The Development of Geometric Satellite Triangulation and Field Operations

LAWRENCE W. SWANSON

THERE HAVE BEEN numerous papers presented at the meetings of, or in the publications of, the American Congress on Surveying and Mapping and the American Society of Photogrammetry and many other engineering and scientific organizations, dealing with some particular aspect of satellite triangulation. In 1963 there were papers dealing with the accuracy, calibration, and logistics of the portable camera system planned and designed by the Coast and Geodetic Survey, now the National Ocean Survey of NOAA. Since then there have been papers comparing satellite and geodetic triangulation, and on world datum and related continental networks.

All of these papers have dealt with what was planned and anticipated; accuracies and logistical support, or calling attention to the effects such a completed world satellite triangulation network might have on the conventional continental and small independent geodetic nets.

Jack Davidson thought it might be interesting to many to give a rather short summary of what actually happened in making passive satellite triangulation a going program. In 1957 geometric satellite triangulation was unknown. But in January of that year three of us—William D. Harris[1], G. C. Tewinkel[2], and myself—visited Dr. Hellmut Schmid at the Ballistic Research Laboratories, Aberdeen Proving Ground. We were there to make the necessary arrangements for these and other employees from the Division of Geodesy to visit and work with Dr. Schmid; to learn his methods of analytic aerotriangulation as he applied this photogrammetric technique to ballistic tracking. This group included Dr. Charles Whitten[2], the chief of the Computing Division, and mathematicians such as Messers, Wallace Blackwell and Erwin Schmidt and Miss Rosemary Riordin.

In December of 1957 and January of 1958 the Russians launched Sputnik I and II. These satellites were photographed at Aberdeen and also their satellite trails were chopped. This work aroused our interest in determining geodetic positions by photographing a passive (sun-illuminated) satellite simultaneously with three cameras at different known positions. Discussions with Dr. Schmid led us to the conclusion that with extreme care in *design* and *operation* of the cameras, timing, and plate measuring systems, an accuracy of 1 part in 250,000 could be expected from the application of ballistic tracking techniques for geodetic triangulation through the use of artificial Earth satellites.

By September of 1959 the Director of the Coast and Geodetic Survey had approved cost estimates for portable camera systems to be submitted for the 1961 budget.

Mr. Harris of the Photogrammetry Research Branch did the research to determine the camera most suited for photographing both flashing-light and sun-illuminated satellites, using the chopping technique for satellite and star imagery. He, with the invaluable help of Mr. Ralph E. A. Putnam, the electronic system designer who designed the Ballistic Research Laboratories' missile tracking electronic system, wrote the specifications for mobile timing and synchronization units; i.e., the original electronic package for the BC-4 system.

The specifications for the purchase of the camera were completed in September of 1960; and the specifications for the C&GS camera modification and shutter, capping shutter control, which would enable the synchronization of the camera shutters with standard radio time signals (WWV) within ±300 microseconds, were completed in May 1961.

Our personnel continued to study the BC-4 operations using different satellites at the Research Laboratories. In October 1961 a C&GS field party was for the first time located at the BRL, with Commander Eugene A. Taylor as chief. He was charged to become the expert on the total BC-4 field operation, i.e., he was given the responsibility of training the new personnel assigned to his party and for making the field equipment operational in any climate, completely self-sufficient, and fully portable for any mode of transportation (Figure 1). Those first assigned to his party of a period of months were LCDR Austin Yeager and Messers. Guy Fisher, Robert Price, Dick Fallgren, Dee Kimble, Larry Schenkat, and Jack Fried. However, he called upon assistance from such people as Dick Ross from the Electronics Branch; John Smith, Chief of the Photographic Lab of Div. of Photogrammetry; Charles Theurer, Chief of Photogrammetry Branch; and Ray Puhl of the same branch. In January 1962 the C&GS received its first modified camera and electronics timing and synchronization system.

Echo I was launched on 31 October 1962; and on 2 November 1962, we were fortunate to photograph the flashing lights that were triggered manually at an altitude of 1,000 km.

Taylor wrote, with the assistance of some of the above personnel, the first *Satellite Triangulation Manual*. As cameras and equipment were to be identical, it was necessary to use the same identical procedures of operation.

He, with the assistance of the U.S. Naval Observatory, Washington, D.C., solved the original basic

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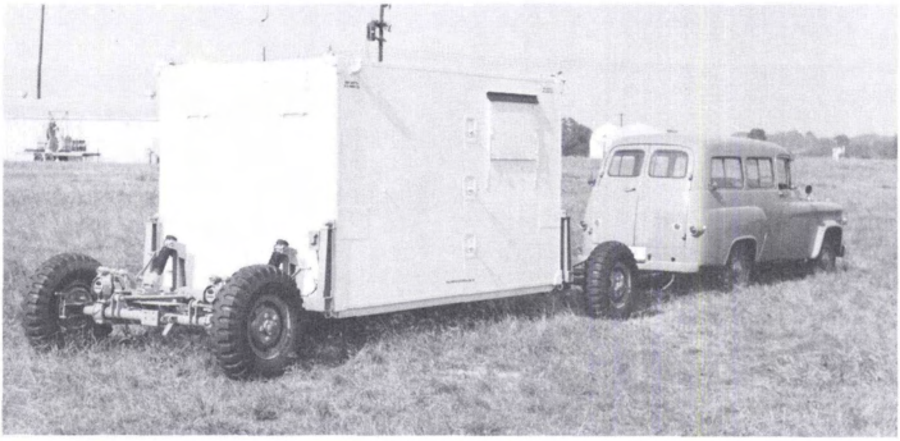

FIG. 1. Setup for transporting the complete equipment for satellite tracking.

problem in geometrical satellite geodesy programs, that is, to record accurately time-correlated satellite and star images on photographic plates. We used a fixed-camera approach, that is, the camera is fixed in orientation during the entire observational period. Accurately timed shutters interrupt the star and satellite trails as they cross the camera's field of view. The result is a photogrammetric record consisting, on an average, of 700 star and 300 satellite images across the plate (Figure 2). The shutters that produce the satellite images must be referred to a time standard to all the other camera systems involved in the simultaneous observation. In the beginning this precise transfer of epoch time was effected by using portable crystal clocks, which were hand-carried, never shipped or checked as baggage. If necessary, an additional seat was paid for on planes and the camera was strapped in a seat alongside the person carrying the clock. The same care was taken regardless of the mode of transportation. This was replaced by a portable cesium clock which was given the same care.

In 1964 or 65, Lt. George M. Cole, C&GS, was one of several who carried these clocks from station to station for synchronization reset. While transferring time, he found there was a signal on Doppler that was as accurate without having to filter out data or information. Because Johns Hopkins University Laboratory was the one that worked on the development and refinement of Doppler, we went to them directly and asked if they could develop an instrument for us to utilize this signal. They agreed, and an accurate and operational instrument was delivered to us. We then contracted with an electrical firm in the instrument business to build ten such instruments. These instruments were used in the Atlantic and Pacific Oceans and Antarctica for time reset capability, utilizing polar orbit Doppler. They proved very effective and accurate. They also solved a problem of time we had not solved because of transportation.

During 1962 we were refining the total camera system and assuring its mobility for all climates and conditions. In the meantime the Photogrammetry Division had been testing the accuracy of measuring images on photographic plates with a stereocomparator, an autograph, and monocomparator. After exhaustive tests it was determined by Mr. Frank Lampton that the monocomparator was slightly more accurate than the regular photogrammetric stereo instruments, and also better adapted to the measurement of images on star and satellite plates. At the suggestion of Mr. Harris we began improving the monocomparators by making them binocular viewing monocularly. We were also improving our measuring and processing techniques and calibration of the instruments.

The Coast and Geodetic Survey's first objective was to strengthen the North American Datum. The original program was modest. It included the 48 states and Alaska, via Canada. But the test of the accuracy of a satellite triangulation was to be made at home first, on a 1500 km triangle with stations located in Maryland, Minnesota, and Mississippi. A fourth station, in Florida, was added to form a second triangle. All stations were located on or tied to first-order triangulation stations. Observations were made on the Echo I satellite, which ranged in altitude from 1300 to 1900 km. In processing and evaluating, the standard error of unit weight of the plate measurements after adjustment was ± 0.3 micrometres. This was a measure of precision of the photogrammetric process. The absolute accuracy of the photographic measurements was better than ± 0.6 micrometres, or better than 1 part in 500,000. The calibrations and comparisons we made with our 1st order network indicated that we consistently obtained accuracies of at least 1 part in 500,000 (all accuracy figures given are standard errors).

Because of these accuracies, we were requested by the Defense Intelligence Agency (DIA) to locate Antigua and Bermuda. We readily agreed, pro-

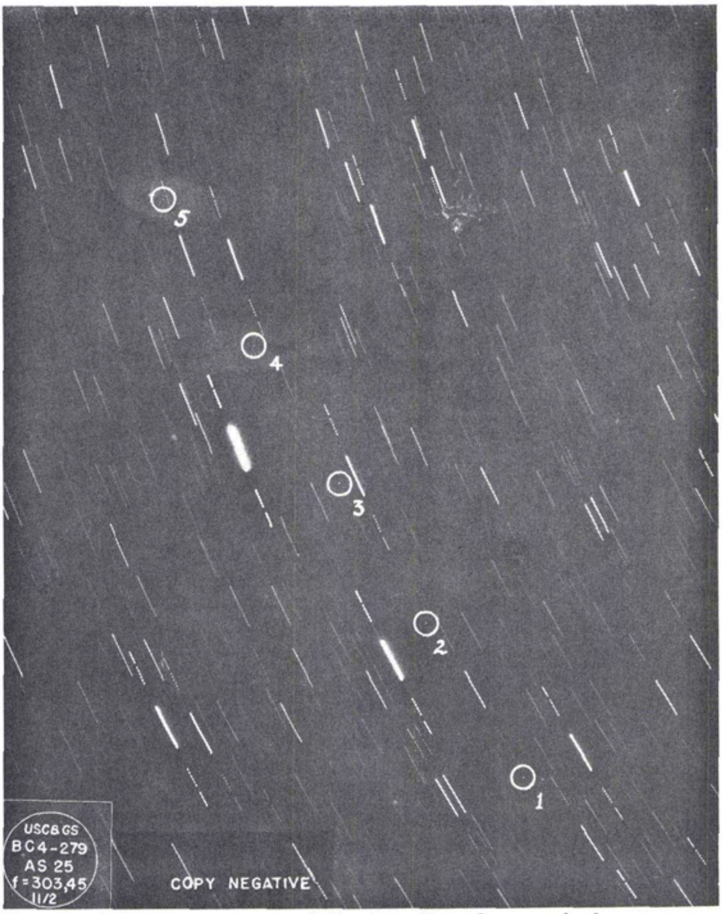

FIG. 2. Successive positions (1-5) of satellite photographed against star background.

viding they furnished the logistics and expenses involved, as these islands were not a part of our plans to reach Alaska.

At this time it was realized we needed to start the measurements of long accurate Baselines, such as Florida to Maryland, Maryland to Minnesota, west from Florida to Mississippi, etc. The Model 4D Geodimeter was the instrument being used by the Division of Geodesy, and Mr. "Red" Smathers of the Research Division suggested that, before starting to measure these long lines, it might double or triple the distance measured if a laser as a light source was used in the instrument. This would certainly speed up the work as it would greatly reduce the number of set-ups. A second-hand Model 4D was purchased for him to work with, funded by the program, as well as new parts required for the use of a laser. With the help of Dr. Robert Straub of the Research Division and Mr. George Lesley of the Division of Geodesy a laser geodimeter was developed, tested, and calibrated. It more than doubled the distances measured with the same, if not greater, accuracy.

The manufacturer of the Geodimeter was requested to make similar instruments for us, using our instrument as a model. We were told that, because the C&GS was the only outfit in the world interested in such an instrument that would measure such long distances so accurately, it would not pay for them to do it. As a result, the Army Map Service (AMS) joined with us in having 12 to 14 Model 4D's transformed to laser instruments.

The C&GS bought ten and AMS bought four second-hand Model 4 Geodimeters, and bids were put out for remodeling these instruments as per the C&GS model. The bid stated that our instrument would be furnished to the successful bidder to be used as a model, that only American-made parts could be used, and required the delivery of at least one instrument per month after a certain number of days following the acceptance of the successful bid. The successful bidder was the manufacturer of the Model 4 Geodimeter. These modified laser geodimeters reduced the number of set-ups and speeded the measurement of accurate (approximately 1:1,000,000) long distance baselines, so that we were not dependent on using scale from 1st order triangulation.

It became certain, with the results we were obtaining on the continuation of the densification network, that with a higher-flying, larger balloon-type satellite of the Echo type, a desired unified three-dimensional reference net could be made accessible to all continents and major islands, thus eliminating the troublesome discontinuities in map, chart, and survey systems that did occur over the oceans and most national frontiers.

A program was presented to Adm. H. Arnold Karo, the Director of C&GS, and in turn he said it would be necessary to present it to Dr. Holoman, Assistant Secretary of Commerce.

However, before it was presented to Dr. Holoman, it was presented to several other government organizations hoping they would join with us and give support to such a world-wide program. This was to no avail as all turned us down.

It was difficult for the C&GS to have this program accepted and treated as a scientific program: one which would use identical instrumentation; one in which rigorous but attainable quality control standards would apply to all data acquisition, measurement, and reduction operations.

We then presented the program to Drs. J. W. Holloman and W. W. Eaton, Assistant Secretary of Commerce and Deputy Assistant Secretary of Commerce, respectively, and the Commerce Science Committee. The acceptance of this program was attained only because of the great support of these two men. They met with their compatriots of the Defense Department and NASA to try and work out a cooperative program between the three agencies. They were successful.

In planning the world network, good geometry and world coverage with a minimum number of stations was stressed. In 1964-5 a network of 36 stations, composed of as nearly equilateral triangles as the land masses and islands of the oceans would allow, was designed (Figure 3). This was the world net that the Commerce Department presented to and was accepted as a part of the NASA Geodetic Explorer Project and incorporated in their Program Plan of 31 August 1964. The plan called for a 100-foot-diameter balloon satellite at approximately 2,300 statute miles (3700 km) altitude, near polar orbit. It took more than another year to work out the cooperative agreement that made this passive geometric satellite program a reality. Final operational arrangements between NASA, DOD, and DOC were agreed to on 12 March 1965. This agreement made the Worldwide Geometric Satellite Triangulation Program an actuality and a part of the National Geodetic Satellite Program (NGSP).

The program represents the cooperative efforts of NASA, which designed and put the satellite into orbit and furnished the elements of the satellite's orbit and had overall management of the NGSP; the Department of Defense, U.S. Army Topographic Command, which had the responsibility for the operational and logistical management of the program; and the Department of Commerce, NOAA, NOS (Coast and Geodetic Survey), which was responsible for the technical direction of the field observations, including maintenance of all the camera systems and laser geodimeters and the furnishing of correct time and predictions. NOS also was responsible for plate selection and plate measuring, processing, and geodetic computations[3] and analysis.

The balloon-type satellite PAGEOS 1, 100 feet in

FIG. 3. BC-4 worldwide geometric satellite network.

diameter, was launched by NASA on 23 June 1965, EST. These orbital characteristics were achieved: apogee, 2300.2 NM; perigee, 2271.8 NM; inclination, 86.97 degrees; and anomalistic period, 181.39 minutes.

27 June 1966 was the date observations began; the network that was originally presented had had 20 stations dropped and 24 new stations added. It was now a 40-station network. Three stations were established on the Australian continent, for better orientation and scale. Scale lines could be measured between these stations on the continent both east and west and north and south. A north and south scale line could be measured in western Europe. Most of the stations were now located near airfields that could handle airplanes of C124 and C130 type loaded. There were of course exceptions, such as Revilla Gigedo Island (Mexico), Heard Island (Australia), South Georgia Island (U.K. and Argentina), Pitcairn Island, Tristan de Cunha (U.K.), and three of the Antarctic stations.

During the over-four-year period of field operations other station changes had to be made. These were brought about because of weather, or to shorten east-west distance between stations, or to strengthen the net where there were deficiencies of acceptable observations; and four nations did not choose to have stations established on their territories. Two nations would not allow radio communication that are a part of the world network.

The field observations of the network were completed at the end of September, 1971, and the network is now composed of 45 stations (Figure 4).

In the spring of 1967, Cdr. Taylor was transferred just 6 or 8 months after observations began on the world network. During this period he had little time to do reconnaissance for more than the few stations that would be observed from immediately. However, he had built an important support facility, "The Beltsville Calibration Site" located at the edge of the Agricultural Research Center's airstrip in Beltsville, Maryland. Here all field personnel received specialized training in all phases of field operations under actual field conditions. Also located at this site were the following sections: electronic maintenance, instrumentation maintenance, timing, supply, and accounting. The Washington Science Center (C&GS) in Rockville, Maryland was the other important support facility for field operations. Here all major logistic problems concerning station moves and actual operational procedures were handled. The "look angle" predictions trans-

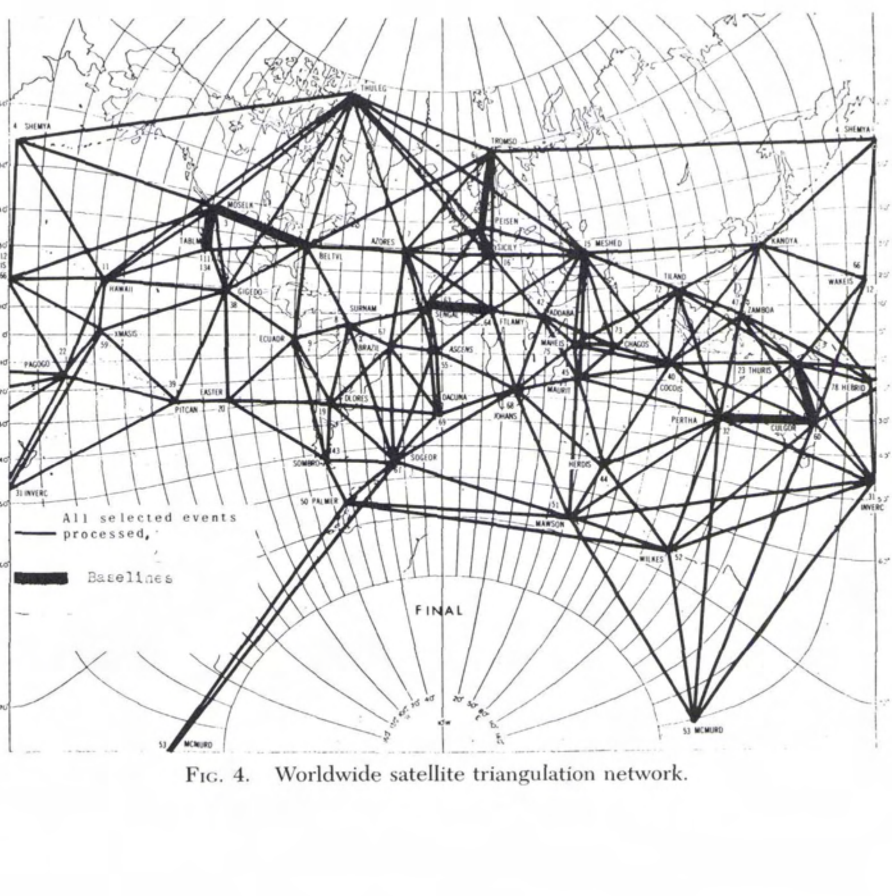

FIG. 4. Worldwide satellite triangulation network.

mitted by teletype to the field units were compiled from basic orbital data furnished by Goddard Space Flight Center in Greenbelt, Maryland. All other communications to and from the field units also were handled in this office. Quality control of all field records was another critical phase of the overall program.

Cdr. Herbert R. Lippold relieved Cdr. Taylor, and to his credit he did an excellent job. He was assisted by Messrs. Clarence Hillegass and his assistant Loren Van Gorder, who were in charge of instrument repairs and maintenance; Peter McDoran and Lt. Fidel T. Smith, in the use of satellites for timing; and Mr. Don D'Onafrio, who assisted with personnel, supplies, and logistics for all field parties and was called upon for special assignments such as the loading and offloading of trailers, generators, living equipment, and supplies on the uninhabited island of Revilla Gigedo, Mexico, and Tristan de Cunha, U.K., where beach landings of equipment were extremely difficult. On each of these islands a bulldozer was required to clear the beach of rocks for an area of movement along the shore to get equipment barged in and offloaded. Then it was necessary to bulldoze a road to higher ground above the alongshore bluffs on each island. Cdr. Austin Yeager relieved Cdr. Leppold to complete all field operations on the world network, including the four stations in the Antarctic and island stations required to bring these stations into a closed world network. These Antarctic stations were probably the most difficult physical field operation as access to these parties was not possible for months. Total supplies for the entire observing period were a necessity, Jamesway shelters were supplied for the safety of personnel trailers and operational equipment.

The completion of field operations was disheartening and difficult for Cdr. Yeager, as many of these dedicated employees had to be separated as such a small organization as the NOS could not absorb them. All of these men deserved continued employment.

Baselines

By invitation, Mr. C. I. Gilchrist, Defense Intelligence Agency, and L. W. Swanson, C&GS, met with geodesists from the nations of the Western European Sub-Commission at a special meeting called during the second meeting of the International Commission for Artificial Satellites to discuss the baseline that was needed in Europe for sealing the world network.

The European Baseline extended from Tromsö, Norway, via Sweden and Denmark, to Hohenpeissenberg, Federal Republic of Germany, thence to Austria and to Catania, Sicily, Italy.

The following were responsible for their countries' cooperation for making the required surveys: Dr. Ole Trovag, Director, Norges Geografiske Oppmaling, Oslo, Norway; Director General H. Wikstrom and Professor Lars Asplund, Geographical Survey Office, Stockholm, Sweden; Dr. Einer A. Anderson, Director, Geodetic Institute, Copenhagen, Denmark; Professor M. Kneisal, Director, Geodätishe Commission, Munich, Federal Republic of Germany; Professor Alois Barvir and Dr. Karl Rinner, Technical Universities, Vienna and Graz, respectively, Austria and Professor A. Marussi, Official Contact, government of Italy, University of Trieste, Italy; Prof. Paolo Dore, University of Bologna, President of Italian Geodetic Commission; and Gen. di. Brig. Manferti, Director General, Istituto Geografico Militare and Col. Prof. Ing. Guiseppe Birardi, Istituto Geografica Militare, Florence, Italy. It was agreed by this sub-commission that they needed such a line for the readjustment of the European network. We were to loan them four or more instruments and see that each nation's surveying team would be properly trained in the use of the laser Geodimeter using the same procedures. Also, in order that all computation would be made the same, Professor M. Kneisal would do the total computations for the European Baseline.

Australia voluntarily measured two baselines, one east and west, Culgoora to Perth, and one north and south, Culgoora to Thursday Island, and also computed these lines. The work was done by the Department of National Development under the direction of Dr. Bruce Lambert, Director of National Mapping, Australia.

The U.S. Army Topographic Command (TOPOCOM) was responsible for the survey of the African baseline. The work was accomplished through the efforts of Messrs. John McCall and William Doxie. The lines extended from Dakar, Senegal, through Mali, Upper Volta, Niger, Nigeria, and Fort Lancy, Chad. One section of this baseline was accomplished through contractual arrangements with France's Institut Geographique National; and the section within Nigeria by the Federal Surveying Department of Nigeria with technical assistance from TOPOCOM. This was computed by the Dept. of Army Commanding Officer U.S. Army Engineers (TOPOCOM).

The Baselines used for the world net in the United States were measured by the National Geodetic Survey from Beltsville, Maryland to Moses Lake, Washington and to Wrightwood, California. These lines were computed by Messrs. B. K. Meade and John G. Gergen, respectively. Mr. Meade also computed the European Baseline.

Data Reduction

The BC-4 data processing work was accomplished by the NOS Division of Photogrammetry, Photogrammetric Branch Chief Charles Theurer, under the direction of Raymond Puhl, Chief of the Astrometric Section.

This massive data reduction program required the efforts of 38 people throughout a 7-year period, 1966-1972. The world net required the preparation, measuring, and data reduction of approximately 3800 satellite and star plates. Hereafter the plates will be referred to as star plates.

Preparation of the star plates required both manual and computer processing. A preliminary plate orientation was required to identify the star images to be measured and, secondly, the preliminary orientation provided the initial parameters for the main single camera orientation. Star plates were prepared for measuring; this required using star charts generated to plate scale from a star catalog program. This portion of the reduction effort, along with the measuring of the plates on Mann comparators, was under the supervision of Lew Williams and, later, Robert Kornspan.

The star plate data reduction system was made of about seven main computer programs, and approximately 100 to 150 plates were processed at these stages at any given time. In the early 1960's the batch mode data were used in data processing on generating "two" hardward. To process the daily workload required the assembly of more than 400,000 punch cards for the computer runs. In the mid 1960's the processing group actually assembled computer runs on punch cards. Over the life cycle of the project, a data base was established which utilized disk storage as the medium. This phase was under the supervision of Robert Wagner and, later, Michael Day. They directed the five sub-phases of the reduction program: plate measurement, star identification, single camera orientation, satellite reduction, and satellite triangulation. These subphases were processed under the direction of John Gerlach, James Lisle, Ivy Rabarn, Dave Alger, and Bill Golden.

The successful completion of the program was truly due to the efforts of many people. Without the dedicated efforts of these people, the project could not have been completed in the allocated timeframe. The Satellite Triangulation Program data reduction itself used 266 man years to produce the 45-station network. "The experience gained from the large amount of work involved in preliminary reduction enabled the development of a new generation of computer programs with a level of sophistication consistent with an ultimate potential accurace of 1 part in 2,000,000; for all stations in the world net for which *no deficiency in observational data exists*. That is, the positional RMS is somewhat better than ±6 metres, or specifically, ±5.0 metres for the horizontal components and at least ±8.5 metres in height.*

Dr. Helmut Schmid was in charge of the computations after receiving the data from the Astrometric section of the Photogrammetry Division. He was ably assisted by Robert Hanson[3], Chester Slama, Irwin Schmidt[4], Anna-May Bash (Millier), and Heinz Poetesque. They wrote most of the programs and assisted in all phases of the preliminary as well as the last sophisticated programs that were developed to get the above final accuracies.

International Cooperation

International cooperation was necessary in order to accomplish such a world network. Practically all nations readily agreed to allowing baselines to be measured and to establish satellite stations in their countries or their possessions and in addition the following nations gave great additional assistance to the program at their expense by furnishing well qualified personnel to operate the camera systems, tie to national datums, and to make such other surveys as were required.

The Federal Republic of Germany, besides measuring their section of the European Baseline, bought two camera systems complete and furnished one camera and team for the entire observing period and a 2nd camera and team for the last phase of the observing program.

The United Kingdom furnished personnel for operation of one camera system for the entire observing program and a second team for the last year and even assisted in observing on the Densification net to Europe for another year. Lieutenant Colonal A. J. Ayers was in charge from 1966 to 1969 and was assisted by Major DMR Batterham, R.E., 1966 to 1967; by Major C. G. Notl-Bower, 1967 to 1968; Major J. J. Codd, R.E., 1968 to 1969; and Warrant Officer L. Terry, R.E., 1966 to 1969. Lieutenant Colonel H. G. W. Crawford, R.E. was in charge from 1969 to 1972 and was assisted by Major J. A. Underwood, R.E., 1969 to 1970; Major D. J. Baker, R.E., 1970 to 1971; Capt. M. St. G. Irwin, R.E., 1971 to 1972; and Capt. P. A. Crighton, R.E., 1969 to 1972.

Australia, besides voluntarily measuring two baselines (that met our accuracy requirements), furnished assistance at three camera stations and furnished transportation for our two parties and their equipment to stations Mawson and Wilkes, Antarctica.

Canada, under the direction of S. G. Gamble, furnished personnel and transportation, which proved very helpful in carrying out the dessification program.

South Africa furnished an observing team by existing NASA contract.

A qualified C&GS chief of our Observing Unit was attached to each team except DIA, TOPOCOM to make certain the operation and maintenance of all camera systems were in accordance with the Satellite Triangulation Manual and to assist when necessary for parts, replacement of equipment, emergency transportation, or such action as may become necessary.

When the World Geometric Satellite Triangula-

* Taken from the *U.S. National Report 1967-1971*, 50th General Assembly International Union of Geodesy & Geophysics, Moscow, USSR, 2-14 August 1971, page 47. Also see the computation and analysis of this satellite program in detail in Vol. II, NASA 365, *National Geodetic Satellite Program,* Chap. 7, pages 527-643, by Dr. H. H. Schmid.

TABLE 7.11.—*Three-Dimensional Cartesian Coordinates*

No.	Station name	X (m)	σ_X ± (m)	Y (m)	σ_Y ± (m)	Z (m)	σ_Z ± (m)
001	Thule	546 567.862	2.297	−1 389 990.609	3.447	6 180 239.602	3.960
002	Beltsville	1 130 761.500	0	−4 830 828.597	0	3 994 704.584	0
003	Moses Lake	−2 127 833.613	.790	−3 785 861.054	2.976	4 656 034.740	2.906
004	Shemya	−3 851 782.861	4.888	+396 404.016	5.654	5 051 347.586	6.673
006	Tromso	2 102 925.118	3.663	+721 667.562	4.772	5 958 188.868	4.748
007	Azores	4 433 636.070	4.737	−2 268 143.467	4.362	3 971 656.223	4.945
008	Surinam	3 623 227.823	4.563	−5 214 231.698	4.502	601 551.302	5.716
009	Quito	1 280 815.597	4.338	−6 250 955.436	5.800	−10 793.013	5.717
011	Maui	−5 466 020.732	5.045	−2 404 435.198	4.352	2 242 229.885	4.703
012	Wake	−5 858 543.398	5.308	+1 394 489.166	5.281	2 093 807.584	5.391
013	Kanoya	−3 565 865.509	5.200	+4 120 692.866	6.694	3 303 428.249	6.131
015	Mashhad	2 604 346.389	3.988	+4 444 141.147	5.513	3 750 323.381	4.974
016	Catania	4 896 383.234	4.080	+1 316 167.822	4.463	3 856 673.791	4.698
019	Dolores	2 280 603.832	4.190	−4 914 545.588	4.789	−3 355 412.286	6.839
020	Easter	−1 888 616.886	4.845	−5 354 892.780	6.246	−2 895 739.444	7.217
022	Pago Pago	−6 099 954.446	5.392	−997 367.321	4.710	−1 568 567.088	5.883
023	Thursday Is.	−4 955 371.694	4.671	+3 842 221.799	5.689	−1 163 828.451	5.852
031	Invercargill	−4 313 815.856	4.687	+891 322.098	5.238	−4 597 238.676	6.398
032	Perth	−2 375 397.874	4.579	+4 875 524.035	5.746	−3 345 372.936	6.170
038	Revilla	−2 160 983.561	2.008	−5 642 711.612	3.653	2 035 371.417	4.062
039	Pitcairn	−3 724 766.403	6.502	−4 421 236.249	6.480	−2 686 072.609	7.288
040	Cocos	−741 969.205	4.859	+6 190 770.789	6.606	−1 338 530.638	5.843
042	Addis Ababa	4 900 734.926	4.844	+3 968 226.427	5.481	966 347.675	5.103
043	Sombrero	1 371 358.188	4.171	−3 614 760.271	4.969	−5 055 928.396	8.156
044	Heard	1 098 896.432	6.448	+3 684 591.597	7.801	−5 071 838.356	9.919
045	Mauritius	3 223 422.870	4.472	+5 045 312.452	6.019	−2 191 780.736	6.065
047	Zamboanga	−3 361 946.845	4.909	+5 365 778.338	6.501	763 644.128	6.121
050	Palmer	1 192 659.730	5.174	−2 450 995.361	7.275	−5 747 040.896	10.171
051	Mawson	1 111 335.585	5.189	+2 169 243.189	5.456	−5 874 307.692	8.002
052	Wilkes	−902 598.435	4.912	+2 409 507.607	5.700	−5 816 527.805	7.901
053	McMurdo	−1 310 841.759	4.993	+311 248.105	5.500	−6 213 251.231	7.886
055	Ascension	6 118 325.238	5.260	−1 571 746.070	4.816	−878 595.457	5.507
059	Christmas	−5 885 331.078	5.213	−2 448 376.867	4.435	221 683.837	5.446
060	Culgoora	−4 751 637.577	4.552	+2 792 039.266	5.653	−3 200 142.319	5.866
061	So. Georgia	2 999 903.036	4.896	−2 219 368.228	6.055	−5 155 246.454	8.547
063	Dakar	5 884 457.561	4.898	−1 853 492.773	4.257	1 612 863.206	5.072
064	Chad	6 023 375.533	4.690	+1 617 924.383	4.242	1 331 742.422	4.834
065	Hohenpeissenberg	4 213 552.554	3.730	−820 823.968	4.444	4 702 787.513	4.620
067	Natal	5 186 398.560	5.260	−3 653 936.203	4.854	−654 277.651	5.569
068	Johannesburg	5 084 812.964	5.229	−2 670 319.559	5.065	−2 768 065.635	6.586
069	De Cunha	4 978 412.958	8.167	−1 086 867.619	6.918	−3 823 159.761	9.443
072	Thailand	−941 692.348	5.593	+5 967 416.884	6.919	2 039 317.530	5.461
073	Chagos	1 905 130.320	4.345	+6 032 252.624	6.702	−810 711.562	5.751
075	Mahe	3 602 810.169	4.910	+5 238 217.287	6.393	−515 928.653	5.650
111	Wrightwood	−2 448 854.721	2.088	−4 667 988.213	3.367	3 582 758.969	3.185

FIG 5. Table 7.11 from Vol. II, NASA 365, *National Geodetic Satellite Program*, Chapter 7, pages 527-643, by Dr. H. H. Schmid.

tion Program was agreed upon, NASA, DMA (DIA & TOPOCOM), and Commerce (NOS-C&GS) worked as a unit—smooth and fruitful for a completed program with an accuracy greater than originally thought possible.

The three-dimensional Cartesian station coordinates used as starting approximations for the adjustment were obtained as follows: The ellipsoidal coordinates (latitude, longitude, and ellipsoid height) of each station (see Table 7.2, p. 264) were first transformed to three-dimensional Cartesian coordinates whose origins were the centers of their respective reference ellipsoids. These station Cartesian coordinates were then translated and rotated, as necessary, to refer them to a common Cartesian reference system whose origin was the center of the Clarke 1966 ellipsoid.

The "free' adjustment, whose results are shown in Table 7.11, p. 632 (see Figure 5), was computed by vigorously fixing the coordinates of station Beltsville and the lengths of 8 baselines (Table 7.3) with essentially infinite weights, and computing corrections to the station coordinates. These corrections were added to the starting coordinates to produce the final values in Table 7.11 (see footnote on p. 1339).

REFERENCES

1. (C&GS) Technical Bulletin #19.
2. (C&GS) Technical Bulletin #21.
3. NOAA Technical Report NOS 55, 1977.
4. NOAA Technical Report NOS 60, 1973.

Author's Note:

The Field Operations were completed. The only country that forwarded information on the personnel who assisted in the operations was the United Kingdom. To name individuals who cooperated and assisted from the United States is impossible; this information is stored on magnetic tape in the Federal Archives and cannot be obtained.