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FEASIBILITY STUDY FINAL REPORT

GEODETIC ORBITAL PHOTOGRAPHIC SATELLITE SYSTEM

VOLUME 4 DATA PROCESSING, PART 2

JUNE 1966

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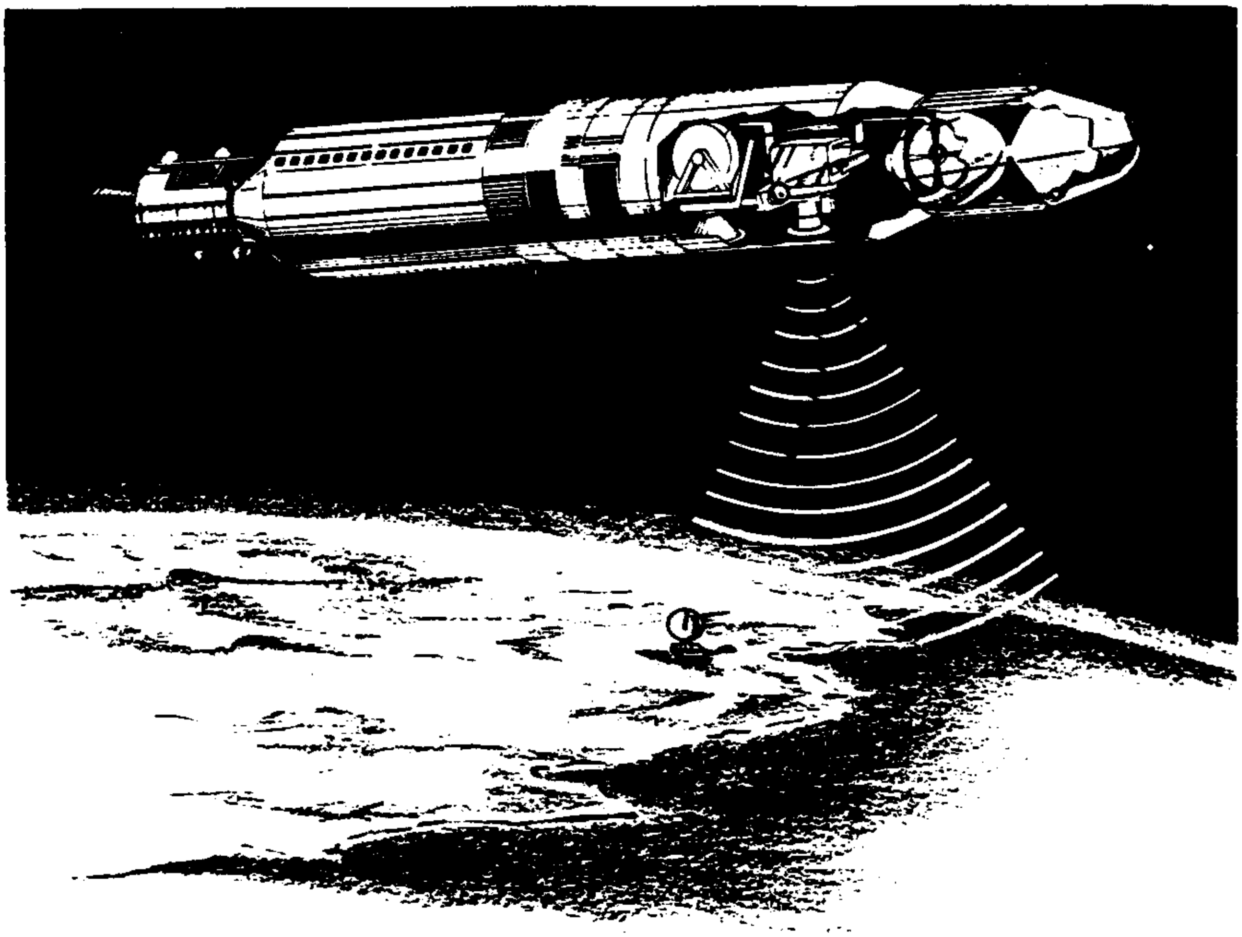

Geodetic Orbital Photographic Satellite System

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PREFACE

The objective of the Geodetic Orbital Photographic Satellite System (GOPSS) is to accurately determine the location of landmarks widely distributed over the earth's surface and provide better information concerning the geophysical parameters which affect this system and other systems operating at similar altitudes. The means chosen to accomplish this objective is to orbit a series of data acquisition systems supported by ground-based instrumentation. The data gathered by this system is incorporated into a sophisticated data reduction scheme which determines the geodynamic parameters and landmark locations.

Detailed studies were conducted to determine the feasibility of the GOPSS. The study period was designated as Phase I, and the results of these studies have been compiled into five volumes for reader convenience.

This volume discusses orbital considerations affecting the feasibility of the GOPSS. Physical models and computational procedures are reviewed and error studies involving typical sensor and model inaccuracies are described. Based on these studies, recommendations are made for tracking networks, auxiliary on-board sensors, and detailed orbit plans. In addition, the data reduction procedure, whereby the acquired data are simultaneously located to yield geodynamic parameters and landmark locations, is considered.

The division of the remaining volumes and their content are now briefly described for information and reference purposes.

Volume 1, Program Compendium and Conclusions, was prepared to provide briefly the details essential to a comprehensive understanding of the effort conducted during Phase I of the GOPSS feasibility study. System concept and objectives are described plus conclusions which concern the attainment or modification of the initial objectives, along with recommendations for a system configuration and a solution of the attendant data handling problems.

Volume 2, Data Collection Systems, describes the effort for implementation of the data acquisition requirements for the GOPSS program. This volume presents the preliminary design which defines and describes the various sensors, considers their functional interdependencies, and shows their evolvement into an integrated GOPSS.

Volume 3, Data Processing, Part 1, considers the photogrammetric data subject to constraints imposed by orbital and auxiliary data, and the mapping capabilities of the system, and ground handling of mission photography.

Volume 5, Phase II-V Program Plan, describes the planning activity as it has been programmed through Phases II to V for the engineering, fabrication and operational support for the delivery of five systems. Continuing studies which are required are also defined in this volume.

SUMMARY

Orbital considerations affecting the feasibility of accomplishing the objectives of the Geodetic Orbiting Photographic Satellite System (GOPSS) have been investigated. The goals of the GOPSS program are found to be realistic and the accomplishment of these goals is within the capabilities of present orbital positioning techniques.

The objectives of the GOPSS have been listed and the approaches taken to investigate these objectives are discussed. The physical models and computational procedures needed to calculate accurate orbital positions and reduce the data are reviewed. The applications of auxiliary sensors or concepts such as accelerometers, zero-g satellites, and passive attitude control systems are investigated.

A number of parametric orbital position covariance and ephemeris-differencing calculations for various uncertainties in observational quantities and model quantities have been performed and are reported. Limitations in the available computer program prevented complete analyses; however, a sufficient number of calculations were performed to substantiate the conclusions. The results of these calculations are discussed. Orbit planning for orbits to accomplish the objectives of the GOPSS is presented. Based on the previous discussions, conclusions are drawn and recommendations are made. Recommendations are made for a tracking network consisting of the TRANSIT and photogrammetric data, and the inclusion of on-board accelerometers. Data reduction is discussed, and recommendations for a final data reduction scheme are included.

4.1 INTRODUCTION

4.1.1 General

The mission of the Geodetic Orbiting Photographic Satellite System (GOPSS) is to locate landmarks over the earth's surface to high accuracies from data collected by an orbiting vehicle and the simultaneous accurate evaluation of the geodynamic parameters which influence the motion of the orbiting vehicle. The principal data gathering system for landmark location is photogrammetric, and consists of a set of cameras, one to photograph the earth's surface and two stellar cameras to define orientations. Orbit position is defined by typical tracking networks, reenforced by selective photogrammetric data. Accurate time in orbit is recorded and auxilary on-board sensors will be employed.

The GOPSS program can be treated as two independent calculating schemes. The first is the utilization of tracking data as the prime input to determine the orbit; the second is the use of this orbit to position the camera stations from which the location of ground points is obtained. In this positioning task, the camera is considered as the prime sensor, so that the production of a landmark catalog is approached as if it were a photogrammetric problem alone.

An approach which treats each of the data types according to independent data reduction schemes, could result in complications, since functional relationships exist between the various types of data, despite the fact that they are independently acquired. For example, ground tracking data are most suited for the determination of orbital parameters, yet these parameters can be weakly determined from the photogrammetric solution. The independent reduction of ground tracking data and the photographic records is theoretically unsound, since these two sets should be consistent with each other through the common factors, namely, the orbital parameters. An integrated approach involving the collective reduction of all observational data is therefore to be desired. However, investigating the feasibility of the GOPSS concept using such an integrated treatment requires the complete data reduction scheme that will be necessary to finally reduce the data from the GOPSS. This data reduction program is not completely available at this time and it is apparent that only partially integrated analyses can be performed in this study. If, by proceeding with partially separated calculating schemes, such as mentioned above, we conclude that meeting the specification is feasible, then the final data reduction involving complete integration would more strongly reenforce this conclusion. The following analyses are based on such an approach.

4.1.2 Orbital Analyses

This volume deals with the considerations, particularly in the field of orbital analysis, associated with accomplishing the objectives of the GOPSS program. These objectives and our approach to the necessary orbital analyses are discussed in Section 4.2 of this volume. Succeeding sections discuss: (1) the state of knowledge of forces acting on the satellite which are important in accomplishing the orbital analyses (Section 4.3), (2) data processing and computational techniques (Section 4.4), (3) a few selected possible auxiliary techniques and instrumentations required to better define or remove uncertainties in the force models (Section 4.5, 4.6, and 4.7), (4) computations and the results of computations made to investigate the feasibility of the program objectives (Sections 4.8 and 4.9), and (5) orbit planning for the GOPSS mission (Section 4.10). Finally, Section 4.11 contains a summary of the preceding sections, conclusions drawn from them and recommendations for accomplishing the GOPSS program objectives as well as for further analyses.

In addition, several conceptual questions are partially or completely considered in the following sections. Some of these questions involve, for example, such considerations as:

1. To what extent can the objectives of the GOPSS be satisfied without recourse to subsidiary data-taking systems or previous measurements, (except, perhaps, for the initial phases) in an iterative "bootstrapping" process?

2. Data reduction concepts: What are the relative values or merits in considering analyses for specialized purposed utilizing very short orbital arcs (i.e., of the order of 1000 miles or less), short arcs (of the order of 4 revolutions), long arcs (up to 7 to 15 days) and very long arcs (greater than 15 days)? To what extent should orbital determination and landmark determination be integrated? Are there advantages to considering orbital determination as partially independent, that is, as only a fixed constraint on the photogrammetry, if auxiliary sensors can accurately define the orbit?

3. Which of the many alternative choices are recommended as efficient, economical, and accurate computational procedures for the required data reductions?

These questions are partially discussed in Sections 4.9 and 4.11.

Section D

ORBIT ANALYSIS

4.2 APPROACH TO ORBITAL ANALYSIS

4.2.1 Objectives

The objectives of the orbital analysis conducted for this feasibility study are:

1. Satellite Positioning. To determine the feasibility of determining satellite orbital positions for the proposed satellite and satellite orbits to accuracies consistent with the landmark location specifications (200 feet horizontally and 40 feet in elevation), using realistically attainable data obtained during the period of observation comprising the mission-flight time.

2. Tests of Calculational Techniques and Adequacy of Physical Models Using 6-Hour Orbit Position Prediction Test Criterion. To determine the adequacy of calculational techniques and physical models using as a test criterion the prediction of satellite orbital.positions for the proposed satellite and satellite orbits. The positions are to be determined to within accuracies consistent with landmark location specifications for a period of up to 6 hours after the cessation of the recording of observations following an extended period of observations using realistically obtainable data.

3. Evaluation of Geodynamic Parameters. To determine the feasibility of evaluating the geodynamic parameters of the earth (including the undulation of the geoid) that are used in the various physical models used in the above orbital calculations to within accuracies consistent with the required accuracies of the orbital calculations. These geodynamic parameters are to be determined from realistically attainable observational data.

4. Datum Ties and Station Locations. To determine the feasibility of improving datum ties and the location of specific stations on the ground to within specified accuracies.

5. Input Data Requirements. To determine the types, geographical distributions, density, and accuracies of the observations required to provide the minimum input to the above calculations necessary to make feasible the calculations to the desired accuracies.

6. Evaluate Physical Models and Computational Techniques. To investiage the adequacy of the available physical models and computational technqiues to accomplish the above objectives.

7. Recommended Sensor Configuration. To recommend additional sensors or instrumentation and model and/or computational program development as needed to accomplish the above objectives.

8. Prepare an Optimized Orbit Plan. To produce a set of optimized orbit plans for the proposed five satellites to optimize the mission objectives.

4.2.2 General Approach

4.2.2.1 Introduction and Comments

The general approach to investigating the feasibility of attaining the objectives cited above is to conduct parametric investigations for each of the cited objectives. Calculations of the pertinent residuals or variances of the orbital coordinates are made for an input range which brackets the expected parametric variations. These calculations are performed using the Aerospace TRACE A and D programs which are typical of one type of highly flexible and refined orbital calculational program.

The adequacy of any proposed calculational framework to reflect all of the pertinent physical phenomena of importance into an orbital position prediction scheme can be evaluated only a posteriori, by comparisons of the predictions made with such a model with observational data. The adjustments of the coefficients or other variable parameters of the model to give a best computed fit to observational data, and the techniques for improving the accuracy and reducing the computational time to achieve such best fitting, are subjects for research in numerical analysis. Ultimately, however, the adequacy of any model is judged on the basis of the magnitude of the residuals in the "computed minus observed" sense for comparisons between computed predictions and observations taken during the prediction period but not used to evaluate model or orbit parameters.

The computation of residuals requires that actual observational data be available with which computed results can be compared. When such data are available, the calculation of residuals as discussed above is to be preferred. In the absence of such data, however, and for system planning purposes, it is desirable that statistical error analyses (covariance analyses) be performed as aids aids in determining the effect of system changes or proposed modifications and errors in the system parameters. Caution must be exercised in interpreting the results of such analyses, however, inasmuch as the usual assumptions of statistical independence and randomness of errors must be invoked and, even more important, assumptions must be made for the physical models and parameters to be employed in the analyses. Thus, for example, the extent of the ill-conditioning of data for various global configurations of observational data sensors can be fairly well treated by covariance analyses, but no conclusions on the validity of the models or physical assumptions can be drawn.

Another useful analytical technique involves the differencing of orbital ephemerides for variations in orbital models or observational parameters. Such differencing techniques are useful in evaluating the degree to which off-nominal variations affect calculated orbital positions. They also lend to valuable insights into physical model effects, and the effects of biases in station locations or observational parameters. Some of these effects are further discussed in Section 4.9. Root-mean-square values of the difference between ephemerides evaluated for the entire mission period should be used for model evolution. This type of calculation is sometimes called "Monte Carlo" by analogy, since statistics on the variation in nominal orbital positions can be accumulated by repeating the ephemeris differencing process for random combinations of variations in the tested parameters.

In assessing models it is therefore necessary to rely upon the observational data taken for orbiting vehicles and on the experience of groups of investigators who have attempted to reduce the residuals from such observations. Most of such attempts have been made for satellites orbiting at altitudes of 500 miles or more, where the effects of air drag and orbit perturbations due to high degree terms in the spherical harmonic expansion of the geopotential are smaller than at the altitudes of interest here (e.g., the results of the Smithsonian Astrophysical Observatory and Kaula at NASA on Baker-Nunn data analysis for Anna, Echo, etc., and especially the work of Johns Hopkins University Applied Physics Laboratory and Naval Weapons Laboratory on the TRANSIT satellites). Some data have been taken for orbiting vehicles in essentially circular orbits at lower altitudes of the order of 150 miles, but this data was reduced using a truncated spherical harmonic model (e.g., the joint Aerospace-Aeronutronics effort using the TRACE 44 program).

An analysis of the errors due to "observational" contributions for the TRANSIT satellites is given by Newton, Guier, and Weiffenbach.[1]* A distinction is drawn between "observational" errors which contain all of the factors affecting the quantity and quality of the raw data fed into the analytic program and "analytical" contributions. The postional errors due to observational contributions are found to be less than 5 meters for colocated satellite passes. "Analytical" contributions are defined as including phenomena which would affect the analytic results but which are not included in the analysis. Included in this group are such effects as neglected gravity components in the estimates of the gravity field, improperly treated air-drag phenomena, and undocumented vehicle originating forces. It was asserted in this report that the neglected components of the gravity field gave rise to the largest "analytic" errors at the TRANSIT satellite altitudes, and that this situation could be remedied by obtaining and treating more observational data.

The results of past analyses have indicated that, with a reasonable geographical distribution of data stations, satellite orbits with low eccentricity and altitudes of 500 miles or higher may be fitted by calculated orbits with residuals of 50 meters or less along-track using a model incorporating zonal harmonics out to about J_{10}, nonzonal harmonics out to J_{88}, and selected resonance terms of higher degrees. The continued activity in these areas together with the extension and elaboration of the existing models and computational programs, and consideration of the much increased coverage and distribution of data from the photographic systems and auxiliary on-board sensors aboard the GOPSS, tend to give confidence that expanded spherical harmonic expansion models utilizing a sufficient number of resonance coefficients will be adequate to produce the desired residuals, even at the reduced altitudes, if the perturbations due to nongravitational effects can be accurately predicted or measured.

It appears that, of the nongravitional perturbations, air drag and vehicle originating forces may have sufficient uncertainties associated with them for the present satellite and satellite orbit as to suggest the desirability of the inclusion of at least a one-axis along-track accelerometer.

4.2.2.2 Discussion of Approaches

4.2.2.2.1 Satellite Positioning

Orbital computations are usually accomplished by using physical models for the forces acting on the satellite to establish its equations of motion. By comparison with observation, parameters in the model are adjusted so as to obtain a "best fit," usually through a least squares procedure that minimizes residuals. The solutions so obtained are iterated until no further reduction in residuals is obtained. Positioning capabilities are thus investigated by an examination of the residuals resulting from the orbital calculations for a proposed physical model, using orbital

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*References are listed in Section 4.2.5.

position observational data obtained from as many sensors as possible for as many different satellites and orbits as possible over as long a period of orbiting as possible. As discussed in Section 4.2.2.1 the accuracy of the orbital position may be tested by computing residuals for observations which have not been used in the least-squares procedure. Additional tests may be performed by ephemeris differencing orbits computed for physical models which differ slightly from one another, within the bounds of knowledge of physical model behavior (Monte Carlo technique).

Thus positioning can only be investigated by utilizing real data for actual flights, since the calculation of "residuals" and model coefficients requires actual observational data. Very few data of sufficient accuracy and proper distribution were available for the observational networks and satellite altitudes of interest here. An example using the available data for a low altitude satellite observed by the SCF network was investigated, as is discussed in Section 4.8. However, by noting the growth of variances for a complete range of simulated input orbital parameters and simulated data, the adequacy of the calculational procedure (not the physical models, or the data processing procedures) and the adequacy of the observational network to satisfy this objective for a given physical model were considered. The capabilities of the computer program to accomplish these calculations is described in Section 4.2.3 and also in the next section. Typical results of satellite position calculations are discussed in Sections 4.8 and 4.9.

4.2.2.2.2 Six-Hour Orbit Position Prediction Test Criterion

The ability to predict orbital position into the future accurately, using observations made in the past, is considered to be a sensitive test of the adequacy of the physical models and calculational procedures used to define the orbit.

The orbital prediction feasibility was investigated by performing the computations described in Section 4.2.2.1, but continuing the orbital computations beyond some termination time for inserting observational data. The "predicted" orbit was then compared either with observational data taken during this prediction period time (but not included in the orbit calculation) to obtain residuals, or the orbital position covariance matrix was computed from an error analysis. The first method was preferred when data were available. Ephemeris differencing calculations were made for several cases (Monte Carol techniques) for small changes in input model parameters.

In the absence of real observational data, simulated observational data were used. The Aerospace Corporation TRACE program contains the provision for computing simulated data for almost any type of sensor (see Section 4.2.3 and 4.2.4). For a given set of physical model parameters, initial orbit conditions, sensor locations and sensor characteristics, the program will compute simulated data for any period of orbiting. The model parameters to be used are taken from the best values available in the literature and from previous experience, initial conditions are estimated for each parametric orbit to be investigated, and sensor locations and characteristics are taken from survey measurements and manufacturers' data and quotations.

The error analysis section of the TRACE program has provision for computing covariance matrices for orbital position (i.e., for estimating the potential accuracy attainable for a given set of physical models and observational network) given the observational station locations, data type, rates and quality uncertainties in the model parameters, station locations, and the specifications of the nominal orbit (see Section 4.2.3). In addition, an estimate of the potential accuracy attainable in solving for station locations (given the uncertainties in other quantities) or several other parameters is available.

The prediction "feasibility" is then investigated by considering the accuracies required in observational data, station locations, etc. for a given set of orbital initial conditions and observation network using covariance matrices for the simulated observational data, covariance matrices for the station locations, biases, etc. The calculational program computes the covariance matrix for the initial conditions for the orbit fitted to the observational data. This covariance matrix is then updated for later times, assuming any desired period for data taking. This allows prediction to be made after any prescribed period of observations.

The results for one example of this type of calculation are shown in the figure on the following page. Simulated data were computed for the seven station SGLS radar net for one day of orbiting in a circular polar orbit at about 150 nautical miles. Standard deviations of 60 feet in range, 0.05 degree in angle, and 0.1 foot per second in range rate were assigned for all of the observations. Data were accumulated out to $t = 1440$ minutes and the covariance matrix for the initial conditions for the best fitted orbit was computed at $t = 0$. This matrix was then updated as a function of time so as to give the covariance matrix for orbital position as a function of time. In Figure 4-6, in-track standard deviations are also shown for the case where the station coordinates are assumed to be uncertain by 100 feet in the horizontal directions. This curve indicates the importance of having accurately known reference points from which to make observations or, more realistically, illustrates the need for solving for station locations in the final data reduction program for orbital positions and landmark locations. It also shows the typical reduction in variance toward the center of the data-taking period and the rapid growth of the variance during the "prediction" period following the taking of observational data. In this case, the "prediction" period was for 6 hours following one full day of observation. Other calculations are discussed in Sections 4.8 and 4.9.

4.2.2.2.3 Evaluation of Geodynamic Parameters

The determination of geodynamic parameters from observational data is usually accomplished in the course of minimizing the residuals in a differential orbit improvement program. The parameters enter the calculation through the physical models and therefore the comments made dealing with the determination of the adequacy of physical models, also apply here. When the residuals are minimized, then the geodynamic parameters which have entered into this calculation, will also be determined as accurately as the adequacy of the physical model and the observational data allow.

It should be pointed out that there are strong correlations among some of the coefficients describing the geodynamic parameters, especially among coefficients in the spherical harmonic expansion for the gravity potential themselves and among some of these coefficients and air-drag coefficients (if only short observational arcs are used). Much of this correlation can be removed by having observational data for as long as possible from satellites in orbits with appreciably different inclinations. At least four of such inclinations are required, at a minimum, to separate out the various terms from an expansion extending up to J_{88}, and the determination of the zonal harmonics will require even more.

The zonal harmonics of the earth's gravitational field produce a fundamentally different effect on the orbit of a close satellite than do the tesseral or sectoral harmonics. The even-degree zonals produce secular variations in ω, Ω, and M, while the odd-degree zonals produce extremely long-period periodic variations in all elements except the semimajor axis. These long-period variations, completing one cycle in approximately 100 days, would hardly be separable from secular variations during the expected lifetime of 15 days. Therefore, the zonal harmonics which are best determined from observations over a period of several months, should not be parametrized in this solution. Instead, the very best available values for the zonal harmonic coefficients should be imposed upon the solution.

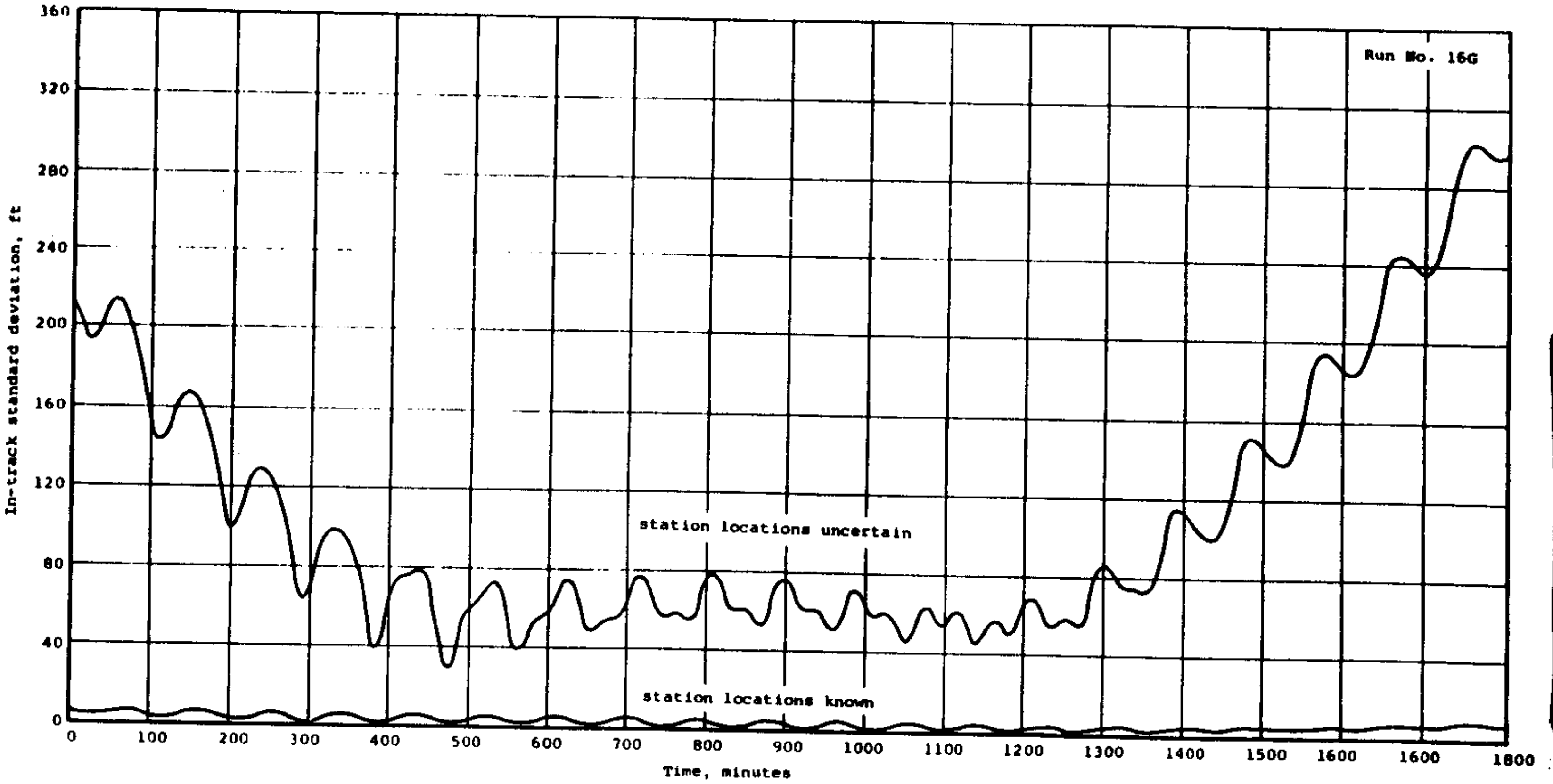
Many critical selected geodynamic parameters will be best determinable from the data collected in this program. For the few remaining parameters, notably the zonal harmonics, the best adjusted values will be taken from the results of other programs. In particular, some of the resonance coefficients and air-drag coefficients which are peculiar to the altitudes being used here should be better defined by this program, as well as some of the higher harmonic terms in the gravity potential, (see Section 4.3.1). Aliasing considerations make difficult the extrapolation of gravity potential coefficients determined at low altitudes to higher altitude orbits. On the other hand, although the low altitude use of such coefficients determined from high altitude data is more valid, the accuracy of determination of high frequency (high degree) terms is reduced at the higher altitudes. In the course of this investigation data has been compiled which could be used to determine the sensitivity of gravitational harmonic coefficient determination to orbital inclinations.

By using the error analysis feature of the TRACE A program, the covariance matrix for any of the coefficients in the TRACE A physical gravity model may be investigated. These include zonal harmonics out to J_5 and tesserals out to J_{44}. The effect of uncertainties in simulated observational data computed with the full TRACE D model, which includes zonals to J_9 and tesserals to J_{66} or uncertainties in any of a number of other parameters in the covariance matrix for the TRACE A gravity coefficients, may be computed. Conversely, the effect of an uncertainty in a gravity model parameter on orbital position uncertainty, can be computed, and tolerances on the allowable uncertainties in these parameters established. By combining both of these types of calculations we may determine the adequacy of any given observational network for the determination of the geodynamic parameters up to at least J_{44}.

Unfortunately, practical numerical difficulties involving the propagation of roundoff errors preclude a complete analysis made in this fashion. It was found, experimentally, that due to these numerical roundoff errors, many of the calculations of uncertainty in orbit postion for uncertainties in gravity model parameters were not well behaved, as was also the case for the calculations of uncertainties in gravity model parameter determination due to uncertainty in the observational data. Some results on the effect of variations in geodynamic parameters on orbital position have been obtained by ephemeris differencing (Monte Carlo) of orbits calculated using different values for the geodynamic parameters. These calculations are reported and discussed in Sections 4.8 and 4.9.

4.2.2.2.4 Datum Ties and Station Location

The evaluation of the accuracy of landmark location must, of course, take into account the interaction and overlap between orbital and photogrammetric analyses. In one extreme case, when the orbit is well defined by observations taken by auxiliary sensors, it can be used as a fixed constraint on the photogrammetry. In the other extreme, when the photogrammetric control is very strong, the photogrammetric measurement can be used to adjust the orbit. In the intermediate situation an integrated analysis of orbital parameters and landmark locations must be used. In particular, when extensive photographic redundancy from a given satellite mission or other satellite missions (especially at other inclinations) is present, both orbit determination and landmark location are considerably strengthened by an integrated, or at least partially integrated analysis. This subject is discussed elsewhere in these reports (see Volume 3 which deals with both the photogrammetric analyses and the data reduction concepts).



Plot of standard deviation of radial component of orbit position error versus time for a 1-day fit to SGLS network radar observations, showing effect of 100-foot horizontal error in station locations. (This plot, shown here for reader convenience, is presented as Figure 4-6 in Section 4.8.1.)

For the purposes of this feasibility study, however, the assumption has been made that it is possible to separate photogrammetric orbital position measurements from the orbital analysis itself. The photogrammetric orbital observations over regions of strong geodetic control are treated as if they were derived from an auxiliary sensor providing independent orbital position information (see Section 4.2.4). This assumption was justified, a posteriori, by finding that the orbit determination was little affected by the photogrammetric data.

Thus, feasibility of determining certain landmarks on the ground to within the accuracies required must be discussed considering the photogrammetric analyses and data analyses covered elsewhere in these reports. However, one aspect of these analyses was done using the error analysis capability of the TRACE program. This involved the calculation of the covariance matrices for station locations (for example, datum locations and the location of auxiliary sensor stations) for simulated observational data using as input uncertainties in the observational data, physical model parameters and biases on the data. The results of these computer runs are discussed in Section 4.8 and 4.9.

4.2.2.2.5 Input Data Requirements

The amounts, types, distributions, and accuracies of observational data necessary to provide sufficient input to make feasible the above objectives was determined in conjunction with investigating the accomplishment of those objectives. The results of these calculations are discussed in Sections 4.8 and 4.9.

4.2.2.2.6 Physical Models and Computational Techniques

As previously discussed, the adequacy of available or projected physical models can only be determined from actual observational data taken for orbiting satellites. A review of these models is given in Section 4.3. A discussion of the various available computational techniques for orbital analysis and of their relative advantages is provided in Section 4.4.

4.2.2.2.7 Recommended Auxiliary Sensors and Other Requirements

The recommendations of additional sensors, instrumentation, and model and/or computational techniques development are partially contingent upon the investigations mentioned above and follow directly from them. For example, it appears from the investigation of uncertainties in air-drag models and in vehicle-originating forces that it will be highly desirable to incorporate at least an in-track accelerometer aboard the satellite. These recommendations are presented in Section 4.11.

4.2.2.2.8 Orbit Planning

The approach to the recommendation of a set of orbit flight plans must be to parametrically investigate the factors affecting the mission objectives as these factors are influenced by orbital parameters, including launch and recovery requirements, and to produce a set of weighted recommendations based upon the possible conflicting results of these investigations. Section 4.10 contains an elaboration of these considerations as well as several detailed orbit plans.

4.2.3 Description of the TRACE Programs

TRACE is an IBM 7090 computer program developed by Aerospace Corporation for use in satellite orbit determination and tracking system analysis and design. This program was generously made available to Itek/Vidya for the current project, and the bulk of the calculations reported below were done with TRACE. A brief description of the TRACE program is presented here. This material has been excerpted from references 2 and 3 (see Section 4.2.5), to which the reader is referred for a thorough treatment of the details.

The applications of TRACE include the following:

1. Simple trajectory and ground trace generation.
2. The calculation of visibility times and simulated observation data.
3. The determination of trajectory and model parameters from observations.
4. An accuracy analysis of a satellite tracking and orbit determination system.

Basic to all applications of TRACE is the satellite trajectory. The trajectory is defined by a set of initial conditions together with the differential equations of motion whose coefficients and parameter values reflect the earth's gravitational and atmospheric forces and those of other bodies affecting the satellite's motion. The trajectory is calculated by numerically integrating the differential equations of motion.

The generation of observation data for a given trajectory is basic to the orbit fitting function of the program. TRACE can handle a wide variety of types of observational data including conventional radar, photo-optical, and interferometer and Doppler tracking data, photogrammetric data of the resection type (by referring observations to an earth-centered X, Y, Z system) and relative intersection or so-called "Q" data, altimeter data, and others. In addition, TRACE can calculate satellite visibility times, given the location and characteristics of the observing station.

TRACE estimates, in the least-squares sense, the trajectory that best fits a set of observations. The trajectory of a space vehicle depends upon the initial conditions of the motion and the differential equation parameters which appear in the equations of motion. From a trajectory one may compute at the observation times the expected values of the observations. These expected values depend also on the locations of the observing stations and biases in the observations. The problem of orbit determination is to solve for the set of parameters that minimizes the differences between the computed and measured observations. TRACE is able to solve for such quantities as the ballistic coefficient (a differential equation parameter) of the vehicle, the location of an observing station, the presence of bias in data from a particular station, in addition to the usual set of initial condition parameters.

The method employed for orbit determination in TRACE is the iterative process of differential orbit improvement. A first guess must be provided for each of the parameters being solved for. A trajectory is generated based on this first guess, and the "computed observations" are calculated along with their partial derivatives with respect to the parameters. The normal matrix of partial derivatives is accumulated, and "residuals" are formed by taking the difference between measured and computed observations. The residuals are multiplied by a weighting factor, and the sum of the squares of weighted residuals is accumulated for all of the observations. A correction to the first guess of the set of parameters is computed by inverting the normal matrix, and when this correction has been applied the whole process is repeated. The root mean square of the weighted residuals provides the measure of convergence of the process.

The accuracy analysis aspects of the TRACE program are based on the fact that under certain conditions the inverse of the weighted normal matrix is the variance-covariance matrix of the solution parameters. These conditions are that the observational model is correct, that the observational errors are independently distributed with mean zero and variance σ^2, and that the weighting factor used is σ^{-1}. With the assumption that these conditions apply, the solution process provides an estimate of the uncertainties in the solution parameters. Insofar as these parameters are differential equation or station or observation parameters, their variances and covariances satisfactorily describe their uncertainties. However, the uncertainties in the motion of the vehicle are not adequately described by the variances and covariances of the inital conditions and other parameters of the trajectory. TRACE has the capability of reporting trajectory uncertainties in several coordinate systems, probably the most useful of which is the orbit plane coordinate system (in-track, cross-track, and radial position and velocity).

A further sophistication arises from the assumption that the value of some of the parameters used in the calculations, but not being estimated by the differential correction process, are also uncertain, thereby inducing uncertainties in the differentially corrected parameters and in the trajectory. (This is a very common situation; most tracking programs do not solve for basic constants and station locations, but their current values must be somewhat uncertain.) Such parameters are referred to as "Q-parameters" in distinction to "P-parameters," which are those being solved for in the differential correction. TRACE will simultaneously report P-parameter and trajectory uncertainties with and without the Q-parameter effects.

4.2.4 Observational Data Sensors and Networks

In the computations that were performed in studying the feasibility of the proposed system, several types of observational data were considered. This section describes the networks of observation sites, lists the assumptions with regard to accuracy and distribution of the data, and discusses the generation of fictitious observational data for simulation purposes.

The SGLS radar network was used. This network is an improved and expanded version of the present Satellite Control Facility (SCF) network, and it is planned that this will be the operational radar tracking and control network at the time that the proposed system will be operating. Locations of SGLS stations assumed in the simulation calculations are given in Table 4-1.

For these stations, the observational data are range, azimuth, elevation and range rate. Standard deviations of the data are 60 feet in range, 0.05 degrees for both angles, and 0.1 feet per second for range rate. For the simulation, observational data were generated, using the data generation option of TRACE, every 30 seconds during the interval that the vehicle was at least 10 degrees above the horizon at each station.

The Navy's TRANSIT network was also used in the simulation. A network of sixteen stations was assumed, with sites as listed in Table 4-2. TRANSIT observations are Doppler frequency shift measurements. The standard deviation of these data, in terms of range rate, was assumed to be 0.5 feet per second. Using TRACE, data were generated for these stations at a rate of one observation per minute, with the restriction of 10 degrees minimum elevation. The areas of tracking coverage from this TRANSIT network are indicated by the shaded areas of the world map in Figure 4-1, for a circular polar orbit of 156.7-millimeter altitude.

The observations from an on-board radar altimeter were also considered. It was assumed that the main use of the altimeter would be over open water areas. Therefore, the data generated to simulate altimeter measurements were restricted to these areas. This restriction was approximately satisfied in using the TRACE program by approximating the outline of the large water areas of the world with a series of circular areas, as shown by the lightly shaded areas in the map of Figure 4-2 (the circles, originally developed on a globe, appear slightly distorted due

Table 4-1 — [redacted]

Site	Latitude, degrees	Longitude, degrees
[redacted]	[redacted]	[redacted]

Table 4-2 — TRANSIT Network Sites

Site	Latitude, degrees	Longitude, degrees
Maryland	39.2	287.1
New Mexico	32.3	253.2
London	51.5	359.9
Sao Paulo	-23.6	313.4
Hawaii	19.5	204.5
Manilla	14.0	123.2
Australia	-34.9	138.5
Japan	40.7	141.3
Kodiak	61.3	210.2
Samoa	-14.3	189.3
Thule	76.5	291.4
South Africa	-25.8	28.2
Seychelle Islands	-5.0	55.0
McMurdo	-77.8	166.7
Ascension Islands	-8.0	345.6
Cocos Islands	-12.0	96.8

to the map projection). The simulated data were then generated in TRACE by using suitable minimum elevation angles for fictitious stations located at the centers of the circular areas, the elevation angle depending on the radius of the circle and the altitude of the satellite. The data rate for the altimeter measurements was taken as one observation every 2 minutes. A standard deviation of 50 feet was used.

A comment should be made about the discrepancy in the data rates that have been assumed for the simulation and the actual data rates possible with the sensors listed. The actual rates are much greater than those assumed. The assumed figures have been chosen to keep a balance between the relative weighting assigned to the different data types due to the quantity of observations. The assumed values also reflect the editing and data compaction procedures necessary to control the quality of the data and eliminate large noise effects. For orbit determination in the proposed system, the quality, distribution, and type of data are more signficant considerations than the quantity of data which is presently available from the sensors discussed above. The high redundancy of 2 data type tends to obscure the effectiveness of the data type in fitting an orbit due to the high correlation of errors of observations spaced closely in time. Hence, the assumed data rates were taken to be much smaller than the actual rates at which the sensors are capable of making observations.

Data from the primary sensor of the system was also simulated. Photogrammetric data of the resection type were handled by the TRACE program in the form of position coordinates in an earth-fixed Cartesian coordinate system. Two restrictions were imposed on the generation of photogrammetric data: (1) that observations be made only over land areas where geodetic control was already well established (excluding the Russian and Chinese domains, see Volume 3), and (2) that the area over which a photogrammetric observation was to be made must be illuminated with a sun elevation angle greater than 19 degrees. The first restriction was imposed in a manner similar to that used in restricting altimeter data to open water areas. The regions of good geodetic control were approximated by circular areas, as shown by the darkly shaded areas in Figure 4-2. Fictitious observation stations were associated with the centers of each circular area, and photogrammetric data (values of x, y, z) were generated whenever the satellite was within the "field of view" of this station. The field of view, or more specifically, the minimum elevation angle, for each station was computed from the radius of the circular area and the satellite altitude. The second restriction, solar illumination, was imposed by hand selection of the data cards generated by the TRACE program. A data rate of four observations per minute was chosen on the basis of the nominal orbit altitude of 160 nautical miles and triple overlap of the elongated format. A standard deviation of 30 feet in each direction was assumed, as a working hypothesis. Concurrent analyses, as discussed in Volume 3, have since showed that the assumption of 30-foot standard deviations was conservative but not unrealistic.

The amount and distribution of tracking coverage obtained with the three foregoing data types is indicated in Figure 4-3 for a polar circular orbit of 156.7 nautical mile altitude. In this figure, the number of observations in a 10-minute interval are plotted as a function of time for each data type for a typical day of orbiting. This figure indicates the way in which the photogrammetric, altimeter, and TRANSIT networks complement each other.

Several other tracking networks were originally considered but were not used in this analysis for various reasons. For example, the Army SECOR system promises to be a very useful network; however, there is some question as to the number and availablity of SECOR installations for this program. Similarly, various optical (e.g., Baker-Nunn) and radar tracking facilities will either not be available or will yield sparse, poorly distributed or inaccurate data which will probably be of doubtful value compared with the tracking networks included in this study.