precise knowledge of the physical parameters defining the force field in which the satellite moves, and the accurate geocentric position of the observer are needed. Since, at least initially, the physical parameters and the tracking station positions are not known adequately, even when the theory of motion is sufficiently extensive, the observed positions and motions of the satellite will differ from the predicted ones. From these differences, corrections to the assumed parameters and station coordinates may be calculated, generally by means of a least squares adjustment procedure.

In the frame of celestial mechanics, a branch of classical mechanics, many improvements on the theory of motion have been developed during the centuries. The best mathematical minds of humanity devoted their energy to this problem, but mostly in connection with planetary motions. The circumstances of an artificial Earth satellite are different from those of an ordinary planet in two main respects: its orbit is much closer to the Earth than the orbit of any planet with respect to its primary, and it moves, at least partially, in an atmosphere while the natural satellites move practically in a vacuum. The first fact implies that the motion of an artificial satellite is significantly affected by the asymmetries of the Earth's gravitational field and by its temporal variations (e.g., tides) and therefore it could be used to determine the parameters defining this field. These coefficients in turn may yield information on the shape, the mass distribution, and the dynamic behavior of the Earth. The second fact opens up possibilities to determine the structure of the atmosphere and provide an insight to its behavior. There are also other phenomena which will influence the motion, such as the attraction of the Sun and the Moon, radiation pressure emanating from the Sun, lunar and solar tidal distortions, effects of the magnetic field of the Earth, etc., but these generally have relatively minor effects compared to those of gravitation and the

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atmosphere. The theory which deals with the motion of an artificial satellite in its orbit around a celestial body is usually called *close satellite theory*. None of the classical texts treat this problem but it is discussed in more recent volumes such as (Brouwer and Clemence, 1961; Mueller, 1964: Kaula, 1966; Hagihara, 1972; Gaposchkin, 1973; and American Geophysical Union, in press).

The geometric purpose of satellite tracking is to observe positions of satellites from several stations of known and unknown positions simultaneously for determining the relative positions of the stations (and the satellites). In this method the satellite is simply regarded as an observational target and the fact that it moves in an orbit describable by the theory of motion is not used, except possibly to provide observational predictions. Depending on which component of the station-satellite vector is observed, it is customary to distinguish between *satellite triangulation* and *trilateration*. In the former case, similarly to traditional geodetic triangulation, only directions are observed; while in the latter, as in geodetic trilateration, only lengths are measured. A suitable combination of the two methods usually yields the best results. The station positions thus determined may be used for a variety of purposes, such as to strengthen a satellite tracking network established for dynamic applications, to provide connections between geodetic datums separated by large distances, to determine distortions within geodetic datums, to detect motions between the stations due to geodynamic phenomena, etc. Theories of satellite triangulation and trilateration may be found in (Schmid, 1972; Mueller *et al.*, 1973; and American Geophysical Union, in press). Due to the fact that the geometric mode is dependent on fewer parameters and a simpler theory, it is believed to produce more accurate results than the dynamic mode. Simultaneous observations, on the other hand, are more difficult to obtain and the resulting station positions are not absolute (geocentric).

In the following sections the principles of dynamic and geometric satellite positioning are briefly described and current results together with their applications are summarized.

2. Principle of Station Positioning

2.1. General dynamic method

In the simplest case, when a spherical satellite moves around its spherical primary in an orbit, affected only by the latter's attraction, the resulting *normal orbit* may be defined by 6 constants ,$E_i (i = 1, 2, \ldots 6)$. These parameters may be selected according to various theoretical and computational criteria. From the didactic point of view, the simplest set is the classical *Keplerian elements*, which define the orientation of the plane of the orbit in space (2 parameters); the size, shape, and orientation of the Keplerian ellipse in that plane (3 parameters) and finally, the position of the satellite at some given epoch (1 parameter). In the gravitational force field of the spherical primary these elements are constant and the satellite moves in its defined orbit in accordance with the laws of Kepler.

As mentioned in the Introduction, the circumstances of a near-Earth artificial satellite are different from the above, the main consequence being that the orbital elements will no longer be time invariant, or in other words, their derivatives with respect to time, $\dot{E}_i$, will not be zero. The variation of a given element from some reference epoch, T_0, to the epoch of utilization, T, can symbolically be described by the following equation:

$$E_i = E_i^0 + \int_{T_0}^{T} \dot{E}_i \, \mathrm{d}T \,, \tag{1}$$

where E_i^0 is the element in question at the epoch T_0, and E_i at T. The integral represents the perturbation of the element E_i. The function $\dot{E}_i$ is the rate of change of the element E_i due to all perturbing forces (non-spherical part of the Earth's attraction, atmospheric drag, etc.) and as such is a function of several hundred parameters, $P_j(j=1, 2, \ldots n)$, defining these forces. For example, an adequate description of the Earth's gravitational field may require as many as 500, the atmospheric drag 10, and the radiation pressure 5 force parameters. The integral may be solved analytically (method of general perturbations) or numerically (method of special perturbations).

Once the orbital elements are thus computed at the epoch T, they can be readily converted into positional and velocity components of the satellite and referenced to some well defined coordinate system. If the parameters defining the observer's position in this coordinate system, $S_k(k=1, 2, 3)$, are also known then the observables can be calculated, i.e., predicted. To refer the positions of the satellite and the observer to the same (usually Earth-fixed) coordinate system, the precise knowledge of precession, nutation, polar motion, and Earth rotation (UT1) is also required.

For principal geodetic results the observables are frequency (range rate), range, range difference, and direction components (e.g., right ascension and declination), either observed individually or in certain combinations. Provided that the theory of motion, e.g., the mathematical model, is correct and that the observations have been reduced to station and freed of systematic errors, the differences between the computed, $C_l(l=1, 2, \ldots m)$, and the observed, O_l, values of the observables will be due to the erroneous geocentric coordinates of the observer S_k and the erroneous orbital elements, that is, the parameters P_j. Assuming that both the differences $O_l - C_l$, and the errors $\mathrm{d}P_j$, $\mathrm{d}S_k$ are differentially small, then the following type of relations may be established:

$$O_l - C_l = \sum_j \frac{\partial C_l}{\partial P_j} \mathrm{d}P_j + \sum_k \frac{\partial C_l}{\partial S_k} \mathrm{d}S_k \tag{2}$$

where

$$\frac{\partial C_l}{\partial P_j} = \frac{\partial C_l}{\partial E_i} \frac{\partial E_i}{\partial P_j}, \tag{3}$$

E_i being an orbital element at the instant of observation.

If Equation (2) is regarded as an observational equation then the quantities $\mathrm{d}P_j$ and $\mathrm{d}S_k$ are the vector components representing the unknown corrections to the assumed parameters and station coordinates, respectively, and $\partial C_l/\partial P_j$ and $\partial C_l/\partial S_k$ are the elements of the corresponding coefficient, or design matrices. In order to obtain a satisfactory solution the number of observations, m, must greatly exceed the number of unknown parameters, n, plus the station unknowns $p \times k$ (p is the number of stations), and a least squares adjustment is performed in the traditional sense. To perform such a calculation is a formidable task, considering that recent solutions, for example, included data from 10–20 satellites observed over 2–4 week periods from as many as 50–100 stations. Thus, the unknowns may include 150–300 components of positions in addition to about 450–500 gravitational coefficients, thousands of orbital constants (e.g., E_i^0), possibly pole position parameters, etc. Such general solutions, because of the high cost of forming the large normal equation matrices and of their inversions, are performed infrequently, and only by a few organizations having access to large computers.

2.2. Partial dynamic method

Once the results of a *general solution*, such as the one outlined above, are available, additional stations can be added on at a much smaller cost. In such *partial solutions*, positions of observing stations are obtained from least squares adjustments, where the Earth's gravity field and the positions of many of the stations are held at values determined in the preceding general solution. Usually a separate computer program is used for this purpose because program efficiency is greater when the objectives are more limited. In these solutions a shorter time span of data (2–5 days) may be used, which will also reduce the effect of some errors in the force field. The unknowns in such a solution, in addition to the coordinates of the new stations, include the 6 initial orbital constants, E_i^0, usually a drag (scaling) parameter, and maybe components of the pole position. In other words, in such solutions most perturbations are treated as known phenomena which can be calculated from the parameters determined in the general solution.

2.3. Short arc, point positioning, and translocation methods

Two special cases of the partial solution are the so-called *short arc* and the *point positioning* methods. In the former, the data are limited generally to satellite passes of 10–30 min lengths. These relatively inexpensive solutions contain as unknowns only 6 initial orbital parameters per pass and the coordinates of the participating stations. The method is limited to relative positioning with respect to a reference station whose coordinates are held to their estimated (not necessarily geocentric) values. Due to the shortness of the arc the perturbation models may be simpler than in the partial solutions; for example, the gravity field may be satisfactorily described by as few as 50–75 parameters, depending mainly on the length of the arc and the altitude of the satellite. The relative station positions obtained from short arc solutions are considered generally free of orbital (or other) biases equally affecting stations observing the same arcs.

In the *point positioning* method the data span is several days long (2 to 7) and the orbital elements are held to the values obtained from a precise satellite ephemeris. Thus, the only unknowns in the solution are the coordinates of the observing stations.

The satellite ephemeris is generated and made available by some organization which keeps continuous track of the satellites in question. A prime example of this method is positioning by using instruments that measure the range difference between a ground station and two satellite positions by means of integrating the Doppler shift of radio transmissions from the Navy Navigational Satellites (NNS). Precise ephemerides of these satellites are generated by the Naval Surface Weapons Center (formerly the Naval Weapons Laboratory) in Dahlgren, Virginia, from which satisfactory orbital elements may be obtained for the instants of the observations. Predicted, and therefore less accurate elements, are also generated and injected into the satellite's memory by the Naval Astronautics Group, Point Mugu, California, which in turn are retransmitted and can be used with certain types of receivers. In this latter case it is advisable to observe the satellite passes from at least two stations simultaneously and to solve only for relative positions which, similarly to the short arc case, will be less affected by the biases in the orbital elements than the positions themselves. This mode of operation is termed *translocation.*

2.4. Geometric method

In cases where simultaneous observations are made of the satellite from two or more stations, the satellite may be used only as the target of observations and the fact that it moves in an orbit can be ignored. The target in fact may as well be a rocket, a balloon, or an airplane carrying proper instrumentation, instead of being a satellite. The orbital elements E_i in Equation (3), in this case become parameters and $\partial E_i/\partial P_j$ are identity matrices. After converting the parameters E_i to satellite-target coordinates, $T_k (k=1, 2, 3)$, referenced to the same coordinate system in which the station coordinates S_k are sought, Equation (2) will have the following form:

$$O_l - C_l = \sum_k \frac{\partial C_l}{\partial S_k} (\mathrm{d}T_k - \mathrm{d}S_k), \tag{4}$$

where, as before, the left side is the discrepancy between the observed and computed (predicted) values of the observables. In the right side, $\mathrm{d}T_k$ and $\mathrm{d}S_k$ are the unknown corrections to the predicted target and assumed station coordinates, respectively, and $\partial C_l/\partial S_k$ is the coefficient matrix.

In this mode of operation the observables at a given station have been mostly restricted to ranges (trilateration) or directions (triangulation), although range differences or a combination of ranges and directions can also be used.

In order to invert a system of geometric normal equations, a certain number of constraints will have to be introduced. This is due to the fact that while in the dynamic solutions the system to which the station coordinates refer is defined through satellite dynamics, in the geometric solutions it is not defined. Thus, in the case of satellite triangulation, when the satellite directions are determined from photographs against the background of stars, the orientation of the system is inherently defined by means of the star catalog used. The origin of the system is to be specified by holding the 3 coordinates of a station to their *a priori* values and the scale is to be defined by constraining the distance between two stations to its measured value. Thus, in this case the minimum number of constraints to be introduced to obtain a solution is 4. In the case of trilateration, only the scale is inherent in the observations; thus, the origin and the orientation of the system is to be defined. This can be done, for example, by holding 6 coordinates distributed between 3 stations to their estimated values. In practice, usually more than these minimum constraints are applied. They are usually available from accurate ground survey information, which may be included in the solution if their values are to be preserved. Such information may be the relative positions of neighboring stations, known distances between stations, heights, etc.

It should be mentioned at this point that the geometric mode is very sensitive to the problem of *critical configurations*. If the stations and target points happen to be in such configurations with respect to each other then the solution will be singular even when the number of observations is sufficient and the coordinate system is properly defined. Near singularity or ill conditioning will occur when the stations or the satellites are near critical configurations. The problem has been well studied and methods of avoiding it for trilateration may be found in Blaha (1971b), for triangulation in Tsimis (1972), and for range differences in Tsimis (1973).

2.5. Additional comments

In all methods described the assumption was made that the observations are of sufficient number and have been preprocessed so as to be free of systematic errors. The latter generally can not be assured and a remedy is sought by trying to model the systematic errors and solve for the model parameters in the course of the adjustment. Although this procedure could significantly increase the number of unknowns, it may be a useful tool in reducing the effects of systematic errors, especially if good approximate parameters are available prior to the calculations. Typical coefficients to be determined this way are constant ranging biases, refraction parameters, and timing biases.

Other types of parameters which may significantly increase the number of unknowns in an adjustment are those peculiar to certain observational systems. A typical example is the reference frequency of a Doppler receiver, which has to be determined for each instrument and redetermined frequently.

The dynamic or geometric solutions described will thus result in corrections to the assumed parameters defining the force field and the assumed station coordinates, possibly in parameters of polar motion, instrumental constants, observational biases, etc. These corrections supposedly account for the discrepancy $(O_l - C_l)$ in Equation (2) or (4). Inspection of the observational residuals after the adjustment will reveal whether the case is such or not. The residuals will reflect, of course, also the discrepancies caused by the incompleteness of the mathematical models represented by the parameters. In the case of the near-Earth satellite orbits this situation will exist, if for no other reason than for the inadequacy of modeling the drag and refraction, and in the case of distant satellites, the radiation pressure effects. Since such errors arise from the environment over which we have no control, it is likely that they will be correlated and the residuals may display a systematic character. Such a display should serve as an incentive for new investigations to improve the existing models and parameters. This question brings up statistical implications and the need to decide on the type of statistical treatment, which problem is beyond the scope of this paper.

3. Review of Recent Solutions in the United States

3.1. Historical Overview of Accomplishments

Satellite tracking stations were planned, already, several years prior to the launch of the first artificial Earth satellite in 1957. The first stations set up in 1957–58 were the 6 Prime Minitrack receivers of the Naval Research Laboratory and NASA for interferometry, and the 12 Baker Nunn cameras of the Smithsonian Astrophysical Observatory for directional observations. The geocentric positions of these stations were known only to perhaps a few hundred metres. One of their primary functions was to improve these coordinates to a level commensurate with tracking requirements at that time. This modest initial effort proliferated by 1972 into over 300 tracking stations, occupied either permanently or occasionally with obtaining positions estimable to 5 to 10 m in a common reference frame.

The most important global networks established during these 15 yr are the following:

(1) *SAO Network*, operated by the Smithsonian Astrophysical Observatory, containing 19 Baker Nunn cameras and 4 laser stations.

(2) *TRANET or Navy Navigational Satellite (NNS) Network*, under the general jurisdiction of the U.S. Navy, consisting of about 24 permanent and over 200 mobile Doppler stations.

(3) *NASA Network*, operated by the Goddard Space Flight Center, including about 30 MOTS cameras, 7C-Band radars, 5 GRARR (Goddard range and range rate) and 3 laser stations.

(4) *NOS Network*, set up by the U.S. Coast and Geodetic Survey (now the National Ocean Survey), consisting of 49 Wild-BC4 camera stations for the worldwide satellite triangulation project.

(5) *SECOR Network*, under the U.S. Army Map Service (now DMA/Topographic Center), consisting of over 40 SECOR ranging stations.

The primary scientific purpose of the SAO, TRANET, and NASA networks was to obtain observations for either general or partial dynamic solutions. The NOS and SECOR networks collected data for geometric solutions.

In addition to these globally distributed stations, large numbers of local nets sprung up also in North and South America, Europe, and Australia, and in the Pacific. Data were collected mostly with cameras, SECOR, and later with portable Doppler receivers for the purpose of obtaining point positioning, short arc, translocation, or geometric solutions.

The progress of data collection and analysis was duly reported at scientific meetings and in publications. If the reader wishes to study these, the proceedings of the 4 international symposiums on the use of artificial satellites in geodesy are especially recommended. These were held at Washington, D.C., in 1962 (Veis, 1963) and 1971 (Henriksen *et al.*, 1972), and at Lagonissi, Greece, in 1965 and 1973 (Veis, 1967 and 1974). In addition, the report on the National Geodetic Satellite Program provides an excellent overview (American Geophysical Union, in press). This program was started in 1965 by NASA primarily in response to pressures from within NASA and from other groups both in the United States and abroad for improvements in the geodetic and geophysical constants used in the computation of orbits. The program effectively correlated the diverse efforts of the networks mentioned above and also of the organizations involved in data analysis only, such as The Ohio State University (Henriksen and Mueller, 1974).

In the following section, recent dynamic and geometric solutions which produced new and useful information on the geocentric or relative positions of tracking systems are briefly described.

3.2. Global Dynamic Solutions

3.2.1. *Goddard Earth Models (GEM) 5–6*

After the earlier solutions, GEM 1–4, by the Goddard Space Flight Center (Lerch *et al.*, 1972a and 1972b), the GEM 5 and 6 solutions (Lerch *et al.*, 1974) have been computed to satisfy the requirements of the National Geodetic Satellite Program. Both are numerically integrated general solutions. GEM 5 was derived solely from satellite tracking data on 27 satellites. It includes camera observations, Doppler data, laser and C-Band ranges, GRARR measurements, and Minitrack interferometric observations – a total of about 400 000 observations. In the GEM 6 solution the same data was amended by the simultaneous camera observations from the NOS Network and 1654, $5° \times 5°$ mean gravity anomalies representing surface gravity data. The dynamic normal equations were combined with geometric normal equations based on the simultaneous camera data. The unknowns solved for were the geocentric positions of 134 stations; 328 spherical harmonic coefficients of the Earth's gravitational field complete to degree and order 16, with additional resonant and zonal terms to degree 22; the equatorial semi-diameter of the best fitting ellipsoid (6 378 144 m) and its flattening (1/298.257) and the equatorial value of the normal gravity (9.780 321 ms^{-2}). It is estimated that the majority of the station coordinates are determined to an accuracy higher than 10 m with respect to the geocenter. The value of the gravitational constant GM was held to $3.986\,013 \times 10^{14} \mathrm{m}^3 \mathrm{s}^{-2}$. A forthcoming improvement of the GEM 6 solution is GEM 7, in which 66 000 laser measurements on 7 satellites, taken during the International Satellite Geodesy Experiment (ISAGEX), were added to the previously used set of observations (Lerch *et al.*, 1975).

3.2.2. *GSFC 73 Station Solution*

This set is a partial solution by the Goddard Space Flight Center (Marsh *et al.*, 1974b). Seventy-two station positions (58 cameras and 14 lasers) were determined from a total of 65 000 optical observations and about 350 passes of laser data on 5 satellites. In the solution 150, 2-day arcs computed through numerical integration techniques were constrained and the coordinates of the stations solved for. The equations of motion included contributions from luni-solar perturbations, solar radiation pressure, polar motion, mechanical drag, and the GEM 1 geopotential set modified with the SE II 12th, 13th, and 14th order resonant coefficients. The estimated accuracy of the station coordinates is less than 5 m. The reference GM in this solution is $3.986008 \times 10^{14} m^3 s^{-2}$.

3.2.3. *Smithsonian Standard Earth (SE) III*

Following previous general solutions, the Standard Earth I and II (Lundquist and Veis, 1966; Gaposchkin and Lambeck, 1970 and 1971), the SE III (Gaposchkin, 1973 and 1974), similarly to GEM 6, is based on a combination of dynamic and geometric normal equations. The latter were generated from simultaneous camera observations within the NOS, the SAO, and some smaller independent networks. The former are based on the SAO network's routine camera and laser observations on 25 satellites, positions of the Deep Space Network stations as determined by the Jet Propulsion Laboratory (see below), and surface gravity data in the form of 19 328, $1^\circ \times 1^\circ$ mean anomalies. The laser observations included those of the SAO, NASA and the Centre National d'Etudes Spatiales (CNES). The dynamic analyses were made by using general perturbation techniques in which the equations of motion were analytically integrated. The parameters determined included geocentric coordinates for 104 stations, 386 spherical harmonic coefficients complete to degree and order 18, plus resonant and zonal terms to degree 36. The force parameters and the station coordinates were determined iteratively. The coordinates of the laser stations are estimated to be accurate to 2 to 4 m, and those of the camera stations 5 to 10 m, both with respect to the geocenter. The semi-major axis of the best fitting ellipsoid is 6 378 140.4 m with a flattening of 1/298.256. The value of the gravitational constant GM was held at $3.986\,013 \times 10^{14} m^3 s^{-2}$.

3.2.4. *NWL 9D Doppler Solution*

The first geodetic results based on Doppler satellite observations were obtained from data on the Transit 1B and 2A satellites (Cohen and Anderle, 1960). Subsequent analyses used Doppler data from Transit 4A and 4B, ANNA 1B, the Beacon Explorers B and C, GEOS 1 and 2, Diademe 1 and 2, Timation 2, and a number of NNS satellites, of which the currently satisfactorily operating include 1967-34A, 1967-48A, 1967-92A, 1968-12A, and 1970-67A (Anderle, 1965 and 1967; Anderle and Smith, 1967 and 1968; Anderle, 1974a).

The observations for the partial solution NWL 9D were carried out by the TRANET network's permanent and mobile stations, some of which were collocated with the BC-4 cameras in the NOS network. The orbits were determined by a least squares fit to observations made in a 48 hour time interval, mostly on the NNS satellites. Parameters of the solution included 6 orbital constants, an atmospheric density scale factor, the components of pole position, the position of recently occupied observing sites, and a frequency and refraction bias parameter for each satellite pass. The satellite orbits were computed by 12th order numerical integration of the equations of motion. Forces considered in the equations of motion included contributions from the Earth's gravity field described by a spherical harmonic expansion including about 450 terms, the direct luni-solar effects, the solid Earth tides, atmospheric drag, and solar radiation pressure.

Positions of the permanent stations (NWL 9C set) and the coefficients describing the Earth's gravity field (NWL 9B set) were held fixed at values determined in least squares fits to observations of satellites having various orbital inclinations. Once the precise orbit has been determined on the basis of observations made at the permanent sites, the positions of the isolated receivers were determined by a least squares fit of observations to the precise orbit, for which the unknowns included the positions of the receiver and a frequency and refraction bias parameter for each pass.

Published results of the NWL 9D solution include only the coordinates of 37 sites occupied by the NOS cameras and are referred to the NWL 8E best fitting ellipsoid, which has a semi-diameter of 6 378 145 m and a reciprocal flattening of 298.25. The estimated accuracy of the positions with respect to the geocenter is 1.5 m in each component with a probable scale bias of 1.1 parts per million (too long) (Anderle, 1974a).

3.2.5. *Department of Defense World Geodetic System (WGS) 72*

This solution resulted from a major combination of normal equations generated by the TRANET, SECOR, SAO, and NOS networks, with weights assigned according to *a priorily* defined root mean square deviations in the station residuals with respect to the originators' individual solutions (2.2 m for TRANET, 6.6 m for NOS, 12.0 m for SECOR, and 9.0 for SAO). Because of the weighting procedure the TRANET Doppler data dominates the solution. Neither the coordinates nor the gravity field is available in the open literature for this solution, which is to replace the WGS 66 reference system for the Department of Defense. The following derived parameters are of interest: the semi-diameter of the best fitting ellipsoid is 6 378 135 m with a flattening of 1/298.26, the equatorial value of the normal gravity is 9.780 332 6 ms^{-2}, and the gravitational constant GM is $3.986\,005 \times 10^{14} \mathrm{m}^3 \mathrm{s}^{-2}$ (Seppelin, 1974).

3.2.6. *SECOR Equatorial Network*

The SECOR ranging system originally was envisioned as a purely geometric construction in which 4 stations observed the satellite simultaneously. In this concept three 'known' stations are held fixed and satellite positions are computed from the simultaneous ranges. The computed positions of the satellite are then held fixed and the position of the unknown fourth station is computed from a least squares adjustment. The stations are moved in a leap frog manner through the network. In order to increase the amount of usable data by not requiring simultaneity within each quadrangle and also to avoid the 'critical configuration' problem arising in such 4-station systems, the final analysis for the 37 stations in the SECOR equatorial network was not done in the geometric mode but by means of a short arc adjustment. Reference orbits were computed by numerical integration, where the equations of motion contained contributions only from the Earth's gravity field. About 48 000 observations distributed over 594 passes were analyzed for the unknown station coordinates and 6 orbital elements per pass. Since 16 SECOR stations were collocated with the BC-4 stations in the NOS network, directions between the stations obtained from the camera observations could be constrained in the solution to add strength to the geometry. Fourteen such directions were actually computed and held. With this amount of directional control the estimated accuracy for the station positions obtained through the short arc adjustment was estimated to be as much as 25–30 m, despite the fact that the *a posteriori* standard deviation of a single range was only 2.7 m (Rutscheidt, 1972; American Geophysical Union, in press). This disparity is likely to occur, due to the lack of adequate directional control. The SECOR system's significant contribution came later when it was used to scale the network in the Ohio State University WN 14 geometric solution (see Section 3.3).

3.2.7. *Deep Space Network (DSN) LS 37*

The Deep Space Network, operated by the Jet Propulsion Laboratory, consists of 8 stations around the globe established for 2-way communications with spacecraft traveling from the Earth to interplanetary distances. The stations are situated in such a way that 3 of them may be selected approximately 120° apart in longitude to provide continuous coverage of a distant satellite. The 2-way integrated Doppler data obtained by the DSN can be utilized to determine the gravitational constant for the Earth, GM, and 2 components of the station positions, namely, distance from the rotation axis and longitude difference between the stations (Moyer, 1971). The 2-way integrated Doppler data actually is the equivalent of the range difference between the station and the spacecraft that occurred during a sample interval (over 10 min).

Several DSN solutions (Location Set 25, 37) have been reported (Mottinger, 1969; American Geophysical Union, in press). The latest set (LS 37) is based on tracking data from intervals of approximately two weeks of duration when between 1965 and 1969 the Mariner-4 and -6 spacecraft were closest to Mars, and during the two weeks when Mariner-5 passed by Venus and also before and after its nearest approach. The solution derived is for all 8 stations (3 at Goldstone, California; Woomera and Canberra, Australia; Johannesburg, South Africa; and 2 at Madrid, Spain). The spin axis distances obtained are believed to be not better than 0.8 m and no worse than 2 m. The standard deviations of the relative longitudes show a spread between $0.2–3.8 \times \times 10^{-5}$ deg. The stations at the Goldstone complex are the best determined ones due to the high quality calibration data not available elsewhere. The absolute longitudes of the stations, referenced through JPL's DE 78 Planetary Ephemeris and UT1 and polar motion from the BIH, show a systematic 0″.6 rotation with respect to longitudes referenced through the FK4 star catalog. This fact brought about much debate about the position (and motion) of the FK4 vernal equinox with respect to the inertial (dynamic) vernal equinox as defined through the planetary ephemeris (see Section 3.4).

3.3. Global geometric solutions

3.3.1. *NOS Worldwide Satellite Triangulation*

In this superbly organized activity between the years 1966 and 1972, the National Geodetic Survey/NOS performed a global satellite triangulation, including about 45 BC-4 camera stations (Schmid, 1974). As mentioned earlier, 16 of these stations were collocated with SECOR sites and 37 with TRANET sites. The scale for the network was obtained by incorporating in the solution the constrained lengths of 7 long baselines (1100 to 3500 km) measured electronically on the ground in Europe, Africa, Australia, and the U.S. Two solutions were computed: a strictly geometric solution based on the camera observations and a combination solution in which the collocated TRANET station coordinates were transformed (scaled and rotated) into the NOS system, and then treated as *a priori* information with standard deviations of 3.5 m for each component. This combined solution significantly improved the strength of the geometric solution, especially in certain geographic areas, but at the same time made it lose its purely geometric character. The average positional standard deviation for the geometric solution is 4.5 m and for the combination solution, 3.7 m. The equatorial radius of the ellipsoid best fitting the 45 stations is 6 378 130 m, significantly smaller than those obtained in the dynamic solutions mentioned in Section 3.2, and has a flattening of 1/298.25.

3.3.2. *OSU Global Satellite Triangulation and Trilateration*

The most extensive purely geometric solutions completed to date were performed at the Department of Geodetic Science, The Ohio State University (OSU) (Mueller *et al.*, 1973 and Mueller, 1974a). The solutions included about 100 000 observations from 158 sites: 36 SECOR stations, 49 BC-4, 21 PC-1000, 16 MOTS, 23 SAO, 6 special camera stations, and 6 C-Band radars. In the basic solution WN 14 the scale was defined through the SECOR observations and by means of weighted height constraints. These constrained geodetic heights were estimated from mean sea level heights to which gravimetrically computed geoidal undulations were added. The undulations were referred to an ellipsoid whose size and shape fits those determined from dynamic solutions ($a = 6\,378\,142$ m and $f = 1/298.25$). The origin of the system was defined through an 'inner constraint' procedure which minimized the trace of the variance-covariance matrix of the station positions (Blaha, 1971a). The average standard deviations of the coordinates are 3.9 m in each component.

A second published solution, WN 12, differs from WN 14 that in it the heights were not constrained; thus, the scale is from the SECOR observations alone. The resulting semi-diameter of the best fitting ellipsoid is 6 378 154 m with the same (1/298.25) flattening. The effectiveness of the height constraints shows not only in the more reasonable equatorial radius in WN 14, but also in the fact that when the geoidal undulations (geodetic minus mean sea level heights) were compared with gravimetrically determined ones, the rms residual was 6.1 m for the WN 14, while for the WN 12 it was 16.1 m.

In a third set, termed OSU 275, to the 158 stations in the WN 14 solution 117 stations were added, either by direct ground survey information or by coordinate transformations. The coordinates of these 275 stations are listed in Annex 1. The system in which the coordinates are presented is oriented towards the Zero Meridian (U-axis), and the Conventional International Origin (W-axis), both as defined by the Bureau International de l'Heure (BIH). The V-axis forms a right handed system. It should be remembered that the origin of the system is arbitrary. Its position with respect to the geocenter can be estimated, however, from comparisons between the coordinates of collocated stations in the OSU 275 and in the dynamic solutions. Such comparisons suggest that the coordinates of the origin with respect to the geocenter are $U_0=16$ m, $V_0=12$ m and $W_0=-2$ m.

3.4. Systematic differences between global satellite systems

For the purpose of this paper a satellite (coordinate) system is defined by a set of station coordinates and their variance-covariance matrix from a given geometric or dynamic solution.

Table I is a compilation of transformation parameters between the OSU WN 14 system and the NWL 9D, SE III, GEM 6, GSFC 73, and NGS systems described in Sections 3.2 and 3.3. Note that all but the last are dynamic solutions. The method of computing the parameters is described in Kumar (1972). In the table the positive angles ω, ψ and ε are counterclockwise rotations about the W, V, and U axes, respectively, as viewed from the end of the positive axis. The scale difference factor Δ is in units of parts per million. In the transformations the variances of both sets of the coordinates were taken into account. Taking the variances of the WN 14 solution as

TABLE I

Transformation parameters between various satellite systems (Satellite system – WN 14)

System	NWL 9D	SE III	GEM 6	GSFC 73	NGS geometric	
					w/o Doppler	with Doppler
Number of stations	32	72	75	26	45	45
Weight factor[a]	4.0	4.0	1.50	22.0	2.25	2.75
ΔU(m)	16.4 $\pm$1.0	15.9 $\pm$1.4	17.6 $\pm$1.1	13.7 $\pm$2.2	$-$ 1.1 $\pm$1.0	18.8 $\pm$0.9
ΔV(m)	10.1 $\pm$1.0	15.2 $\pm$1.4	11.0 $\pm$1.1	12.9 $\pm$2.4	$-$ 7.2 $\pm$1.2	9.3 $\pm$0.9
ΔW(m)	$-$ 3.4 $\pm$1.1	$-$11.2 $\pm$1.5	4.5 $\pm$1.2	$-$ 1.7 $\pm$2.9	11.6 $\pm$1.3	$-$ 3.2 $\pm$1.0
$\Delta(10^{-6})$	0.39$\pm$0.16	0.97$\pm$0.21	0.81$\pm$0.17	0.74$\pm$0.34	$-$ 2.29$\pm$0.18	$-$ 2.33$\pm$0.15
$\omega('')$	0.72$\pm$0.04	0.38$\pm$0.05	0.09$\pm$0.04	$-$ 0.38$\pm$0.08	0.11$\pm$0.04	0.08$\pm$0.04
$\psi('')$	$-$ 0.15$\pm$0.04	0.02$\pm$0.06	0.14$\pm$0.05	0.19$\pm$0.10	$-$ 0.05$\pm$0.05	$-$ 0.06$\pm$0.04
$\varepsilon('')$	$-$ 0.17$\pm$0.04	$-$ 0.06$\pm$0.06	0.11$\pm$0.04	0.24$\pm$0.11	$-$ 0.04$\pm$0.04	$-$ 0.08$\pm$0.04
σ_0^2	1.16	1.01	1.06	1.10	1.05	1.14

[a] Weight factor $=\sigma^2_{0,i}/\sigma^2_{0,\mathrm{WN14}}$.

standard, those of the other solutions are scaled by the weight factors indicated. These numbers are indicative of the relative over-optimism of the quality of some of the published solutions. For example, a weight factor of 25 would indicate that the published standard deviations of a given solution need to be multiplied by $\sqrt{25}=5$.

As the numbers in Table I indicate, there is a fairly good agreement between the translational elements ΔU and ΔV within the dynamic solutions, and there is an average discrepancy of about 16 m (in U) and 12 m (in V) with respect to the WN 14 system. The largest discrepancy occurs in the ΔW components, where there seems to be a 15.7 ± 1.6 m difference between the SE III and the GEM 6 solutions. The weighted mean discrepancy in W between the dynamic solutions and WN 14 is only -2 m.

The differences in scale between the dynamic systems are within the noise level and, on the average, differ from the scale of the WN 14 system by $\Delta = (-0.62 \pm 0.06) \times 10^{-6}$, or about one part in 1.6 million. The scale factor, -2.3×10^{-6}, for the NGS systems seems to be excessively large.

The largest discrepancies occur in the orientation of the various dynamic systems with respect to each other and to WN 14. In the rotation about the W axis (ω), the largest difference occurs between the NWL 9D and the GSFC 73 solutions, where $\omega = 1\overset{''}{.}1$, or about 34 m on the equator (Figure 1). The other differences are smaller, but significant. These rotations may be partly due to the definition of the zero meridian in the case of purely electronic systems (e.g., Doppler), partly to the various definitions of the vernal equinox in the star catalogs used, and also to its possible motion with respect to inertial space in the case of optical observations. The latter alone requires a correction to the FK4 right ascensions amounting to $+0\overset{''}{.}65$ at 1960.0, changing with a rate of $+1\overset{''}{.}36$ per century (Martin and Van Flandern, 1970). The weighted mean ω of the dynamic solutions, excluding NWL 9D, is $0\overset{''}{.}17 \pm 0\overset{''}{.}02$.

The rotations about the axes U and V are even more confusing. Figure 2 illustrates the situation at the pole. The discrepancy between the poles, as determined separately from the SE III 6000 (BC-4) stations and from the 9000 stations, is unexplained at this time. It is interesting to note that the weighted mean pole position computed from the

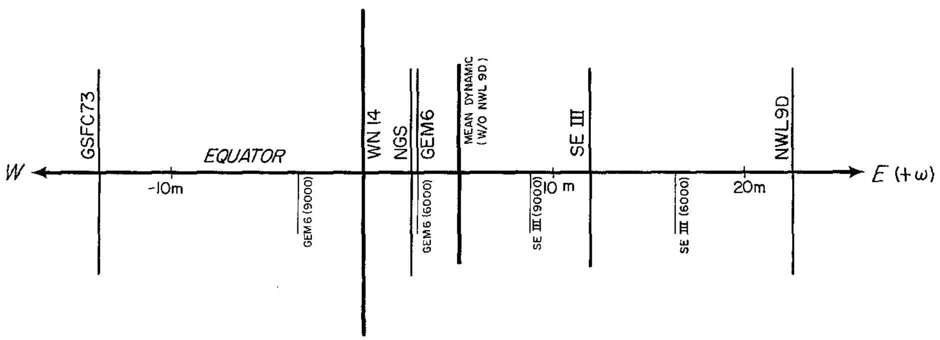

Fig. 1. Zero meridians of various satellite systems with respect to the WN 14 zero meridian.

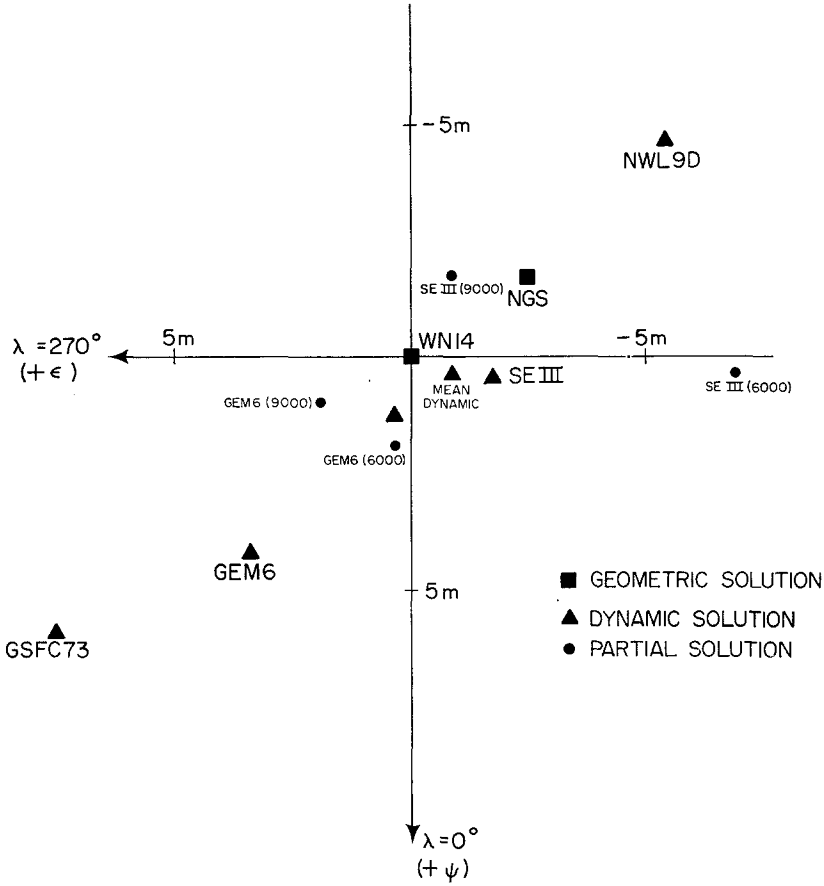

Fig. 2. Pole positions of various satellite systems with respect to the WN 14 pole.

dynamic solutions hardly differs from that of the WN 14 solution ($\psi = 0\overset{''}{.}01 \pm 0\overset{''}{.}02$, $\varepsilon = -0\overset{''}{.}03 \pm 0\overset{''}{.}02$).

The only general conclusion that can be drawn from the rotation parameters is that the coordinate systems used in the dynamic solutions need to be more carefully defined and conditions enforcing these definitions should be more strongly applied than is evidenced from the solutions discussed.

3.5. Non-global solutions

In addition to the global dynamic and geometric solutions, a number of solutions were also performed using satellite observational data obtained in more local areas. The most significant ones are listed below by geographic areas.

3.5.1. *Europe*

(1) *GSFC European Solution*, – consists of over 31 000 optical observations on GEOS 1 and 2 in 70, 48-hour orbital arcs from 15 tracking stations on the European Datum.

In addition to the stations in Europe proper, this partial dynamic solution also provided geocentric coordinates of stations in India, Iran and Ethiopia (Marsh *et al.*, 1972). An important contribution of the paper is the discovery of a scale error in the European datum, apparently due to neglected geoidal undulations, and a discrepancy between satellite and survey results in south eastern France and Switzerland.

(2) *CNES-SAO Observational Campaign*, – in 1968 this linked 9 camera stations and 2 laser stations with about 2000 quasi-simultaneous observations on 6 satellites carrying laser retro-reflectors (Beacon Explorer 2 and 3, Diademe 3 and 4, GEOS 1 and 2) (Cazenave *et al.*, 1972). The solution confirmed the findings of the GSFC solution described above, namely, the scale discrepancy within the European datum.

(3) *ISAGEX (International Satellite Geodetic Experiment) Campaign*, – conducted under the coordination of CNES during the period December 1970 to September 1971. Over 40 optical and laser tracking stations participated in the data gathering. These included those of the GRGS (Groupe de Recherches de Géodésie Spatiale), SAO, NASA optical and laser networks, camera stations from ASTROSOVIET, and independent stations from Eastern and Western Europe. The useful data, especially the laser data, were incorporated in the SE III, GEM 6–7, and GSFC 73 solutions described earlier. Station positions for certain European, African, and Asian stations previously not included in any solution have been newly calculated from analysis in the partial dynamic mode (Marsh *et al.*, 1973 and 1974a). These stations are Oulan Bator in Mongolia, Helwan in Egypt, Ondrejov in Czechoslovakia, and Potsdam, GDR. The positions are good to about 20 m in each coordinate.

(4) *WEST (West European Sub-Commission for Artificial Satellites/International Association of Geodesy) Campaign*, – between 1966 and 1972 resulted in simultaneous direction observations of 1500 events on 5 satellites (Echo 1 and 2, PAGEOS, and Beacon Explorers 2 and 3). About 35 sites equipped with various types of cameras participated in the observations. The reduced observations were collected for analysis at two computing centres at Feltham, G.B. (UK) and Munich, FRG. The final results are being evaluated in Munich (Ehrnsperger *et al.*, 1972 and Ehrnsperger, 1974) and also at The Ohio State University.

3.5.2. *North America*

Probably the most significant effort is the current saturation of Canada, Mexico, and the U.S., with positions determined by means of portable Doppler receivers (manufactured by Magnavox, Canadian Marconi, ITT, or JMR Instruments, Inc.). So far over 100 stations have been positioned, most of them with the Magnavox Geoceivers, the majority along the 22 000 km long, transcontinental traverse in the U.S. The Geoceiver work has been executed by both the Defense Mapping Agency and the National Geodetic Survey, employing the method of point positioning utilizing the precise satellite ephemerides of the Naval Surface Weapon Center. Marconi and ITT equipment have been used mostly by the Geodetic Survey of Canada.

The positions are to be used in the readjustment of the North American datum. Doppler stations show excellent agreement (1–2 m) with the survey coordinates of the transcontinental traverse, which has estimated relative accuracies in the order of one part per million (Defense Mapping Agency, 1972; Anderle and Tannenbaum, 1974; Kouba, 1974; Meade, 1974; Peterson, 1974; Wells, 1974; Wells *et al.*, 1974; American Geophysical Union, in press; Brown, 1975 and Strange *et al.*, 1975).

3.5.3. *South America*

Similarly to the North American effort, Doppler operations are in progress in South America using the ITT receivers and Geoceivers (Andregg, 1974). They began with observations in Argentina and Chile in 1971. Five stations were observed in Chile and 2 in Argentina by means of both point positioning and translocation. During 1972 and 1973 over 60 additional stations were placed in Bolivia (7), Brazil (13), Columbia (13), Ecuador (9), Paraguay (6), and Venezuela (14). About 10 of these stations are located on ground control points where coordinates are known in a national geodetic datum. This set provides relationships between the various national datums used in South America and the regional South American datum (SAD) established in 1969. The other stations are located in unsurveyed areas for the purpose of establishing geodetic control. Significant similar efforts are currently underway in Brazil to control the Amazonia region and in other unsurveyed areas described earlier.

3.5.4. *Australia*

There are 8 Doppler sites in Australia and an effort to densify this network with portable Doppler receivers has just begun. These observations will initially strengthen existing ground control and later move into unsurveyed areas to establish new control.

4. Geodetic Applications of Satellite Derived Positions

It goes without saying that for the geodesist it is important to know the positions of a large number of well distributed stations, especially if these positions are determined accurately in some homogeneous way and are referred to a well defined and accessible coordinate system. Even with the present modest accuracies there are a number of immediate applications which come to mind. In addition to the most obvious one, namely, to aid in the accurate determination of orbits, some of the most important geodetic applications are as follows:

(1) Unification of independent geodetic datums by determining transformation parameters between them and a satellite system.

(2) Detection of certain possible distortions within a geodetic network by inspecting the residuals after systematic components arising from the above transformation are removed. These distortions may be present due to various errors which are partly observational and partly computational in nature. This application presumes that the satellite determined positions are more accurate and homogeneous than those estab-

lished by ground surveys. It is likely that only Doppler or laser determined positions are accurate enough for this purpose.

(3) Strengthening a primary geodetic network by incorporating accurate satellite (Doppler or laser) positions in the adjustment process.

(4) Establishment of mapping control in unsurveyed areas.

(5) Geodynamic applications to monitor crustal motions, variations in the position of the pole, and in the rate of rotation of the Earth. Only laser determined positions are (or rather will be) sufficiently accurate for this purpose.

Items 3 and 4 do not require further elaboration. The first two items will be illustrated through actual examples involving some of the major geodetic datums. The last application currently is in initial stages. Some general comments are offered in Sections 4.3 and 4.4.

4.1. Datum Transformation Parameters

In order to avoid certain numerical and geometric problems which may arise when transformation parameters are determined from the two sets of Cartesian (geodetic and satellite determined) coordinates of stations located within relatively small areas, two precautionary measures are applied.

First, the rotations are computed about the origin (initial point) on the geodetic datum, rather than about the origin of the Cartesian coordinates. These rotations may be about axes parallel to the Cartesian axes U, V, W (ε, ψ, ω), or about axes pointing South, East, and up (η, ξ, α). The latter set has more geometric meaning in the geodetic sense, since α is a rotation in azimuth, while ξ is in the meridian and η in the prime vertical plane. Note that both sets of rotation angles refer to right handed coordinate systems; thus, positive angles represent counterclockwise rotations when viewed from the positive ends of the axes.

The second precautionary measure is to reduce correlations between the translatory, rotational, and scaling parameters. This is achieved by computing first the scale factor from chordal distances, and the rotational parameters from direction-cosines between the stations. The translational parameters are then computed from a subsequent 7 parameter adjustment in which the scale and the rotations are constrained to their previously determined values with weights corresponding to their variances. Since both the chordal distances and the direction cosines are independent of the origins of the systems, this procedure will result in less correlated transformation parameters (Kumar, 1972).

Figure 3 shows the geodetic datum blocks in existence today. The description of these datums may be found in NASA (1973). Datum parameters are also listed in Mueller (1974a). Table II contains the transformation parameters of the major horizontal datums with respect to both the WN 14 and NWL 9 satellite systems as determined by means of the procedure just described. Parameters referring to the NWL 9 system are based on Geoceiver observations evaluated in the point positioning mode. Note from Table I the parameters relating the WN 14 and NWL 9D systems, which need to be considered when comparing the transformations in Table II.

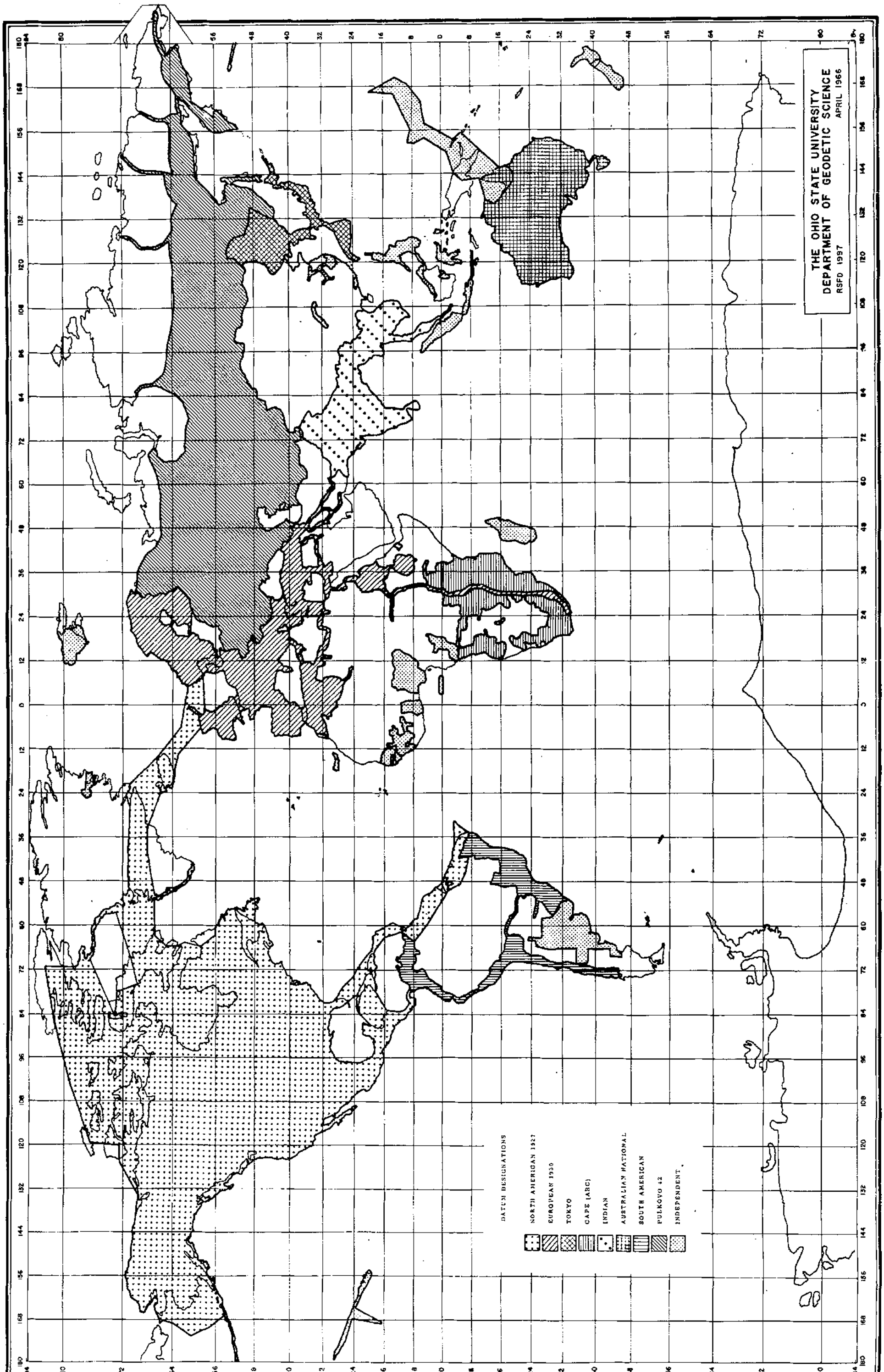

Fig. 3. Major geodetic datum blocks.

TABLE II

Datum transformation parameters to satellite system
(Satellite – Datum)

Datum / Transformation Parameters	Australian National		European (ED 50)	North American (NAD 27)		South American (SAD 69)	
	NWL 9 9 Stations	WN 14 3 Stations	WN 14 16 Stations	NWL 9 67 Stations	WN 14 21 Stations	NWL 9 9 Stations	WN 14 10 Stations
ΔU (m)	−122.4 ±1.4	−157.0 ±3.2	− 99.4 ±5.0	− 28.5 ±0.4	− 31.7 ±1.7	− 77.8 ±4.7	− 96.6 ±4.0
ΔV (m)	− 30.4 ±1.4	− 59.1 ±3.2	−132.0 ±5.0	153.8 ±0.4	142.3 ±1.6	− 12.4 ±8.6	− 13.7 ±4.3
ΔW (m)	140.0 ±1.4	131.2 ±3.6	−116.0 ±4.8	179.8 ±0.4	177.3 ±1.5	− 49.5 ±4.2	− 29.4 ±4.1
$\Delta (10^{-6})$	0.36±0.91	1.14±1.83	6.06±2.83	1.28±0.30	− 0.96±0.98	− 0.99±1.16	− 6.67±1.41
ω (″)	0.07±0.24	− 1.03±0.48	0.08±0.67	0.30±0.06	− 0.86±0.20	1.18±0.86	0.63±0.43
ψ (″)	− 0.52±0.24	− 0.99±0.48	− 0.03±0.93	0.01±0.07	− 0.23±0.19	− 0.90±0.33	− 0.25±0.31
ε (″)	0.35±0.25	0.25±0.59	0.41±0.74	− 0.38±0.14	− 0.33±0.34	0.16±0.26	0.12±0.34
α (″)	− 0.59±0.19	− 0.35±0.38	0.30±0.65	0.22±0.06	− 0.33±0.18	0.33±0.25	− 0.02±0.29
ξ (″)	0.10±0.29	0.49±0.64	− 0.13±0.98	− 0.38±0.14	− 0.34±0.35	− 0.48±0.26	− 0.03±0.35
η (″)	0.20±0.25	1.31±0.52	0.26±0.70	− 0.21±0.07	0.84±0.21	− 1.37±0.89	− 0.66±0.43

Transformation parameters for these and other geodetic datums referring to various satellite systems may also be found in (Anderle, 1974a and 1974b; Gaposchkin, 1974; Mueller, 1974a and Schmid, 1974). Other problems related to positioning of horizontal geodetic datums with respect to satellite systems are treated in (Vanicek and Wells, 1974; Wells and Vanicek, in press).

4.2. Network distortions

Network distortions between geodetically and satellite determined station positions may be discovered by inspecting the residuals in the coordinates after an adjustment for the transformation parameters, as described in Section 4.1. If the satellite determined positions are considerably better and more homogeneous than the geodetic ones and if the residuals show a systematic pattern then this may indicate certain shortcomings either in the observations or computations in the geodetic net.

As an example, Figure 4 shows the height residuals of a 7 parameter transformation adjustment performed between the NAD 27 and the OSU 275 systems. Since these systems are (at least theoretically) oriented the same way, it seems important to discover the reason for the apparent rotations. For this purpose a 3 parameter (translations only) transformation was also executed and the residuals compared with those from the 7 parameter transformation. The patterns for the latitude and longitude residuals were found to be practically the same, but the height residuals (Figure 5) showed a definite east-west tilt which is not present in Figure 4. This tilt may be attributed to the tilt of the astrogeodetic geoid in the area. If this is the case then the rotations would not be part of the horizontal datum transformation, but rather of the vertical (ellipsoidal height) system. Other causes for possible network distortions are elaborated in (Mueller, 1974b).

4.3. Geodynamic applications

Some of the geodetic space techniques for metric measurements have the fundamental capability of accurately monitoring the motion in space of a point on the Earth's surface or the capability of measuring the changes in the distance and/or direction between two or more points. The present capabilities, when improved, would make it possible to measure with unprecedented accuracies certain important geodynamic phenomena, such as tectonic plate motions, movements around fault zones, Earth tide displacements and apparent positional changes due to polar motion, and variations in the rotational rate of the Earth. Some of these phenomena have been measured and monitored in the past by means of traditional instrumentation. Prime examples are the polar motion and Earth rotation efforts coordinated by the International Polar Motion Service (IPMS) and the Bureau International de l'Heure (BIH), based on optical astronomic techniques such as use of zenith telescopes and astrolabes. Doppler satellite techniques also provide information on the motion of the pole. These techniques allow the determination of polar motion to an accuracy of 50-100 cm and of Earth rotation to $0.7-1$ m over 2–5 days averaging time.

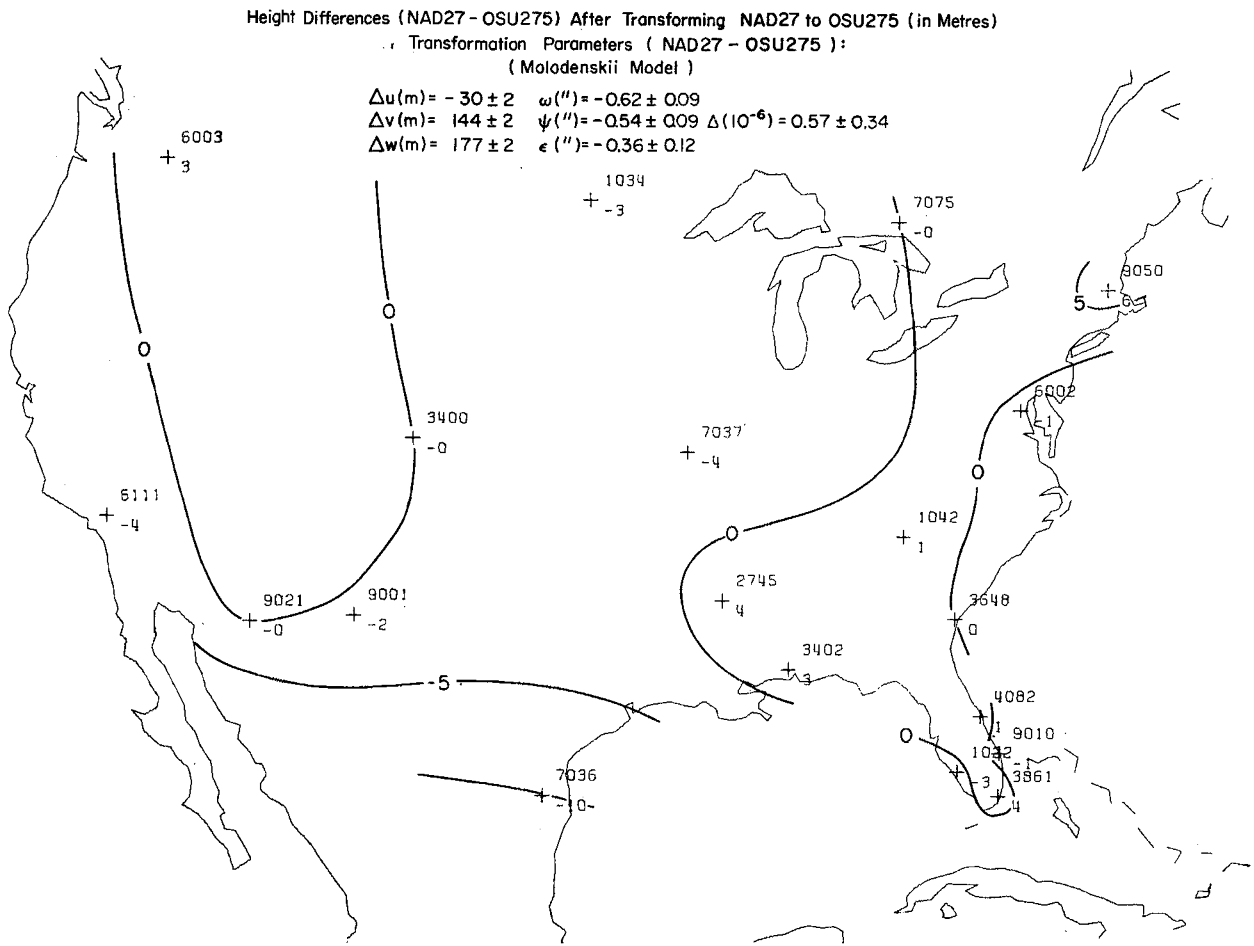

Fig. 4. Height differences from a 7 parameter transformation.

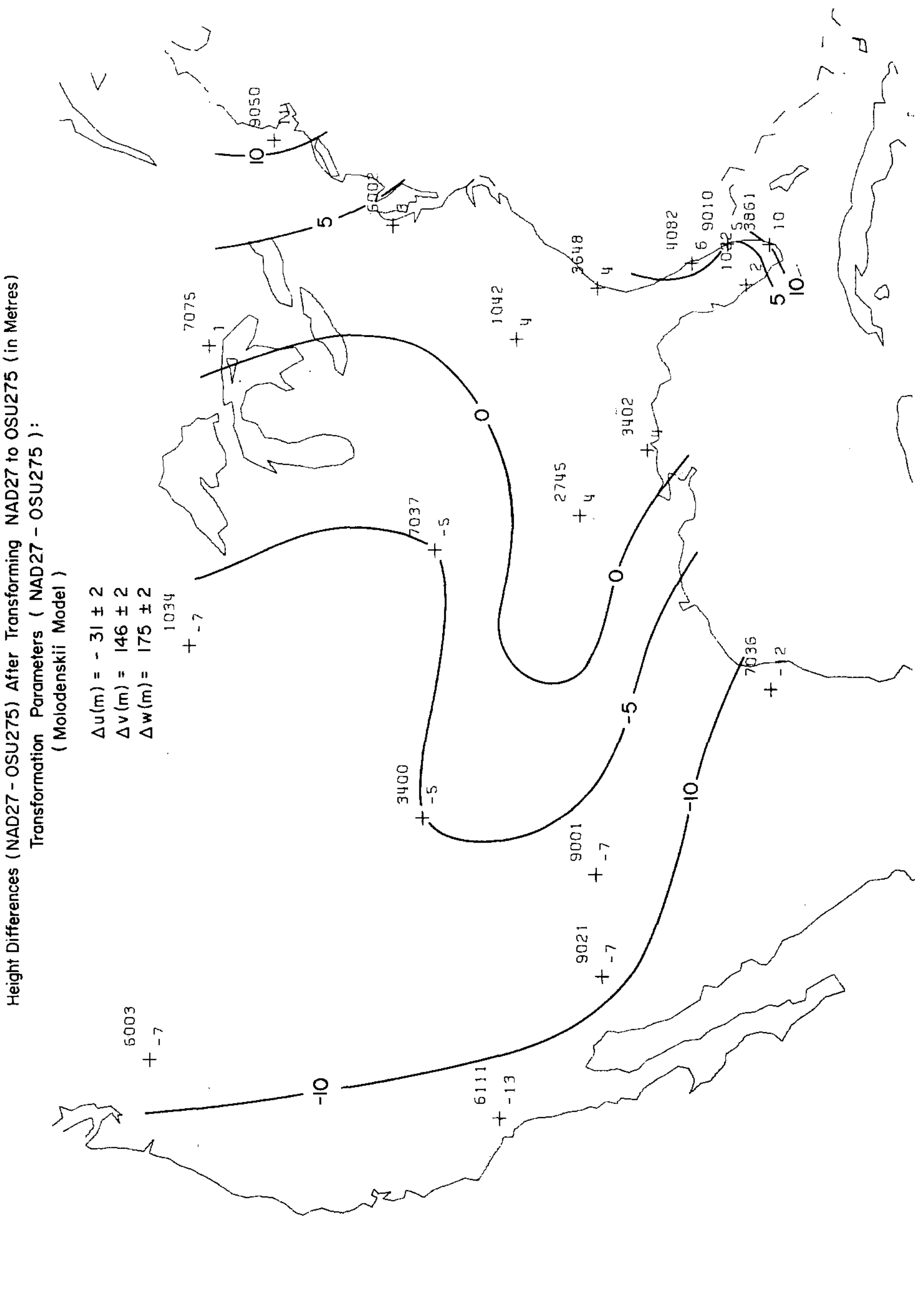

Fig. 5. Height differences from a 3 parameter transformation.

The main candidate systems for improved measurements of geodynamic phenomena are the Very Long Baseline Interferometers (VLBI), the lunar laser rangers, and the satellite laser rangers. These systems have already demonstrated accuracies which match those of the traditional techniques quoted above. It is estimated that their improved versions will determine geodynamic phenomena with the following accuracies: plate and fault motions, 1–2 cm/yr; polar motion, 2–3 cm over 12 h averaging; and Earth rotational rate, 0.05 ms over 12 h averaging. Since neither VLBI nor lunar laser ranging are artificial satellite techniques, the description of their current and future status is outside the scope of this paper. If the reader is interested to learn about recent results and developments associated with these systems then the review articles by Bender *et al.* (1973), Shapiro *et al.* (1974), Bender (1975) and Counselman (1975) will provide a good start.

The feasibility of using pulsed lasers to range to artificial Earth satellites was first demonstrated in 1964 with the returns from the Beacon Explorer satellite. Since that time 11 retroreflector equipped satellites have been launched and tracked. Two satellites, the French STARLETTE launched in February of 1975 and LAGEOS to be launched next year, were specifically designed for precise laser tracking and Earth dynamic studies. Present day lasers operated by both NASA and the Smithsonian Astrophysical Observatory, as well as by a number of foreign countries (e.g., France, Czechoslovakia, FRG), demonstrated accuracies of 7–15 cm for a single range and about 1–2 parts in 10^7 in distance-precision over baselines of 900–3000 km (Smith *et al.*, 1975). Improvements of the results to meet the quoted geodynamic goals is expected from the following system improvements:

(1) Use of much narrower pulse laser transmitter. The current 4 ns ruby lasers are to be replaced by 0.2 ns Nd:Yag lasers (Plotkin, 1973).

(2) Incorporation of image coverters and two-color ranging to reduce errors in atmospheric propagation.

(3) Launching special satellites such as LAGEOS, with better retroreflector array geometry and with specially selected orbital (high altitude) and satellite (small and heavy) characteristics.

These improvements are expected to increase the accuracy of a single laser range to 2–3 cm, and that of an interstation distance to 5–10 parts in 10^9.

4.4. Establishment of a Terrestrial Reference Frame for Earth Dynamics

The expected increase in observational accuracy and the resulting increase in the resolution of geophysical phenomena requires a redefinition of many of the concepts used in the more traditional analysis described earlier, in which, with the possible exception of the Earth tides phenomena, the Earth was assumed to be a rigid body. It is the departures from rigidity which are interesting and are to be studied in suitable reference systems needing definition. A reference frame is needed that readily displays the phenomena of interest in an unambiguous way and free from detailed assumptions. The realization of such a reference system must necessarily use observations from the Earth and it could be defined through the adopted coordinates of *super control* *stations*, determined with high precision from laser observations to satellites or to the Moon and VLBI observations. The following criteria seem desirable for such a coordinate system:

(i) The system should be as invariant as possible with respect to changes in the number, distribution and data acquisition rates of observing stations in different parts of the world.

(ii) The system should facilitate the rapid determination of sudden changes in the position of motion of individual stations, as well as sudden changes in polar motion and the rotation of the Earth.

(iii) The system should be approximately fixed with respect to the mantle in some average sense.

These criteria lead to the choice of a coordinate system in which our previous knowledge of the motion of the stations with respect to each other and to the mantle is used to model the station motions due to plate movements, etc. Such a coordinate system conceptually would be similar to that used by astronomers in the fundamental star catalogs, where the adopted coordinates of stars together with their proper motions define the frame of reference. To maintain such a system an international service, similar to the BIH, would need to be set up, whose responsibilities would include coordinating the continuing observations at the fundamental stations and issue directives on changes in the adopted coordinates and motion parameters or models, when the need for such changes arises from the data analysis. An international terrestrial reference frame would then be realized through the coordinates of the fundamental stations at some reference epoch. Other problems related to reference systems for geodynamic applications may be found in Kolaczek *et al.* (in press).

5. Summary

Station positions from artificial satellite observations may be determined dynamically or geometrically. In the former case the analysis takes full advantage of the fact that the satellite moves in an orbit describable by the equations of motion. In the geometric case the satellite is used only as a target for simultaneous observations from several stations. During the past 15 yr important results were obtained in both modes of operation. Positions for over 400 tracking stations situated around the globe were determined by using both electronic and optical observations. The results indicate that relative positions are available to 1–2 parts in 10^6 over distances of 500 km or longer. Positions with respect to the geocenter are accurate to 5–10 m, and almost a full order better for laser stations. In geodetic applications most major datums have been unified in that their relative positions are known within few metres, sufficient for most geodetic work. Using present day lasers, distances ranging from 900 km to 3000 km were determined to 1–2 parts in 10^7. It is expected that, following system improvements in the future, inter-station distances will be determined to 5–10 parts in 10^9, which should be sufficient for certain geodynamic applications. One of the most important future utilizations of laser satellite tracking should be to establish, in

conjunction with VLBI and lunar laser observations, a suitable reference frame in which the dynamic behavior of the Earth can be monitored.

Acknowledgments

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Annex 1. Coordinates of 275 Stations

In the table the numbering system corresponds to the one in NASA (1973), where the stations are also described in detail. The first digit indicates the type of instrumentation at the site as follows: 1 – MOTS camera, 2 – Doppler site, 3 – PC-1000, 4 – C-Band radar, 5 – SECOR, 6 – BC-4 camera, 7 – Special optical site, 8 – Special camera and 9 – SAO optical site. The letters C or T after the station numbers indicate that the coordinates were calculated either from ground connections or from transformations, respectively. The listed standard deviations for these C and T stations are estimated values and are not from the WN 14 solution; they are rounded to the nearest metre. Unit = 1 m.

STATION			STATION COORDINATES : OSU275.					
NO		LOCATION	U	V	W	σ_u	σ_v	σ_w
80	C	SAN FERNANDO	5105601.7	-555293.7	3769644.7	5.0	12.0	6.0
1021		BLOSSOM POINT	1118023.1	-4876323.4	3942963.9	2.8	2.6	2.8
1022		FORT MYERS	807851.9	-5651989.6	2833500.2	2.2	1.9	2.3
1024	C	WOMERA	-3977293.6	3725625.1	-3302986.6	8.0	8.0	9.0
1025	C	QUITO	1263619.8	-6254990.6	-68890.1	5.0	5.0	6.0
1028	T	SANTIAGO	1769701.1	-5044622.9	-3468258.5	26.0	26.0	26.0
1030		GOLDSTONE	-2357242.9	-4646338.5	3668306.8	5.6	3.3	3.2
1031	C	JOHANNESBURG	5084771.1	2670396.9	-2768146.7	5.0	5.0	6.0
1032		ST. JOHN'S	2602688.6	-3419228.9	4697637.3	39.3	46.7	13.8
1033		FAIRBANKS	-2299282.6	-1445693.7	5751811.6	6.9	9.7	5.7
1034		E. GRAND FORKS	-521704.5	-4242064.3	4718716.8	3.1	3.0	2.7
1035	T	WINKFIELD	3983098.8	-48514.0	4964714.0	8.0	8.0	11.0
1036	T	FAIRBANKS	-2282362.1	-1452662.9	5756892.0	8.0	8.0	11.0
1037	C	ROSMAN	647505.0	-5177934.9	3656705.5	4.0	4.0	5.0
1038	C	ORRORAL	-4447503.1	2677146.4	-3695065.0	8.0	5.0	5.0
1042		ROSMAN	647497.5	-5177935.6	3656705.9	2.8	2.4	2.8
1043	T	TANANARIVE	4091856.4	4434279.4	-2064728.7	9.0	9.0	9.0
1122	T	TANANARIVE	4091206.0	4434257.1	-2066017.2	9.0	9.0	9.0
1123	T	TANANARIVE	4091326.3	4434221.3	-2065973.7	9.0	9.0	9.0
1126	T	ROSMAN	647171.1	-5178338.6	3656134.3	5.0	5.0	6.0
1128	T	FAIRBANKS	-2282517.6	-1453391.1	5756698.7	15.0	15.0	15.0
1152	C	CARNARVON	-2328271.4	5299689.0	-2669355.6	5.0	11.0	16.0
2002	C	AUSTIN	-741649.6	-5462247.2	3198081.2	6.0	6.0	7.0
2014	T	ANCHORAGE	-2656190.3	-1544375.0	5570644.0	15.0	15.0	15.0
2017	C	TAFUNA	-6100020.7	-997208.5	-1568460.0	6.0	6.0	7.0
2018	C	THULE	539377.6	-1388386.5	6181061.0	4.0	4.0	5.0
2019	C	MCMURDO STATION	-1310721.9	310448.9	-6213363.5	6.0	6.0	6.0
2020	T	MAHE	3602881.9	5238204.1	-515934.4	7.0	6.0	7.0
2049	T	PUERTO RICO	2440932.8	-5538065.9	2006220.8	5.0	5.0	5.0
2092	T	AUSTIN	-741659.3	-5462215.8	3198133.2	5.0	5.0	5.0
2100	C	WAHIAWA	-5504153.4	-2224161.2	2325298.3	5.0	6.0	5.0
2103	T	LAS CRUCES	-1556231.4	-5169428.4	3387246.7	15.0	15.0	15.0
2106	T	LASHAM	4005420.1	-71762.3	4946709.4	15.0	15.0	15.0
2111	T	HOWARD COUNTY	1122633.1	-4823045.4	4006469.0	6.0	6.0	6.0
2115	C	PRETORIA	5051963.2	2725632.7	-2774463.8	5.0	5.0	6.0

2117	C	TAFUNA	-6100023.8	-997202.3	-1568461.9	5.0	5.0	6.0
2203	C	WALLOPS ISLAND	1261662.0	-4881250.9	3893555.7	5.0	4.0	5.0
2707	C	DARWIN	-4071536.8	4714301.7	-1366474.1	5.0	5.0	6.0
2708	C	WAKE ISLAND	-5858533.2	1394519.7	2093933.9	4.0	4.0	5.0
2709	T	MUCHEA	-2377598.6	4889656.1	-3323432.3	34.0	28.0	36.0
2715	C	GUAM	-5064993.0	3582905.4	1475804.0	5.0	5.0	5.0
2717	C	MAHE	3602862.4	5238212.1	-515923.3	6.0	5.0	6.0
2722	C	ASCENSION ISLAND	6118412.3	-1571576.3	-878436.0	4.0	4.0	5.0
2723	C	COCOS ISLAND	-741998.7	6190792.2	-1338560.1	6.0	5.0	6.0
2724	C	MIDWAY ISLAND	-5619643.2	-256328.2	2995770.7	5.0	5.0	6.0
2726	C	MANUS	-5367631.3	3437930.1	-226705.2	5.0	5.0	5.0
2727	C	TERCEIRA	4433585.5	-2268184.1	3971697.6	4.0	5.0	5.0
2735	C	FORT STEWARD	832485.3	-5349594.9	3360533.6	6.0	5.0	6.0
2738	C	MOSES LAKE	-2127836.2	-3785839.3	4656059.3	4.0	4.0	4.0
2739	C	SHEMYA	-3851550.9	397259.4	5051470.4	5.0	5.0	6.0
2742	C	BELTSVILLE	1130771.0	-4830825.8	3994718.5	4.0	4.0	4.0
2744	C	THURSDAY ISLAND	-4955422.5	3842218.0	-1163792.2	5.0	5.0	6.0
2745	T	STONEVILLE	-85010.6	-5327963.0	3493447.7	6.0	6.0	6.0
2765	T	CHIANG MAI	-941675.7	5967443.3	2039341.4	35.0	28.0	37.0
2766	T	WAKE ISLAND	-5858540.6	1394520.9	2093920.5	34.0	28.0	36.0
2801	T	PALAU	-4433465.2	4512966.3	810002.7	35.0	28.0	37.0
2803	C	ROTA	5093550.4	-565320.7	3784279.1	4.0	5.0	5.0
2805	C	CULGOORA	-4751646.9	2792064.7	-3200170.9	5.0	5.0	5.0
2809	C	INVERCARGILL	-4313802.5	893029.2	-4596968.0	5.0	6.0	6.0
2811	C	MAUI	-5468016.8	-2381416.1	2253220.6	5.0	5.0	5.0
2812	C	CATANIA	4901577.8	1305816.5	3853648.4	4.0	4.0	4.0
2813	T	DAKAR	5884479.5	-1853566.1	1612735.8	5.0	5.0	5.0
2815	C	PARAMARIBO	3623258.4	-5214227.4	601519.1	4.0	4.0	5.0
2817	C	MASHHAD	2604345.4	4444161.8	3750336.7	4.0	4.0	4.0
2818	C	TROMSO	2102936.3	721655.7	5958182.4	4.0	5.0	5.0
2820	T	VILLA DOLORES	2280571.4	-4914564.8	-3355440.7	8.0	8.0	8.0
2821	T	ZAMBOANGA	-3361919.5	5365834.0	763659.0	7.0	6.0	7.0
2822	C	FORT LAMY	6023398.7	1617918.2	1331709.4	5.0	4.0	5.0
2823	T	CASEY	-902608.3	2409529.7	-5816541.2	7.0	6.0	7.0
2825	T	PALMER STATION	1192559.3	-2451018.0	-5747057.2	7.0	6.0	7.0
2830	C	HOHENPEISSENBERG	4213528.3	820858.6	4702811.7	4.0	4.0	4.0
2831	C	SOCORRO ISLAND	-2160953.0	-5642737.8	2035332.5	4.0	5.0	6.0
2832	T	SASEBO	-3417816.6	4115338.4	3461705.6	35.0	28.0	37.0
2837	C	NATAL	5186351.6	-3654224.1	-653024.9	4.0	4.0	4.0
2838	T	MAURITIUS	3223444.2	5045328.7	-2191792.0	7.0	6.0	7.0
2840	T	ADDIS ABABA	4900753.9	3968227.8	966356.7	5.0	5.0	5.0
2844	T	QUITO	1280851.8	-6250961.6	-10839.8	5.0	5.0	5.0
2847	C	CERRO SOMBRERO	1371379.0	-3614788.6	-5055908.2	5.0	6.0	6.0
2849	C	CHRISTMAS ISLAND	-5885335.4	-2448384.7	221670.8	5.0	5.0	6.0
2907	C	CYPRUS	4361707.6	2868048.6	3652828.0	4.0	5.0	5.0
3106		ANTIGUA	2881838.3	-5372164.6	1868538.6	3.7	3.3	4.3
3334		STONEVILLE	-84963.8	-5327974.9	3493428.3	13.6	6.8	9.0
3400		COLORADO SPRINGS	-1275207.2	-4798029.3	3994208.3	9.1	5.1	5.7
3401		BEDFORD	1513136.1	-4463576.8	4283055.8	3.2	3.4	3.0
3402		SEMMES	167259.7	-5481971.0	3245037.0	3.9	2.8	3.5
3404		SWAN ISLAND	642491.4	-6053940.3	1895688.6	4.7	3.7	4.9
3405		GRAND TURK	1919482.9	-5621088.1	2315775.3	3.3	3.5	4.0
3406		CURACAO	2251800.2	-5816912.9	1327191.1	2.4	2.1	3.4
3407		TRINIDAD	2979891.1	-5513530.9	1181129.3	4.7	3.4	5.3
3413		NATAL	5186348.4	-3654222.4	-653018.9	2.1	2.2	2.7
3414		BRASILIA	4114977.8	-4554142.5	-1732154.0	7.7	6.1	7.2
3431		ASUNCION	3093045.4	-4870081.7	-2710823.0	7.6	6.5	10.8
3476		PARAMARIBO	3623277.3	-5214210.7	601515.3	2.2	2.0	3.0
3477		BOGOTA	1744650.2	-6114286.7	532208.6	10.2	6.6	9.6
3478		MANAUS	3185777.0	-5514585.9	-347703.2	18.7	14.5	35.1

3499		QUITO	1280834.2	-6250955.9	-10800.6	3.6	3.4	4.1
3648		HUNTER AFB	832566.2	-5349540.7	3360585.3	3.6	2.5	3.6
3657		ABERDEEN	1186787.1	-4785193.1	4032882.3	3.1	3.0	3.0
3861		HOMESTEAD	961767.9	-5679156.6	2729883.5	3.0	2.3	2.6
3902		CHEYENNE	-1234700.7	-4651242.8	4174758.6	8.6	6.3	6.3
3903		HERNDON	1088989.7	-4843005.4	3991776.6	12.1	8.5	8.9
4050		PRETORIA	5051608.1	2726603.3	-2774166.8	3.2	3.2	4.4
4061		ANTIGUA	2881592.3	-5372523.9	1868024.4	3.8	3.5	4.3
4081		GRAND TURK	1920410.9	-5619417.8	2319128.5	3.3	3.6	4.0
4082		MERRITT ISLAND	910567.2	-5539113.2	3017965.3	2.6	2.4	2.8
4280		VANDENBERG AFB	-2671873.8	-4521210.5	3607490.4	3.8	3.3	3.6
4740		NBER 34	2308887.3	-4874298.2	3393082.1	3.3	3.1	3.8
4760	C	BERMUDA	2308896.6	-4874304.9	3393069.9	5.0	5.0	5.0
4840	C	WALLOPS ISLAND	1263971.0	-4882273.1	3891536.3	5.0	4.0	5.0
4860	C	WALLOPS ISLAND	1261586.3	-4881561.0	3893196.2	6.0	5.0	6.0
4946	C	WOOMERA	-3999056.7	3750306.2	-3248686.4	9.0	9.0	10.0
5001		HERNDON	1088849.4	-4842948.7	3991840.2	3.6	3.0	3.7
5201		MOSES LAKE	-2127802.2	-3785911.5	4656012.1	2.3	2.2	2.4
5410		MIDWAY ISLANDS	-5618754.1	-258237.5	2997250.2	2.3	2.8	3.6
5648		FORT STEWART	794691.0	-5360051.1	3353082.4	3.6	2.5	3.6
5712		PARAMARIBO	3623289.8	-5214188.0	601673.2	2.1	2.0	2.9
5713		TERCEIRA	4433637.8	-2268153.2	3971656.8	2.0	2.2	2.5
5715		DAKAR	5884468.8	-1853580.1	1612760.1	1.6	2.0	2.3
5717		FORT LAMY	6023410.7	1617946.5	1331655.8	2.0	2.0	2.7
5720		ADDIS ABABA	4900749.1	3968253.0	966354.7	2.0	2.1	2.9
5721		MASHHAD	2604404.8	4444122.3	3750344.3	2.1	2.1	2.7
5722		DIEGO GARCIA	1905127.0	6032287.5	-810716.2	3.5	4.1	4.3
5723		CHIANG MAI	-941709.4	5967445.0	2039322.9	2.5	2.3	3.5
5726		ZAMBOANGA	-3361946.8	5365837.0	763627.8	2.3	2.2	3.2
5730		WAKE ISLAND	-5858574.6	1394467.2	2093847.4	2.1	2.5	3.1
5732		PAGO PAGO	-6099970.5	-997355.3	-1568570.9	3.6	3.5	4.1
5733		CHRISTMAS ISLAND	-5885333.9	-2448380.4	221670.7	2.7	2.9	3.9
5734		SHEMYA	-3851799.0	396409.3	5051342.0	2.7	3.3	3.9
5735		NATAL	5186350.6	-3654223.7	-653018.9	2.0	2.1	2.5
5736		ASCENSION ISLAND	6118340.3	-1571761.9	-878553.6	2.3	2.2	2.7
5739		TERCEIRA	4433629.3	-2268186.2	3971647.0	2.0	2.2	2.5
5744		CATANIA	4896437.7	1316125.0	3856626.2	1.8	2.2	2.3
5907		WORTHINGTON	-449417.5	-4600905.5	4380288.1	4.2	3.2	4.5
5911		BERMUDA	2307991.2	-4873773.2	3394463.4	2.6	2.3	3.0
5912		PANAMA	1142644.5	-6196109.1	988336.6	3.1	3.4	4.1
5914		PUERTO RICO	2349456.9	-5576027.1	2010342.6	10.5	7.0	6.4
5915		AUSTIN	-744091.1	-5465238.7	3192467.4	3.8	3.8	4.7
5923		CYPRUS	4363332.2	2862254.9	3655380.7	1.9	2.1	2.4
5924		ROTA	5093556.2	-565322.3	3784268.3	1.9	2.6	2.9
5925		ROBERTS FIELD	6237366.3	-1140241.5	687740.2	2.3	2.6	3.0
5930		SINGAPORE	-1542549.4	6186956.7	151833.8	2.6	2.7	3.4
5931		HONG KONG	-2423914.9	5388250.3	2394869.2	2.5	2.5	3.6
5933		DARWIN	-4071568.4	4714253.3	-1366528.3	3.2	3.2	3.7
5934		MANUS	-5367663.1	3437869.9	-225416.0	2.5	2.5	3.3
5935		GUAM	-5059825.7	3591186.0	1472762.5	2.1	2.2	2.8
5937		PALAU	-4433463.6	4512930.3	809958.7	2.2	2.2	3.2
5938		GUADALCANAL	-5915096.5	2146860.8	-1037909.5	3.0	3.0	3.5
5941		MAUI	-5467757.3	-2381246.7	2254033.8	2.5	2.8	3.8
6001		THULE	546568.7	-1389993.7	6180236.7	2.6	2.4	3.4
6002		BELTSVILLE	1130764.9	-4830831.9	3994704.0	2.0	1.7	1.9
6003		MOSES LAKE	-2127832.1	-3785863.0	4656037.2	2.1	2.0	2.3
6004		SHEMYA	-3851797.5	396409.4	5051340.5	2.7	3.3	3.9
6006		TROMSO	2102927.4	721668.5	5958180.8	2.4	2.9	2.9
6007		TERCEIRA	4433637.3	-2268151.4	3971655.0	2.0	2.2	2.5
6008		PARAMARIBO	3623241.0	-5214233.7	601536.1	2.1	2.0	2.9

6009		QUITO	1280834.2	-6250955.9	-10800.6	3.6	3.4	4.1
6011		MAUI	-5466018.6	-2404431.5	2242224.4	3.0	2.9	3.3
6012		WAKE ISLAND I	-5858569.3	1394508.7	2093820.3	2.1	2.6	3.2
6013		KANOYA	-3565892.8	4120713.6	3303428.3	3.3	4.4	4.9
6015		MASHHAD	2604353.3	4444166.0	3750320.5	2.1	2.2	2.6
6016		CATANIA	4896388.3	1316172.1	3856668.2	1.8	2.2	2.2
6019		VILLA DOLORES	2280627.1	-4914543.2	-3355402.8	2.4	2.7	3.7
6020		EASTER ISLAND	-1888614.3	-5354894.4	-2895749.0	5.4	4.5	5.5
6022		TUTUILA	-6099961.7	-997362.2	-1568585.5	3.4	3.6	4.7
6023		THURSDAY ISLAND	-4955386.8	3842247.8	-1163847.4	3.2	3.0	4.0
6031		INVERCARGILL	-4313825.3	891333.9	-4597265.8	3.4	3.9	3.8
6032		CAVERSHAM	-2375420.6	4875546.7	-3345411.1	3.3	3.2	3.9
6038		SOCORRO ISLAND	-2160980.9	-5642710.5	2035367.8	2.5	2.8	3.8
6039		PITCAIRN ISLAND	-3724765.9	-4421237.6	-2686084.7	6.2	5.4	5.5
6040		COCOS ISLAND	-741981.7	6190792.9	-1338546.3	4.5	3.7	4.2
6042		ADDIS ABABA	4900750.7	3968252.7	966325.3	2.0	2.1	2.9
6043		CERRO SOMBRERO	1371375.9	-3614750.3	-5055927.8	3.3	3.8	4.8
6044		HEARD ISLAND	1098897.9	3684606.6	-5071873.1	6.8	6.2	7.8
6045		MAURITIUS	3223432.0	5045336.3	-2191805.7	3.2	3.1	3.9
6047		ZAMBOANGA	-3361976.9	5365811.9	763624.7	2.4	2.3	3.2
6050		PALMER STATION	1192678.8	-2451015.6	-5747034.2	4.9	6.1	6.1
6051		MAWSON STATION	1111336.1	2169262.7	-5874334.1	4.9	3.7	4.4
6052		WILKES STATION	-902608.8	2409522.1	-5816551.8	4.4	4.0	5.4
6053		MCMURDO STATION	-1310852.3	311257.5	-6213276.5	4.6	4.5	4.3
6055		ASCENSION ISLAND	6118334.2	-1571748.3	-878596.5	2.3	2.3	2.8
6059		CHRISTMAS ISLAND	-5885333.5	-2448379.0	221671.1	2.7	2.9	3.8
6060		CULGOORA	-4751650.0	2792058.1	-3200164.0	3.3	3.3	3.7
6061		SOUTH GEORGIA IS.	2999915.6	-2219369.3	-5155246.0	3.7	5.7	5.3
6063		DAKAR	5884467.4	-1853495.8	1612855.1	1.7	2.1	2.5
6064		FORT LAMY	6023386.7	1617931.9	1331733.2	2.7	2.6	3.2
6065		HOHENPEISSENBERG	4213564.6	820830.0	4702784.4	2.0	2.4	2.3
6066		WAKE ISLAND II	-5858571.2	1394466.4	2093846.0	2.1	2.6	3.2
6067		NATAL	5186397.1	-3653933.3	-654276.9	2.1	2.2	2.6
6068		JOHANNESBURG	5084830.4	2670341.2	-2768095.2	3.0	2.9	4.2
6069		TRISTAN DA CUNHA	4978421.7	-1086874.0	-3823167.8	6.5	6.4	8.1
6072		CHIANG MAI	-941702.1	5967455.1	2039311.6	5.7	4.0	4.3
6073		DIEGO GARCIA	1905134.1	6032282.4	-810732.7	3.4	3.7	4.2
6075		MAHE	3602820.6	5238240.7	-515948.3	3.8	3.6	4.0
6078		PORT VILA	-5952303.4	1231904.9	-1925972.5	9.7	8.0	12.4
6111		WRIGHTWOOD I	-2448853.3	-4667985.8	3582754.9	2.6	2.1	2.4
6123		POINT BARROW	-1881799.4	-812439.0	6019590.7	4.6	4.4	4.5
6134		WRIGHTWOOD II	-2448907.0	-4668075.9	3582449.6	2.6	2.1	2.4
7034	C	EAST GRAND FORKS	-521704.5	-4242064.3	4718716.8	5.0	5.0	4.0
7036		EDINBURG	-828487.0	-5657471.3	2816816.0	3.5	2.4	2.9
7037		COLUMBIA	-191291.0	-4967293.9	3983252.6	2.9	2.2	2.4
7039		BERMUDA	2308213.4	-4873598.3	3394558.5	3.3	3.1	3.6
7040		SAN JUAN	2465049.5	-5534930.0	1985513.1	3.7	3.2	4.0
7043		GREENBELT	1130708.6	-4831331.3	3994135.5	2.0	1.7	1.9
7045		DENVER	-1240470.2	-4760242.1	4048985.3	4.2	2.8	2.9
7050	C	GREENBELT	1130670.3	-4831367.2	3994104.0	4.0	3.0	4.0
7052	C	WALLOPS ISLAND	1261545.1	-4881587.5	3893166.1	4.0	3.0	4.0
7053	T	GREENBELT	1130638.1	-4831360.6	3994149.6	6.0	6.0	6.0
7054	C	CARNARVON	-2328216.4	5299636.8	-2669490.9	6.0	12.0	17.0
7071	C	JUPITER	976257.5	-5601406.0	2880230.9	4.0	4.0	4.0
7072		JUPITER	976261.3	-5601399.9	2880241.9	2.2	1.8	2.3
7073	C	JUPITER	976267.8	-5601399.1	2880240.0	5.0	5.0	5.0
7074	C	JUPITER	976268.4	-5601396.3	2880246.4	5.0	5.0	5.0
7075		SUDBURY	692620.7	-4347076.5	4600475.4	3.7	3.8	3.4
7076		KINGSTON	1384158.7	-5905662.0	1966545.7	4.1	4.4	5.3
7077	C	GREENBELT	1130055.7	-4833042.4	3992258.0	4.0	3.0	4.0

7078	C	WALLOPS ISLAND	1261576.5	-4881356.8	3893441.7	4.0	3.0	4.0
7079	C	CARNARVON	-2328631.8	5299347.4	-2669682.9	7.0	13.0	18.0
7809	T	HAUTE PROVENCE	4578327.5	457964.9	4403174.3	8.0	8.0	11.0
7816	T	STEPHANION	4654320.2	1959163.4	3884368.0	13.0	13.0	13.0
7818	T	COLOMB-BECHAR	5426310.7	-229340.2	3334616.4	13.0	13.0	13.0
7912	T	MAUI	-5466070.3	-2404290.3	2242183.7	10.0	10.0	10.0
8009		WIPPOLDER	3923397.4	299869.4	5002975.5	8.5	10.1	6.9
8010		ZIMMERWALD	4331307.0	567490.8	4633108.3	5.7	8.3	5.4
8011		MALVERN	3920153.5	-134804.5	5012734.8	8.9	14.3	6.9
8015		HAUTE PROVENCE	4578322.1	457936.5	4403195.3	4.2	8.0	4.4
8019		NICE	4579463.2	586573.5	4386419.2	4.1	7.9	4.3
8030		MEUDON	4205626.9	163683.4	4776540.6	6.5	9.7	5.8
8804	C	SAN FERNANDO	5105601.7	-555293.7	3769644.7	5.0	12.0	6.0
8815	C	HAUTE PROVENCE	4578365.0	457920.7	4403150.9	6.0	10.0	6.0
8820	T	DAKAR	5886248.2	-1845660.0	1615260.7	12.0	14.0	16.0
9001		ORGAN PASS	-1535750.7	-5167014.4	3401039.4	4.2	2.8	2.7
9002		OLIFANTSFONTEIN	5056108.4	2716508.7	-2775768.8	3.0	3.0	4.2
9003	C	WOOMERA	-3983807.5	3743068.5	-3275543.4	6.0	6.0	7.0
9004		SAN FERNANDO	5105581.5	-555271.5	3769676.0	3.4	10.0	4.0
9005		TOKYO	-3946730.5	3366286.1	3698822.9	9.2	9.0	7.5
9006		NAINI TAL	1018164.5	5471108.7	3109625.6	12.4	5.5	6.0
9007		AREQUIPA	1942760.9	-5804088.2	-1796900.9	2.5	2.9	4.4
9008		SHIRAZ	3376875.2	4403976.2	3136257.3	6.8	6.1	6.1
9009		CURACAO	2251810.7	-5816917.6	1327163.4	2.4	2.1	3.4
9010		JUPITER	976276.2	-5601402.2	2880234.5	2.1	1.8	2.3
9011		VILLA DOLORES	2280575.3	-4914580.2	-3355383.7	2.4	2.7	3.7
9012		MAUI	-5466067.8	-2404312.7	2242188.4	3.0	2.9	3.3
9021		MOUNT HOPKINS	-1936789.3	-5077714.7	3331922.7	7.1	5.3	5.3
9022	T	OLIFANTSFONTEIN	5056103.6	2716508.0	-2775771.3	7.0	7.0	7.0
9023	C	WOOMERA	-3977795.7	3725081.8	-3303010.7	7.0	7.0	8.0
9025	C	DODAIRA	-3910474.4	3376348.0	3729210.1	11.0	11.0	9.0
9027	T	AREQUIPA	1942757.6	-5804104.5	-1796894.7	6.0	6.0	6.0
9028		ADDIS ABABA	4903726.6	3965206.3	963859.6	2.1	2.1	2.9
9029		NATAL	5186441.4	-3653871.9	-654314.1	2.1	2.2	2.7
9031		COMODORO R'DAVIA	1693797.3	-4112353.1	-4556622.0	8.3	8.8	11.2
9039	T	NATAL	5186452.6	-3653855.6	-654320.7	9.0	9.0	9.0
9049	C	JUPITER	976266.3	-5601404.1	2880229.2	4.0	4.0	4.0
9050	T	HARVARD	1489733.9	-4467483.4	4287304.9	12.0	11.0	15.0
9051		ATHENS	4606861.5	2029692.2	3903562.2	4.2	10.3	4.4
9091		DIONYSOS	4595158.9	2039417.6	3912670.6	4.2	10.3	4.4
9424		COLD LAKE	-1264831.9	-3466915.4	5185450.9	4.7	5.5	4.3
9425		EDWARDS AFB	-2450012.7	-4624431.6	3635036.6	2.6	2.2	2.4
9426		HARESTUA	3121261.3	592605.7	5512723.0	8.6	9.4	5.8
9427		JOHNSTON ISLAND	-6007428.7	-1111852.5	1825733.9	8.9	19.8	8.6
9431		RIGA	3183897.6	1421426.7	5322814.7	12.3	9.4	7.0
9432		UZHGOROD	3907419.2	1602378.6	4763922.1	7.9	10.4	5.9
9711	C	GOLDSTONE	-2351452.4	-4645087.1	3673767.7	5.0	5.0	5.0
9712	C	GOLDSTONE	-2350465.9	-4651987.1	3665632.7	5.0	5.0	5.0
9714	C	GOLDSTONE	-2353644.6	-4641350.3	3677056.2	4.0	4.0	4.0
9741	C	WOOMERA	-3978731.3	3724832.0	-3302190.6	5.0	5.0	6.0
9742	C	TIDBINBILLA	-4460996.9	2682397.8	-3674596.2	12.0	23.0	10.0
9751	C	JOHANNESBURG	5085428.9	2668245.4	-2768706.6	5.0	5.0	6.0
9761	C	MADRID	4849230.8	-360340.2	4114880.5	8.0	12.0	6.0
9762	C	MADRID	4846688.5	-370258.6	4116903.7	9.0	13.0	7.0
9901	T	ORGAN PASS	-1535779.5	-5166998.0	3401052.4	8.0	8.0	8.0
9902	C	OLIFANTSFONTEIN	5056108.3	2716508.6	-2775768.7	5.0	5.0	6.0
9907	C	AREQUIPA	1942761.1	-5804088.7	-1796900.7	4.0	5.0	6.0
9921	C	MOUNT HOPKINS	-1936788.2	-5077711.7	3331927.9	9.0	7.0	7.0
9929	C	NATAL	5186441.7	-3653872.0	-654314.2	4.0	4.0	4.0
9930	C	DIONYSOS	4595215.1	2039399.9	3912624.2	6.0	12.0	6.0

References

American Geophysical Union: (in press), *The National Geodetic Satellite Program*, NASA Special Publication, U.S. Government Printing Office, Washington, D.C.

Anderle, R. J.: 1965, 'Geodetic Parameter Set NWL 5E 6 Based on Doppler Satellite Observations', *Naval Weapons Lab. Rep.*, NWL-1978, Dahlgren, Va.

Anderle, R. J.: 1967, 'Geodetic Parameter Set NWL 6E 6 Based on Doppler Satellite Observations', *The Use of Artificial Satellites for Geodesy* **2**, (ed. by G. Veis), National Technical University of Athens, Greece.

Anderle, R. J.: 1974a, 'Transformation of Terrestrial Survey Data to Doppler Satellite Datum', *J. Geophys. Res.* **79**, 5319–5331.

Anderle, R. J.: 1974b, 'Role of Artificial Earth Satellites in Redefinition of the North American Datum', *Canadian Surveyor* **28**, 590–597.

Anderle, R. J. and Smith, S. J.: 1967, 'NWL8D Geodetic Parameters Based on Doppler Satellite Observations', *Naval Weapons Lab. Tech. Rep.*, TR-2016, Dahlgren, Va.

Anderle, R. J. and Smith, S. J.: 1968, 'Observation of Twenty-Seventh and Twenty-Eighth Order Gravity Coefficients Based on Doppler Observations', *J. Astronaut. Sci.* **15**, 1–4.

Anderle, R. J. and Tannenbaum, M. G.: 1974, 'Practical Realization of a Reference System for Earth Dynamics by Satellite Methods', *Naval Weapons Lab. Tech. Rep.*, TR-3161, Dahlgren, Va.

Andregg, C. H.: 1974, 'Doppler Geodetic Point Positioning in Latin America', *Mem. Primer Congr. Panam. de Fotogr. Fotoint. y Geod.* **2**, 1276–1297, Mexico City, Mexico.

Bender, P. L.: 1975, 'Laser Measurements of the Lunar Distance', U.S. National Report to the IUGG, Grenoble, France, *Rev. Geophys. Space Phys.* **13**, 271–272; 290–291.

Bender, P. L., Currie, D. G., Dicke, R. H., Eckhardt, D. H., Faller, J. E., Kaula, W. M., Mulholland, J. D., Plotkin, H. H., Poultney, S. K., Silverberg, E. C., Wilkinson, D. T., Williams, J. G., and Alley, O.: 1973, 'The Lunar Laser Ranging Experiment', *Science* **182**, 229–238.

Blaha, G.: 1971a, 'Inner Adjustment Constraints with Emphasis on Range Observations', *Rep. Dept. Geod. Sci.*, 148, Ohio State Univ., Columbus, Oh.

Blaha, G.: 1971b, 'Investigations of Critical Configurations for Fundamental Range Networks', *Rep. Dept. Geod. Sci.*, 150, Ohio State Univ., Columbus, Oh.

Brouwer, D. and Clemence, G. M.: 1961, *Methods of Celestial Mechanics*, Academic Press, New York.

Brown, D. C.: 1975, 'Central Florida Test of Doppler Surveying with JMR-1 Receiver', *DBA Tech. Note* No. 75-001, DBA Systems Inc., Melbourne, Fla.

Cazenave, A., Dargnies, O., Balmino, G., and Lefebvre, M.: 1972, 'Geometrical Adjustment with Simultaneous Laser and Photographic Observations on the European Datum', *The Use of Artificial Satellites for Geodesy* (ed. by S. W. Henriksen *et al*), *Geophys. Monogr.* **15**, Am. Geophys. Union, Washington, D. C.

Cohen, C. J. and Anderle, R. J.: 1960, 'Verification of Earth's Pear Shaped Gravitational Harmonic', *Science* **133**, 807–254.

Counselman, C. C. III: 1975, 'Geodesy by Very Long Baseline Interferometry', U.S. National Report to the IUGG, (Grenoble, France,) *Rev. Geophys. Space Phys.* **13**, 270–271; 290.

Defense Mapping Agency: 1972, 'Report of the DOD Geoceiver Test Program', *DMA Rep.* 0001, Defense Mapping Agency, Washington, D. C. [Prepared by The Johns Hopkins University, Applied Physics Lab., Silver Spring, Md.]

Ehrnsperger, W.: 1974, 'Numerical Investigations on the Strength of Figure in the Western European Satellite Triangulation', *The Use of Artificial Satellites for Geodesy and Geodynamics* (ed. by G. Veis), National Technical Univ. of Athens, Greece.

Ehrnsperger, W., Munford, C., Nabauer, M., Schnadelbach, K., Seifers, H., and Weightman, J.: 1972, 'Western European Satellite Triangulation Program, Second Experimental Computation, Joint Report by the two Computing Centres', *Proceedings I.A.G. International Symposium on Satellite and Terrestrial Triangulation* (Part 1), 69–106, Technische Hochschule, Graz, Austria.

Gaposchkin, E. M. (ed.): 1973, '1973 Smithsonian Standard Earth (III)', *SAO Special Rep.* 353, Smithsonian Astrophysical Observatory, Cambridge, Mass.

Gaposchkin, E. M.: 1974, 'Earth's Gravity Field to the Eighteenth Degree and Geocentric Coordinates for 104 Stations From Satellite Terrestrial Data', *J. Geophys. Res.* **79**, 5377–5411.

Gaposchkin, E. M. and Lambeck, K.: 1970, 'The 1969 Smithsonian Standard Earth II', *SAO Special Rep.* 315, Smithsonian Astrophysical Observatory, Cambridge, Mass.

Gaposchkin, E. M. and Lambeck, K.: 1971, 'Earth's Gravity Field to the Sixteenth Degree and Station Coordinates from Satellite and Terrestrial Data', *J. Geophys. Res.* **76**, 4855–4883.

Hagihara, Y.: 1972, *Celestial Mechanics* **2**, The MIT Press, Cambridge, Mass.

Henriksen, W. S. and Mueller, I. I.: 1974, 'Major Results of the National Geodetic Satellite Program', *J. Geophys. Res.* **79**, 5317–5318.

Henriksen, S. W., Mancini, A., and Chovitz, B. (eds.): 1972, *The Use of Artificial Satellites for Geodesy*, *Geophys. Monogr.* **15**, Am. Geophys. Union, Washington, D.C.

Kaula, W. M.: 1966, *Theory of Satellite Geodesy – Applications of Satellites to Geodesy*, Blaisdell Publishing Company, Waltham, Mass.

Kolaczek, B., Sledzinsky, J., and Weiffenbach, G. (eds.): (in press), *Proceedings of the International Colloquium on Reference Coordinate Systems for Earth Dynamics*, Inst. of Higher Geodesy and Geodetic Astronomy, Warsaw Tech. Univ. and The Smithsonian Astrophysical Observatory, Cambridge, Mass.

Kouba, J.: 1974, 'Reduction of Doppler Data Observed in Canada', *Canadian Surveyor* **28**, 480–486.

Kumar, M.: 1972, 'Coordinate Transformation by Minimizing Correlations between Parameters', *Rep. Dept. Geod. Sci.*, 184, Ohio State Univ., Columbus, Oh.

Lerch, F. J., Wagner, C. A., Smith, D. E., Andson, M. L., Brownd, J. E., and Richardson, J. A.: 1972a, 'Gravitational Field Models for the Earth (GEM 1 and 2)', *GSFC Doc.* No. X-553-72-146, Goddard Space Flight Center, Greenbelt, Md.

Lerch, F. J., Wagner, C. A., Putney, B. H., Sandson, M. L., and Brownd, J. E.: 1972b, 'Gravitational Field Models (GEM 3 and 4)', *GSFC Doc.* No. X-592-72-476, Goddard Space Flight Center, Greenbelt, Md.

Lerch, F. J., Wagner, C. A., Richardson, J. A., and Brownd, J. F.: 1974, 'Goddard Earth Models (5 and 6)', *GSFC Doc.* No. X-921-74-145, Goddard Space Flight Center, Greenbelt, Md.

Lerch, F. J., Richardson, J. A., and Brownd, J. E.: 1975, 'Improvement in the Gravitational Potential Derived from Satellite Data', abstract in *EOS*, *Trans. Am. Geophys. Union* **56**, 349.

Lundquist, C. A. and Veis, G.: 1966, 'Geodetic Parameters for a 1966 Smithsonian Institution Standard Earth', *SAO Special Rep.* 200, Smithsonian Astrophysical Observatory, Cambridge, Mass.

Marsh, J. G., Douglas, B. C., and Klosko, S. M.: 1972, 'The Relation of the European Datum to a Geocentric Reference System', *Bull. Géodés.*, No. 106, 407–424.

Marsh, J. G., Douglas, B. C., and Klosko, S. M.: 1973, 'Analyses of Precision Reduced Optical Observations from the International Satellite Geodesy Experiment (ISAGEX)', *GSFC Doc.* No. X-590-73-340, Goddard Space Flight Center, Greenbelt, Md.

Marsh, J. G., Douglas, B. C., and Walls, D. M.: 1974a, 'Geodetic Results from ISAGEX Data', *GSFC Doc.* No. X-921-74-250, Goddard Space Flight Center, Greenbelt, Md.

Marsh, J. G., Douglas, B. C., and Klosko, S. M.: 1974b, 'A Global Station Coordinates Solution Based upon Camera and Laser Data – GSFC 1973', *The Use of Artificial Satellites for Geodesy and Geodynamics* (ed. by G. Veis), National Technical Univ. of Athens, Greece.

Martin, C. F. and Van Flandern, T. C.: 1970, 'Secular Changes in Lunar Ephemeris', *Science* **168**, 246–247.

Meade, B. K.: 1974, 'Doppler Data versus Results from High Precision Traverse', *Canadian Surveyor* **28**, 462–466.

Mottinger, N.: 1969, 'Status of D.S.F. Location Solution for Deep Space Probe Missions', *Deep Space Network, Space Programs Sum*, 37–60, **2**, 77–89, Jet Propulsion Lab., Pasadena, Cal.

Moyer, T. D.: 1971, 'Mathematical Formulation of the Double Precision Orbit Determination Program (DPODP)', *JPL Rep.* No. TR 32-1527, Jet Propulsion Lab., Pasadena, Cal.

Mueller, I. I.: 1964, *Introduction to Satellite Geodesy*, Frederick Ungar Publishing Co., Inc. New York, N.Y.

Mueller, I. I.: 1974a, 'Global Satellite Triangulation and Trilateration Results', *J. Geophys. Res.* **79**, 5333–5347.

Mueller, I. I.: 1974b, 'Review of Problems Associated with Conventional Geodetic Datums', *Canadian Surveyor* **28**, 514–523

Mueller, I. I., Kumar, M., Reilly, J., Saxena, N., and Soler, T.: 1973, 'Global Satellite Triangulation and Trilateration for the National Geodetic Satellite Program (Solutions WN 12, 14, and 16)', *Rep. Dept. Geod. Sci.* 199, Ohio State Univ., Columbus, Oh.

NASA: 1973, 'Directory of Observation Station Locations', Goddard Space Flight Center, Greenbelt, Md.

Peterson, A. E.: 1974, 'Merging of the Canadian Triangulation Network with 1973 Doppler Satellite Data', *Canadian Surveyor* **28**, 487–495.
Plotkin, H. H.: 1973, 'Laser Technology for High Precision Satellite Tracking', *Proc. Symp. Earth's Gravitational Field and Secular Variations in Position*, (ed. by R. S. Mather and P. V. Angus Leppan), The School of Surveying, Univ. New South Wales, Sidney, Australia.
Rutscheidt, E. H.: 1972, 'Preliminary Results of the SECOR Equatorial Network', *The Use of Artificial Satellites for Geodesy* (ed. by S. W. Henriksen *et al.*), *Geophys. Monogr.* **15**, American Geophysical Union, Washington, D.C.
Schmid, H. H.: 1972, 'Triangulation mit Satelliten', Ch. II, Part II in *Handbuch der Vermessungskunde*, **IIa/3** (ed. by K. Rinner), J. B. Metzlersche Verlag, Stuttgart, Germany.
Schmid, H. H.: 1974, 'Worldwide Geometric Satellite Triangulation', *J. Geophys Res.*, **79**, 5349–5376.
Seppelin, T. O.: 1974, 'The Department of Defense World Geodetic System', *Canadian Surveyor* **28**, 496–506.
Shapiro, I. I., Robertson, D. S., Knight, C. A., Counselmann III, C. C., Rogers, A. E. E., Hinteregger, H. F., Lippincott, S., Whitney, A. R., Clark, T. A., Neill, A. E., and Spitzmesser, D. J.: 1974, 'Transcontinental Baselines and the Rotation of the Earth Measured by Radio Interferometry', *Science* **186**, 920–921.
Smith, D. E., Kolenkiewicz, R., and Dunn, P. J.: 1975, 'San Andreas Fault Experiment, 1974', abstract in *EOS*, *Trans. Am. Geophys. Union* **56**, 351.
Strange, W. E., Hothem, L. D., and White, M. B.: 1975, 'Results of Doppler Station Positioning in the United States', abstract in *EOS, Trans. Am. Geophys. Union* **56**, 351.
Tsimis, E.: 1972, 'On the Geometric Analysis of Adjustment of Optical Satellite Observations', *Rep. of the Dept. Geod. Sci.* **185**, Ohio State Univ., Columbus, Oh.
Tsimis, E.: 1973, 'Critical Configurations (Determinantal Loci) for Range and Range-Difference Satellite Networks', *Rep. of the Dept. Geod. Sci.* 191, Ohio State Univ., Columbus, Oh.
Vanicek, P. and Wells, D. E.: 1974, 'Positioning Horizontal Geodetic Datums', *Canadian Surveyor* **28**, 531–538.
Veis, G. (ed.): 1963, *The Use of Artificial Satellites for Geodesy*, John Wiley and Sons, Inc., New York.
Veis, G. (ed.): 1967, *The Use of Artificial Satellites for Geodesy* **2**, National Technical Univ. of Athens, Greece.
Veis, G. (ed.): 1974, *The Use of Artificial Satellites for Geodesy and Geodynamics*, National Technical Univ. of Athens, Greece.
Wells, D. E.: 1974, 'Doppler Satellite Control', *Dept. of Surveying and Engineering Tech. Rep.* No. 29, Univ. of New Brunswick, Fredericton, Canada.
Wells, D. E. and Vanicek, P.: (in press), 'Alignment of Geodetic and Satellite Coordinate Systems to the Average Terrestrial System', *Bull. Géodés.*
Wells, D. E., Krakiwsky, E. J., and Thompson, D. B.: 1974, 'Internal and External Consistency of Doppler Satellite Triangulation and Terrestrial Networks', *Canadian Surveyor* **28**, 467–473.