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Geodetic Control with Doppler

Positions of geodetic control points can be determined within 1 m accuracy for an area of one million square miles by use of Doppler satellite observations made with a **Geoceiver.**

ABSTRACT: *Positions of geodetic control points can be determined to 1 m accuracy for a one-million-square-mile area by use of Doppler satellite observations made with a "Geoceiver." The Geoceiver weighs less than 100 pounds and automatically acquires and punches satellite observations on teletype tape. The accuracy objective can be achieved on the basis of data acquired in less than 36 hours if precise ephemerides are available for all five operating Navy Navigation Satellites. Often, a precise ephemeris is computed for only one satellite, so that a longer observing period may be required. The precise ephemeris is computed using numerical integration of the equations of motion by making a least-squares solution to determine the satellite positions that best fit observations made during a 24-hour period by stations distributed around the world.*

INTRODUCTION

HISTORY

DOPPLER *satellite observations,* which were first used in the development of the Navy Navigation Satellite System, were soon found to be useful in determining the position of geodetic control points. The first positions were determined in 1963 when accuracies of 5 m to 100 m were achieved depending on the location of the ground points. Currently, the accuracy is estimated to be 1 m for areas of a million square miles, and 3 m world wide. The principal increase in accuracy was made possible by improved knowledge of the earth's gravity field which allowed more precise computation of the orbits of the satellite. Recent contributions to increased accuracy have been made by improved instrumentation accuracy, better data filtering techniques, improved coordinates of the base stations used to determine the satellite orbit (Beuglass and Anderle, 1972) and semi-daily determinations of the orientation of the earth's spin axis with respect to the crust (Anderle, 1972).

METHOD

Geodetic control points can be established by making Doppler observations on one or more of the Navy Navigation satellites with a *Geoceiver,* a portable receiver weighing less than 100 lbs. If the orbit of the satellite is accurately known, observations for each pass of the satellite can be used to determine two components of position of the receiver. One component of position is parallel to the direction of motion of the satellite and the other is along the range vector to the satellite at the time of closest approach of the satellite to the station. Observations for 35 satellite passes are sufficient to determine all three components of the position of the receiver to 1 m accuracy. As there are five satellites in orbit, 35 passes can be observed in less than 36 hours. However, precise positions may be computed for only one of these satellites each day, whereas ephemerdies for the other satellites are computed on an irregularly scheduled basis.

The precise ephemerdies are based on observations made at 15 to 20 stations distributed around the world. A least-squares fit is made to data observed in 48-hour intervals to find constants of integration for an orbit which will best fit the observations. The solution includes other parameters which vary

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from day to day, but the coefficients of the accelerations arising from the earth's gravity field are determined in other major least-squares solutions which are conducted at one to two-year intervals.

REFERENCE SATTELLITE ORBITS

SATELLITES

Currently five satellites are operating in the Navy Navigation Satellite System, 1967-34A, 1967-48A, 1967-92A, 1968-12A, and 1970-67A. The satellites are in nearly circular polar orbits at an altitude of about 1000 km. The orbit planes are separated so that if the satellites were perfectly spaced, the average elapsed time between satellite passes would be about an hour at the equator and about 20 minutes at the poles. The satellites radiate at two stable coherent frequencies, 149,988,000 Hz, and 399,968,000 Hz. The Doppler shift of these signals caused by the motions of the satellite with respect to the receiver is used to deduce the relative position of the receiver.

Two frequencies are used in order that the first-order ionospheric refraction effects may be deduced. The satellite signal is also modulated at precise two-minute intervals to provide a time standard (which is accurate to better than 50 μ-sec) for the receivers. The satellites also transmit their positions for use in real-time navigation; however, these positions do not have the accuracy required to determine precise geodetic positions.

BASE STATIONS

Precise satellite positions are computed on the basis of observations made at the sites shown in Figure 1. The Navy Navigation Satellite System provides their observations for use in determining precise ephemerides. The other sites are operated by New Mexico State University, the University of Texas, or host country personnel. The stations beat the signals received from the satellites against 150 Mhz and 400 Mhz signals generated by a ground oscillator, and record the time required to measure a preset number of beat cycles. Depending on the equipment, measurements are either made discontinuously each four seconds over intervals of less than one second, or made continuously at 10- to

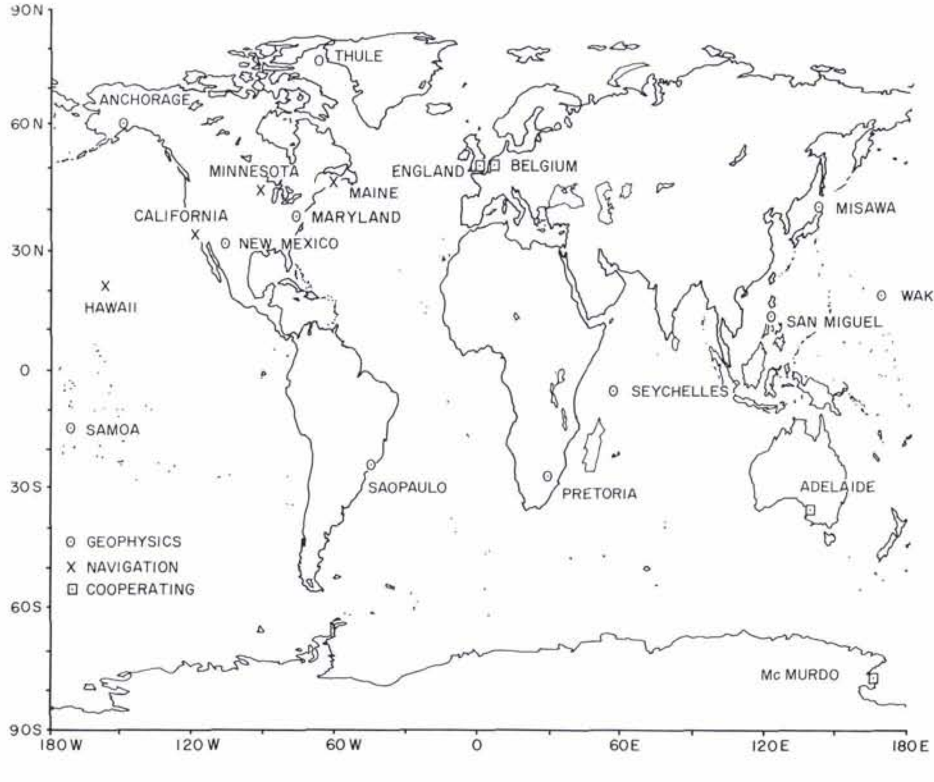

FIG. 1. Doppler Station Locations.

20-second intervals. Data at the two frequencies are combined to correct for the first-order ionospheric refraction. The measurements are punched on teletype tape and transmitted to a control center at the applied Physics Laboratory of the Johns Hopkins University at convenient times each day. There the data are transferred to magnetic tape and sent to the Naval Weapons Laboratory once each day.

COMPUTATIONAL METHOD

The satellite position is computed by numerical integration of the equations of motion of the satellite. The equations are integrated in an inertial reference frame defined by the mean equator and equinox at the start of the integration. The equations of motion include the effects of atmospheric drag, solar radiation, lunar-solar gravitation, lunar-solar solid earth tides, and the earth's gravity as defined by a spherical harmonic expansion which includes about 450 terms. The constants of integration and other parameters are determined by least-squares fit to observations made in 48-hour intervals.

Observations are first calibrated and filtered. The time signals transmitted by the satellite are used to correct the local station clocks. As the time signals are recorded at two-minute intervals, 5 to 10 time corrections are available for each satellite pass; these are filtered and averaged to determine a mean correction for the pass. The Doppler data are filtered by comparing the observations with data computed for satellite positions predicted from the preceding day. Data deviating from the trend of the residuals are rejected, and a weight for the accepted data points is computed from the random variations in the good data.

The data are still subject to an uncertainty in the satellite or ground station oscillators and to climatic variations in tropospheric refraction. Therefore, a frequency-bias parameter and tropospheric refraction-bias parameter for each satellite pass are included as unknowns in the least-squares solution. Other parameters besides the six orbit constants include a scaling factor for the nominal atmospheric drag effects on the satellite, the orientation of the spin axis of the earth with respect to the crust, and the components of position of any new observing stations. Partial derivatives of the data with respect to these parameters are obtained using the predicted satellite position for the geometric parameters and are obtained by integration of the variational equation for the dynamical parameters.

These partial derivatives and the residuals of observation corresponding to a predicted ephemeris are used to form a linearized least-squares solution for improved parameters. In practice, the predicted ephemeris is close enough to the improved ephemeris so that iteration of the solution is not required despite the linearization. The ephemeris best fitting the observations is then rotated into an earth-fixed reference frame determined by the pole position parameters and is used to obtain precise geodetic positions of satellite receivers.

GEODETIC POSITIONING METHOD

GEOCEIVER EQUIPMENT

Positions of hundreds of sites have been determined using precise satellite ephemerides calculated in the manner described above. Satellite observations were made with mobile Doppler satellite receivers which were placed at the sites. The equipment was originally housed in vans which weighed about 10,000 pounds. In 1970, delivery was begun of production models of new receivers weighing less than 100 lbs. The new equipment is designated AN/PRR-14, but is usually referred to as a *Geoceiver*. Accuracy obtained with the new equipment is comparable to that obtained with the older equipment. The Geoceiver can operate from a variety of power sources including portable gasoline generators weighing less than 100 lbs. It is not necessary to man the equipment continuously because the receiver automatically searches in frequency for the satellite signal and, when locked on, initiates the measurements and punches the teletype tape containing the observations.

DATA REDUCTION

Data reduction procedures for Geoceiver data are similar to those applied to data from the base stations. Geoceiver Doppler counts are initiated by the time modulations transmitted by the satellite. Therefore, time calibrations can be obtained by comparing the recorded time of receipt of the time signals with the time the signals are transmitted by the satellite, after making the correction for the time required for the signal to travel from the satellite to the station. An average value of the calibrations determined during the pass is applied to each time of observation in the pass. The ionospheric refraction corrections, which are recorded at each time of observation, are applied to the data. Then the corrected observations are compared with data computed from the precise ephemeris and an estimate of the position of the receiver.

Residuals deviating from the trend in the residuals in a satellite pass are rejected from further processing. A least-squares solution is made to determine a station position which minimizes the residuals for the obserevd satellite passes. In addition to the three components of station position, the parameters of the solution include a frequency bias and a tropospheric refraction-scaling factor for each pass.

ACCURACY EVALUATION

SIMULATION

The principal source of error in the satellite orbit is due to uncertainties in the description of the earth's gravity field. Simulations (Anderle, Malyevac and Green, 1969) have shown that these uncertainties cause periodic errors of about 4 m in the computed satellite positions. However, the errors vary from pass to pass so that the periodic errors are not expected to contribute over a 1 m error if data for 20 or more satellite passes are used in the solution for station positions. But additional biases arise from uncertainties in gravity coefficients. It is estimated that the reference system for the station coordinates may be displaced 5 m parallel to the earth's spin axis due to uncertainties in the earth's zonal gravity coefficients. In addition, the scale of the reference system may be in error by 0.5 parts per million, which means all station heights may be biased by 3 m.

CONSISTENCY

Residuals of observation for the worldwide stations with respect to the precise ephemerides have been found to correspond to an *rms* error in satellite position of 3 m. This result is consistent with the simulation of the effects of uncertainties in the gravity field on the computed satellite orbit. In another test of the consistancy of the results, positions of the base stations in the Doppler network were recomputed at various times during the past 10 years. The standard deviation of these position determinations was also about 1 m in each component.

EXTERNAL TESTS

In 1971 a number of Geoceivers were positioned at various sites along a precise base line established by the National Geodetic Survey by Geodimeter traverse (DoD Coordinating Committee for the Geoceiver Test Program, 1972). Positions of the Geoceivers determined by the satellite observations are compared with the terrestrial survey in Figure 2. The standard deviation of the differences for 17 sites in the eastern half of the United States is 1 m in each component of position. Differences for the western sites are somewhat larger, but not excessively so considering possible errors of nearly one part per million in both the satellite and the ground surveyed positions.

SUMMARY OF ERRORS

The estimated accuracy of relative positions derived by analysis of Geoceiver observations is 1 m in each component for areas 1 million square miles in size. A scale error

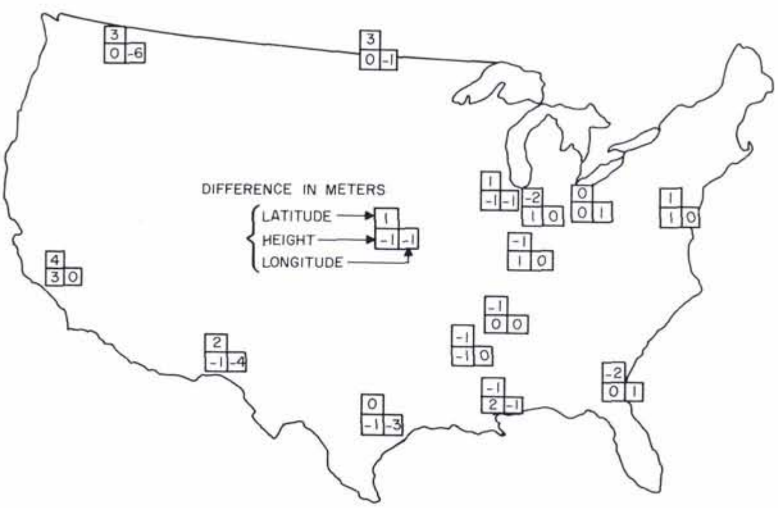

FIG. 2. Geodimeter Survey: Satellite Versus Geodimeter.

of 0.5 parts per million can be expected with a corresponding possible height bias of 3 m. The coordinate system may be biased 5 m parallel to the earth's spin axis. These estimates are confirmed by independent measurements for the local area.

References

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Book Review

Fortran Program for Photogrammetric Block Triangulation with the Bundles Method, Anton Schenk, 1972 (in German). Institut fur Geodasie und Photogrammetrie, E. T. H., Zurich, Switzerland. 8 by 11½ inches, 142 pages, paperback.

Listing and documentation is given for the solution of a block of 500 photographs including a maximum of 49 points per photo and a maximum of 2048 points for the block. The programs are written in Fortran IV for the CDC 6400/6500 computer. The approach is based on the work of Dr. Hellmut Schmid and also resembles the system devised by Keller and Tewinkel.
