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FEASIBILITY STUDY FINAL REPORT

GEODETIC ORBITAL PHOTOGRAPHIC SATELLITE SYSTEM

VOLUME 1 PROGRAM COMPENDIUM AND CONCLUSIONS

JUNE 1966

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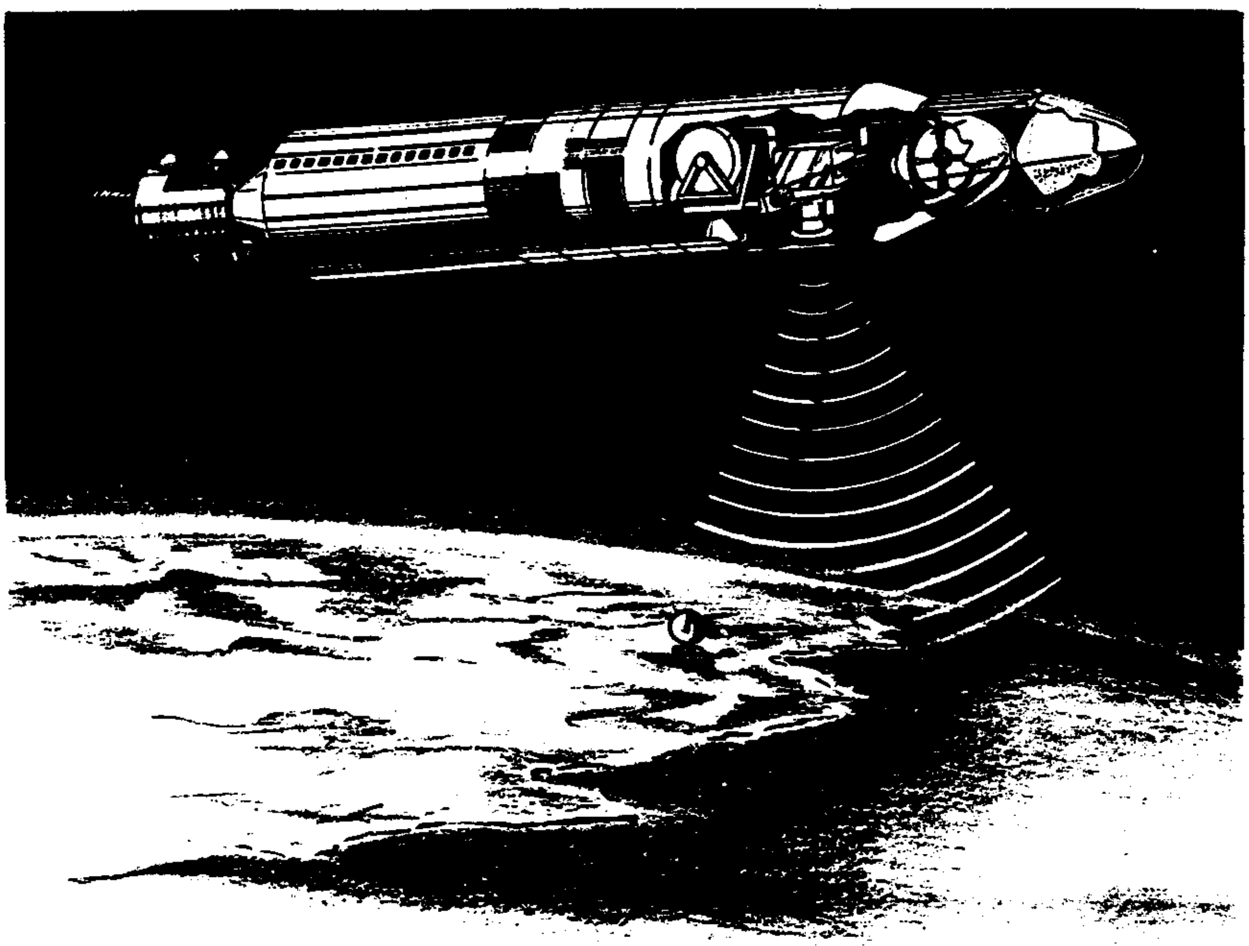

Geodetic Orbital Photographic Satellite System

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PREFACE

The objective of the Geodetic Orbital Photographic Satellite System (GOPSS) is to determine accurately 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 the 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 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.

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

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, the mapping capabilities of the system, and ground handling of mission photography.

Volume 4, Data Processing, Part 2, discusses orbital considerations affecting the feasibility of the GOPSS. Physical models and computational procedures are reviewed and error studies involving typical sensors 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 reduced to yield geodynamic parameters and landmark locations, is considered.

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

The feasibility of the Geodetic Orbiting Photographic Satellite System (GOPSS) has been established. The analysis performed has demonstrated that the projected system is capable of providing sufficient, well distributed, high quality data to achieve the system objectives. These objectives are (1) to determine landmark locations over the earth's surface with planimetric accuracies of 200 feet and elevation accuracies of 40 feet with respect to an earth-centered reference system, and (2) to improve the state of knowledge of the geophysical parameters of the earth including especially the gravitational field of the earth, atmospheric density, and density fluctuations. The studies reported here have shown that the elevation requirement is the most difficult objective to satisfy; however, the achievement of the required accuracies will be ensured by the utilization of the redundant data which will be available from this program.

The program objectives will be achieved by implementing a data gathering phase in which a metric camera will photograph all continents and islands, and in which data will be collected from auxiliary satellite sensors and ground-based tracking instrumentation. Camera orientation will be obtained from two stellar cameras. An integrated data reduction operation will be performed to compute the vehicle orbit while simultaneously providing the location of selected landmarks and pertinent geodynamic coefficients.

This volume summarizes the results of the Phase I studies to investigate the feasibility of the GOPSS and to provide a preliminary design for the data collection system. The photogrammetric and orbital feasibility studies performed to investigate the concept and the derived conclusions are discussed in this volume. The suggested data reduction plan is summarized, and typical orbital plans for the proposed missions are discussed. A description of the preliminary design of the proposed vehicle and components is given, and plans for follow-on phases of work on the system are presented.

1.1 INTRODUCTION

The GOPSS bridges the gap between the target surveillance systems and the purely geodetic systems. Specifically, it is a system of cameras supported by tracking and auxiliary sensors which provide data that are incorporated into the data reduction scheme. This system has been considered as a photogrammetric problem in which the solution is constrained to the various auxiliary and orbit tracking data.

The primary objective of the GOPSS, that of producing an accurate landmark catalog, requires that data be acquired from a system of instrumented close-earth satellites and from ground-tracking networks. Thus, these data consist of two distinct sets: The first set contains accurate tracking data obtained from ground-based observing stations; the second set consists of photography and mission data recordings recovered from the instrumented satellites.

These data are refined and subjected to an integrated data reduction scheme to furnish the coordinates of the selected landmarks. This computational scheme determines the orbital parameters of the satellites, and, in so doing, provides a means of determining the geophysical parameters and other forces affecting the satellite orbits. This satisfies the secondary objective of the GOPSS, namely, a more accurate solution of those geodynamic terms which presently are not well known.

If it were only necessary to determine the orbital parameters and the specific values of the perturbing forces, tracking data alone would be sufficient. The determination of landmark locations requires the use of photogrammetric techniques. Knowing the orbital positions of the camera exposure stations, adequate coordinates of landmarks can be obtained. However, since both the orbital and photogrammetric results are based on observational data, the orbit determination and the reduction of landmark coordinates are best accomplished by an integrated adjustment of all observation data to preclude discrepancies between terrestrial and orbital positions, and also to provide for the most accurate results.

The feasibility study, designated as Phase I, has examined the quantity and quality of various types of data that might be obtained to provide accurate orbital positions, and has determined the optimum system necessary to support the photogrammetric camera. The density and accuracy of the tracking data have been examined to determine the inherent accuracies in orbit determination by a detailed orbit simulation using the Aerospace Trace D program. This study investigated the ability of the TRANSIT Doppler tracking network and the SLGS radar network supplemented by photogrammetric and auxiliary data to establish the required precision of orbit determination.

A need for auxiliary data was established by the orbit and photogrammetric analyses. Low-g accelerometers to define the nongravitational forces and a radar altimeter to provide elevation control to the photogrammetry were considered for inclusion within the data acquisition system. An altimeter, in addition to supplying necessary constraints to the photogrammetry, also provides data for determining geoid undulations when traversing oceanic surfaces.

A practical data reduction system which appropriately weighs the required ground tracking, photogrammetric, and auxiliary data sources is then required. The computer program developed within the data reduction scheme will permit a least-squares adjustment of the observation data from all sensors and furnish precise orbital ephemerides, geodynamic parameters, and landmark locations.

The relationship between the acquired data and the subsequent reduction of these data is conceptually presented in Figure 1-1. This is not the actual flow of data within the computational scheme; however, it is indicative of the considerations that were required during the feasibility study.

With the required satellite and ground-based instrumentation defined in the orbital and photogrammetric analyses, a preliminary design of a satellite configuration employing the recommended sensors was developed, plus a program plan for converting the results of the feasibility study into an operational system.

This study, then, has been concerned with the basic factors limiting the system objectives: their impact on the camera design and acquired data; the various acquisition devices that might be included in the instrument package; the system optimization and packaging; and the required data reduction techniques.

To expedite this study, the major program tasks have been separated into the disciplines of orbital analysis, photogrammetric analysis, and optical design and camera system engineering. These disciplines were integrated in a system engineering activity to ensure that all interpendencies were investigated and optimized.

Since the orbital and photogrammetric analyses are interdependent, the structure of this volume will consist of the following ordered sections.

1. Specific problems and solutions encountered in the data processing task, subdivided according to orbital analysis, photogrammetric analyses, orbit planning, and data reduction.
2. A brief description of the data collection system
3. A brief description of the planned activities for Phases II through V for implementing the preliminary design of the GOPSS into an operational system
4. Conclusions of the results of the Phase I Feasibility Study

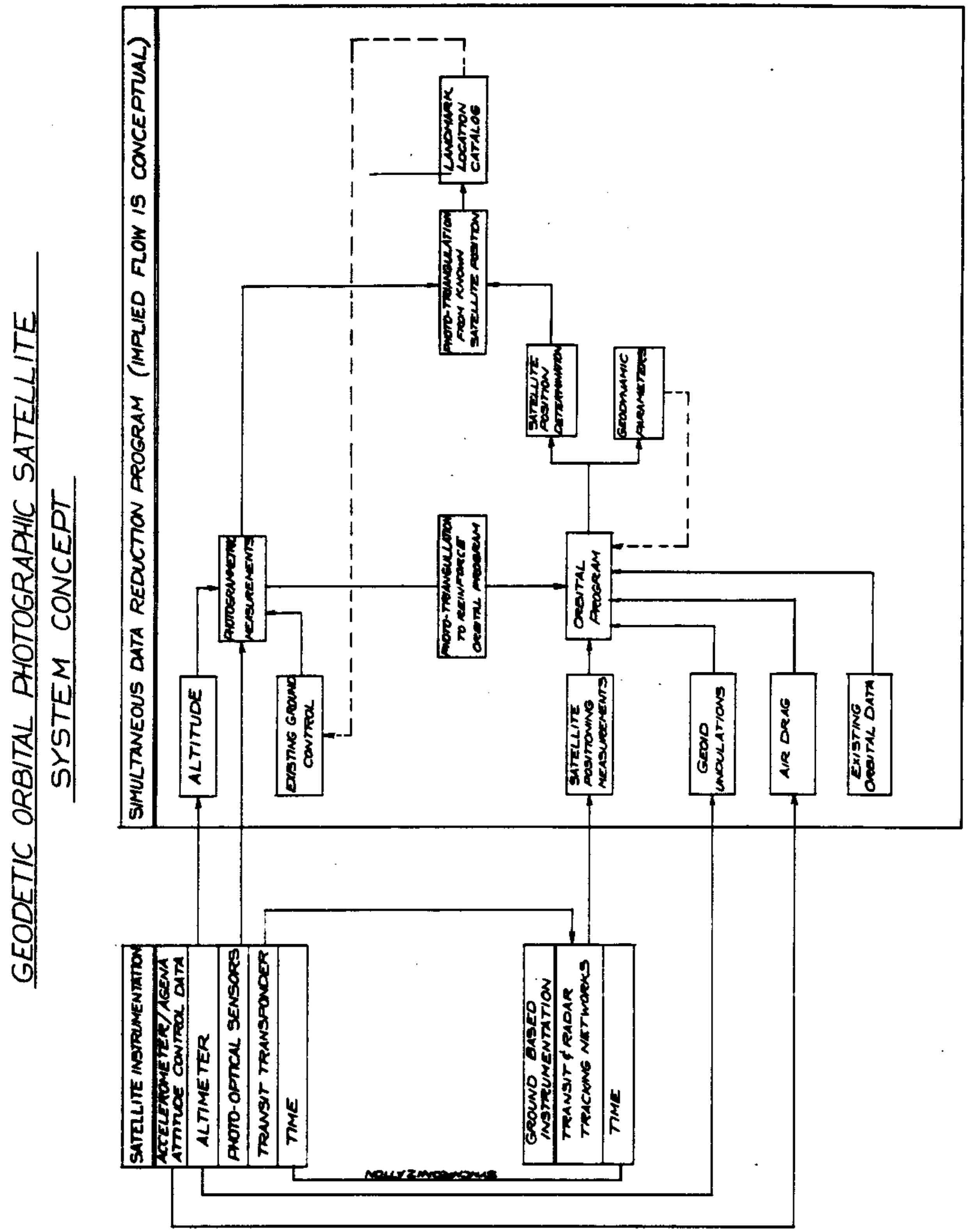

Fig. 1-1 — Geodetic Orbital Photographic Satellite system concept

1.2 DATA PROCESSING

1.2.1 Introduction

The GOPSS program can be treated as two independent computational 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 be involved, 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 was not completely available at the time of this study, and it is apparent that only partially integrated analyses could be performed in this study. If, by proceeding with partially separated calculating schemes, as mentioned, it is concluded that meeting the specification is feasible, then the final data reduction involving complete integration would more strongly re-enforce this conclusion. The analyses which are summarized below were based on such an approach.

In the following analyses, the camera positioning and landmark location requirements could be treated as a photogrammetric problem, subject to functional constraints and constrained to various auxiliary and orbit tracking data. This assigns the photogrammetric subsystem the primary role. This is the approach taken in the photogrammetric studies discussed below. However, this is only a specific aspect of the overall data reduction scheme, and, provided that the correct functional relationships are enforced, it is irrelevant. In other words, the same data could be equally viewed as an orbit determination in which the photogrammetric data are a minor set of tracking information. The last approach is the one used in the orbital analyses which are summarized in the next section. It is important to recognize, however, that the separation is only a convenience used for studying and discussing the feasibility of the system, and that an integrated approach will be taken in the final data reduction program.

1.2.2 Orbital Analysis

1.2.2.1 Objectives

The objectives of the orbital analysis conducted for this feasibility study were as follows:

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 in track and cross track, and 40 feet in altitude), using realistically attainable observational data obtained during the period of observation comprising the mission flight time.

2. Evaluation of Geodynamic Parameters. To determine the feasibility of evaluating the geodynamic parameters of the earth (including the undulations of the geoid) which are used in the various physical models used in the above orbital calculations. These geodynamic parameters are to be determined from realistically attainable observational data.

3. Recommended Sensor Configuration. To recommend the sensors or instrumentation needed to accomplish the above objectives which include determination of the types, geographical distribution, density, and accuracies of the observations required.

1.2.2.2 Satellite Positioning

The orbital computations were 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 were adjusted so as to obtain a "best fit," usually through a least-squares procedure that minimizes residuals. The solutions so obtained were iterated until no reduction in residuals were obtained. Positioning capabilities were thus investigated by an examination of the residuals resulting from the orbital calculations for a proposed physical model, using orbital position observational data obtained from the sensor systems adaptable to this program. As discussed in Volume 4, 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 best be investigated by utilizing real data for actual flights, since the calculation of "residuals" and model coefficients requires actual observational data. An example of this type of computation using the available data for a low altitude satellite observed by the SCF radar network was investigated, and is discussed in Volume 4. However, by noting the growth of variances, for a complete range of simulated input orbital parameters and simulated data, the adequacy of the available observational networks to satisfy this objective for a selected physical model have been considered.

Effectiveness of photogrammetric data taken over strongly controlled areas, Doppler, and altimeter data in accurately defining orbital position can be seen from the results tabulated in Table 1-1, case 1, where orbital position uncertainties are given as functions of time from epoch, for observations of a satellite in a circular polar orbit, at 156.7-nautical miles altitude. Typical observational uncertainties have been assumed, but the physical models, station locations, biases, etc., are assumed to be fixed and known. Similar results for a circular polar orbit at 225 nautical miles altitude are shown in case 2 of Table 1-1.

The use of photogrammetric data alone is shown in Table 1-1, case 4. It is seen that a fairly realistic set of photogrammetric data, using only 50 percent of the total to simulate cloud cover yields in-track standard deviations of from 38 to 40 feet. Poorly distributed data results shown in Table 1-1, cases 5 and 6 (neglecting cloud cover) can double or triple (100 feet) this uncertainty

Table 1-1 — Selected Computed Results Showing Effects of Observation Errors on Orbit Position Errors

		Orbit Plane Error Components, feet			
Case	Time, minutes	Radial, maximum	In-Track, maximum	Cross-Track, maximum	Comments
1	0	2.4	12.0	8.7	50 percent photogrammetric plus full TRANSIT plus full altimeter 156.7 nautical miles
	720	2.4	9.1	8.6	
	1440	2.4	8.4	8.6	
	1800	2.4	13.0	8.5	
2	0	2.0	11.1	6.0	50 percent photogrammetric plus full TRANSIT plus full altimeter 225 nautical miles
	720	1.9	8.1	5.7	
	1440	1.8	8.2	5.8	
	1800	1.9	11.9	5.6	
3	0	3.4	16.0	23.0	TRANSIT only 156.7 nautical miles
	720	3.4	12.0	22.0	
	1440	3.4	14.0	22.0	
	1800	3.5	24.0	22.0	
4	0	6.6	27.0	7.0	Full set photogrammetric observations
	720	6.7	26.0	6.9	
	1440	6.7	26.0	6.9	
	1800	6.7	30.0	6.7	
5	0	18.0	72.0	22.0	Northern half photogrammetric only
	720	18.0	83.0	22.0	
	1440	18.0	76.0	22.0	
	1800	18.0	69.0	22.0	
6	0	26.0	110.0	20.0	Southern half photogrammetric only
	720	26.0	100.0	21.0	
	1440	26.0	100.0	21.0	
	1800	26.0	100.0	21.0	
7	0	9.4	38.0	9.9	50 percent photogrammetric, 156.7 nautical miles
	720	9.5	37.0	9.8	
	1440	9.5	37.0	9.8	
	1800	9.5	40.0	9.7	

even if the total quantity of data is not appreciably reduced. The effect of adding limited altitude data from the ocean areas reduces the in-track uncertainty considerably to a range of from 29 to 32 feet, as discussed in Volume 4.

The addition of the TRANSIT network data, case 1 in Table 1-1, to the above data taking network reduces the in-track uncertainties even more drastically to a range of from 8.4 to 13 feet. It is evident that the high accuracy and good distribution of the TRANSIT data are very effective in defining the orbit.

The TRANSIT data are not as effective, however, in defining the cross-track position in orbit, as compared with the photogrammetric network (23 feet versus 10 feet, Table 1-1, case 3).

Radial position uncertainties are well controlled by both the TRANSIT network and the photogrammetric network with the TRANSIT network exhibiting stronger control.

1.2.2.2.1 Station Location Errors

The results of the calculations for orbital position uncertainties for various combinations of tracking networks shows the large effect which would be introduced by typical values for uncertainties in the station locations. This effect is illustrated by comparing results in Table 1-1 with those in Table 1-2. Here typical in-track standard deviations due to observational errors alone can be compared with in-track standard deviations for both observational errors and station location errors. Cases 4 and 5 shown in Table 1-2 illustrate this increased uncertainty by comparing the results of radar simulated photogrammetric observations with and without simulated datum location uncertainties.

A typical ephemeris differencing example including randomized station location and datum location uncertainties is shown in Table 1-3, case 1. It is obvious that typical station location uncertainties can increase orbital position uncertainties by as much or more than a factor of 2. This is especially true for the most highly effective tracking networks. On the other hand, this large effect tends to give confidence that it will be possible to better define station locations accurately from tracking data derived from such sources in the final data analysis.

The effect of the altimeter data is its obvious utility in defining the undulations of the geoid over ocean areas, and applications to constraining photogrammetric data over land areas as far as orbit definition is concerned. The utility of altimeter data and/or photogrammetric data will be limited when TRANSIT data are available.

1.2.2.2.2 Bias Effects

The calculation of the effects of biases in observational data on orbiting positioning accuracies was performed by ephemeris differencing orbits obtained using observations with and without biases, respectively. A combined observational sensor network of TRANSIT, photogrammetry, and altimeter was used. Biases in altimeter and photogrammetric observations contributed very little to changes in the calculated orbit presumably because of the overriding effectiveness of the TRANSIT network data. On the other hand, biases in TRANSIT data (range rate) contribute appreciable uncertainties (about -60 to +110 feet) into the in-track positions as well as smaller uncertainties into the cross-track and radial positions.

These results indicate the strong necessity for eliminating biases from the observations by instituting analytical procedures to test for biases in the data, to solve for them, and to eliminate them from the data and, if possible from the original sensors. The final data analysis program

Table 1-2 — Selected Computed Results Showing Effects of Observation and Station Location Errors on Orbit Position Errors, Feet

Case	Time, minutes	Radial, maximum	In-Track, maximum	Cross-Track, maximum	Comments
1	0	14.0	62.0	19.0	50 percent, 156.7 nautical miles
	720	14.0	56.0	19.0	
	1440	14.0	54.0	19.0	
	1800	14.0	60.0	19.0	
2	0	8.6	51.0	19.0	50 percent photogrammetric, plus 10 percent altimeter, 156.7 nautical miles
	720	8.6	40.0	19.0	
	1440	8.6	35.0	19.0	
	1800	8.7	44.0	19.0	
3	0	5.8	31.0	18.0	50 percent photogrammetric, plus full TRANSIT, 156.7 nautical miles
	720	5.8	25.0	18.0	
	1440	5.7	24.0	18.0	
	1800	5.8	33.0	18.0	
4	0	6.6	27.0	7.0	No errors in photogrammetric datum locations (4 datums)
	720	6.7	25.0	6.9	
	1440	6.7	26.0	6.9	
	1800	6.7	28.0	6.9	
5	0	21.0	106.0	27.0	50- × 50- × 30-foot datum location error, (4 datums)
	720	21.0	97.0	28.0	
	1440	21.0	87.0	27.0	
	1800	21.0	117.0	26.0	

Table 1-3 — Selected Computed Results for Four Cases Showing Effects on Orbit Position Errors, Feet

Case	Time, minutes	Radial, minimum	Radial, maximum	In-Track, minimum	In-Track, maximum	Cross-Track, minimum	Cross-Track, maximum	Comments
1	0	- 8	12	30	50	-50	15	Ephemeris differencing station location and datum position errors
	720	- 8	11	- 35	0	-50	+50	
	1440	- 10	7	40	10	-50	+50	
2	0	- 10	+100	- 300	+ 40			Ephemeris differencing atmospheric drag models
	720	- 5	+ 2	- 0	+ 10			
	1440	-100	+100	- 40	+ 400			
3	0	-405	+350	-2300	- 700			Ephemeris differencing gravity models
	720	-250	+300	-3000	-1900			
	1440	- 70	+100	-1600	-2000			
4	0			+ 350	+ 350			Ephemeris differencing gravity models with three higher order resonance terms
	720			150	170			
	1440			300	300			

must also have provision for properly treating biases in the data when solving for geodynamic parameters or landmark locations.

1.2.2.2.3 Air Drag and Ballistic Coefficient Errors

The results of calculations investigating the sensitivity of orbiting position determination to uncertainties in drag forces included error propagation studies (covariance analyses) and ephemeris differencing (Monte Carlo techniques). A 1 percent variation in the ballistic coefficient (W/C_DA = 120) for the 156.7-nautical mile circular polar orbit, using the nominal observation network, yielded standard deviations of up to 250 feet in track. The differences in ephemeris arising from attempting to fit an ARDC atmospheric density model to data generated using the Lockheed-Jacchia model (Table 1-3, case 2) and with W/C_DA = 75 for the same altitude exhibit magnitudes of -300 to +400 feet in track and large radial magnitudes. Cross-track differences are small. Ephemeris differences between cases with a 1 percent difference in ballistic coefficient show differences of -200 to +400 feet in track and +20 to -20 feet in the radial coordinate.

At a higher altitude (225 nautical miles), the results of ephemeris differencing for the two different atmospheric models (ARDC versus Lockheed-Jacchia) show a reduction of a factor of 4 to 5 over lower altitude (156.7 nautical miles). Similar ephemeris differencing for a 1 percent change in W/C_DA at 75 nautical miles shows a reduction of a factor of 4 to 5 over the lower altitude case.

The importance of the air-drag uncertainties is reduced at the higher altitudes primarily because of the lower air densities encountered, hence lower drag perturbation forces, and also because of the increased coverage of the tracking networks. The inclusion of the low-g accelerometer also provides a means for measuring the drag forces, and introducing them into the computational model. It is anticipated that the recommended in-orbit calibration procedure will further enhance measurement of these drag forces.

1.2.2.2.4 Gravity Models

Several ephemeris differencing calculations were performed in order to indicate the magnitude of the effects of gravity model coefficient errors. These calculations indicate the effects of model truncation from J_{66} to J_{44} and J_9 to J_5, differences between two different models (standard TRACE and the NWL-5E-6), and the effects of adding several resonance terms to the standard TRACE model. These calculations were run for fairly low altitude circular polar orbits, i.e., 140 nautical miles for the first case and 156.7 nautical miles for the second and third. The effects of model truncation on orbit position are very severe, where in-track differences of up to 3000 feet are noted. At least equally severe are the differences arising from the use of the different models (Table 1-3, case 3), leading to differences of thousands of feet both in-track and cross-track, as well as the large radial differences. Resonance terms introduce much smaller effects over the short times used in the calculations, but are also not negligible as shown in Table 1-3, case 4.

It is important to point out that the most recent and accurate gravity models which are available today could not be compared in this analysis because of the limitations of the computational program used here. Similarly, proper error analysis could not be performed. It is impossible to assess the validity of any given physical model except by comparison with real data; however, it is expected that comparison of ephemerides calculated using the most recent models would yield much smaller differences.

The calculations performed indicate the strong sensitivity of orbital position determination to the magnitude of higher harmonics in the gravity potential. This sensitivity will permit much more accurate evaluation of these coefficients (assuming that correlating terms such as air drag can be independently evaluated), and hence lead to accurate orbital position determinations. These results also indicate the strong necessity for obtaining the best determination of the various gravity model parameters possible and, in particular, at the altitudes used here since the effect of the higher degree harmonics can be very important. It is thus essential that the capability for incorporating gravity models which include the high degree terms as well as selected resonance terms be included in the data analysis program.

1.2.2.3 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. When the residuals are minimized, 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 to separate out the various terms from an expansion extending up to $J_{[illegible]}$, and the determination of the zonal harmonics will require even more.

It is thus evident that only a few selected geodynamic parameters will be determinable from the limited number of satellite inclinations available in this program and that the best adjusted values for most of the other parameters will have to 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 as well as some of the higher harmonic terms in the gravity potential should be better defined by this program.

Some results on the effect of variations in geodynamic parameters at the 156.7-nautical mile altitude on orbital position have been obtained by ephemeris differencing (Monte Carlo) of orbits calculated using different values for the geodynamic parameters. Typical of these results is the variation of the in-track standard deviation obtained from differencing atmospheric models. In this case (Table 1-3, case 3), observations generated from a Lockheed-Jacchia atmospheric model were fitted to an orbit using the ARDC standard atmosphere. The fitted solution was then compared with the nominal solution obtained with the Lockheed-Jacchia atmosphere, using the ephemeris differencing technique. Although the residual errors in this calculation are outside of the specification (-300 to +400 feet), the use of auxiliary information from the accelerometers will provide sufficient information to reduce the residuals created by the nongravitational forces to the levels illustrated in Tables 1-1 and 1-2.

1.2.3 Photogrammetric Analysis

1.2.3.1 Introduction

The photogrammetric analysis was specifically designed to evaluate certain aspects of the GOPSS. The basic question answered was the accuracy with which landmarks could be located on the earth's surface with respect to an earth-centered coordinate system. In this regard, one of the most important aspects was the accuracy with which the combined orbital and photogrammetric data could be used to determine the positions of landmarks in unknown territory.

In addition to determining the accuracy of locating landmarks, the analysis evaluated the accuracy to which the metric camera could locate the camera station with respect to the centroid of five landmarks imaged on three adjacent photographs.

Several studies were conducted as a prerequisite to the preceding analysis. These included format and overlap optimization necessary for the tradeoff analyses optimizing the lens and camera system designs, and an assessment of the quality of the photographic measurements.

The photogrammetric computations were constrained to orbital parameters. Auxiliary data such as radar altimeter and stellar-determined orientations also were imposed on the solutions as if such data had been preprocessed to furnish values and accuracies for certain parameters. Although a completely integrated data reduction scheme could not be performed during the course of this study, the orbital simulation utilized photogrammetry and tracking data in the computation of orbital covariance matrices that were imposed on the photogrammetric studies.

Throughout these studies, it was assumed that timing accuracies were limited by a standard error of 1 millisecond. These errors were assumed to be uncorrelated and therefore represent an absolute positioning error on the orbital path. Relative inaccuracies between the time of exposure at adjacent camera stations may be considered negligible, since this time will be almost perfectly correlated. This means that no matter what accuracy the individual times might have, the relative times of exposure, i.e., the difference between successive times will be of orbitally exact.

One other study performed under the photogrammetric task was the possible application of the GOPSS photography to the production of maps.

The various analyses performed as photogrammetric tasks were:

1. The determination of the accuracy with which landmarks could be coordinated, with respect to an earth-centered coordinate system
2. The accuracy with which the photogrammetric camera could locate the exposure station, with reference to the centroid of five landmarks
3. The accuracy with which the photographic data could be extracted from the photographs
4. The optimum photographic overlap
5. The mapping capabilities of the GOPSS photography

The results of these analyses are now briefly described.

From the tabulated data in Table 3-10, it is derived that the horizontal accuracies of landmark locations can be maintained to a level of ±200 feet, even when the orbital covariance matrix is multiplied by a factor of 100. Vertical accuracies, on the other hand, are not maintained within the desired ±40-foot accuracy, unless additional elevation control is provided to the photographs.

Additional computations enabled the positioning capability of the camera to be evaluated, with respect to the centroid of five landmarks, and with respect to known control points. These data are listed in Table 1-4.

Table 1-4 — Accuracy of Camera Station Determinations in Meters*

Conditions		120 Nautical Miles			160 Nautical Miles			200 Nautical Miles		
Weight	Altimeter	Cross Track	In Track	Elevation	Cross Track	In Track	Elevation	Cross Track	In Track	Elevation
$0.075/n^2$	No	11.4	12.6	10.9	15.1	17.3	14.4	17.6	19.8	16.9
$0.075/n^2$	Yes	11.4	12.5	7.1	15.0	17.2	8.2	17.5	19.6	9.0
$(0.166/n)^2$	No	7.4	8.2	7.1	9.8	11.2	9.6	11.3	12.9	11.0
$(0.166/n)^2$	Yes	7.4	8.2	4.7	9.8	11.2	5.4	11.2	12.7	6.0

*Considered as the centroid of five landmarks known to ± 1000 feet. Angular orientations known to ± 5 arc-seconds.

NOTE: This table also appears in Volume 3 as Table 3-12.

One further calculation performed evaluated the relative accuracy with which vertical and horizontal positions could be determined with respect to some point within the photogrammetric model. These data (Figure 3-4), indicate that relative accuracies in the order of ±40 feet are maintained at horizontal distances of 140 nautical miles.

Due to the extensive amount of photogrammetric data expected to be available from each mission, analyses were also conducted to evaluate the ability of the photogrammetric data to determine landmark locations and orbit parameters with respect to known ground control in the same local geodetic system.

The computational programs for this exercise were basically constrained strip triangulations.

The detailed analysis of the extensions has shown that the system specification can be maintained with and without altitude data in all areas where trilap is available, and if adequate control points are provided in the first frame. With the inclusion of the altimeter data into the extensions, improved elevation control is anticipated although planimetric errors will not greatly exceed those without the altimeter data (see Table 3-17 - Maximum Errors in Landmark Location at an Altitude of 160 Nautical Miles).

1.2.3.2 Landmark Location Accuracy

The evaluation of the accuracy of landmark locations takes into account the interaction between orbital and photogrammetric parameters. In one extreme situation, if the orbit is exactly defined by ground tracking data, it will be used as a fixed constraint on the photogrammetric determination of landmark locations. On the other hand, if only accurate ground control exists, the photogrammetric solution for location of camera stations can be used to adjust the orbital parameters. For the intermediate situation, which exists in practice, an integrated reduction of orbital parameters with the photogrammetric reduction is performed. When extensive photographic redundancy from a given satellite mission or from multiple missions (especially at other inclinations) is present, both orbit determination and landmark location are considerably strengthened by an integrated analysis.

A set of orbital covariances was generated in a simulated orbit reduction, utilizing both ground tracking data and photogrammetric data acquired over a 24-hour period. These data were contaminated by typical errors in tracking observations and ground station locations. The data were then applied to the photogrammetric computations to evaluate the capabilities of the system to locate photo-identifiable landmarks in areas where no ground control exists, and in areas where ground control is available.

The ability of the system to locate the positions of landmarks with respect to the orbit, over areas with no known control, is described in Table 1-5. In this calculation, the orbital covariance matrix was subsequently degraded by factors of 10, 100, and 1000, and showed that the orbital errors combine with the photogrammetric errors in a root-sum-squares manner.

1.2.3.3 Residual Data Extraction Errors

The desirability of maintaining reduced photo-coordinate measurements to a one-sigma value of 4 microns requires that the corrections for systematic errors within the camera system and the processing equipment be well controlled. The major components of the linear error model contributing to this total error are due to camera calibration, film distortion, camera mechanism errors, resolution, and comparator calibration errors.

Table 1-5 — Average Photogrammetric Errors on Landmark Location

Altitude, nautical miles	Cross-Track Error Average, feet		In-Track Error Average, feet		Elevation Error Average, feet		Orientation Error	
	Without Altimeter Control	With Altimeter Control	Without Altimeter Control	With Altimeter Control	Without Altimeter Control	With Altimeter Control	Average Error, arc-seconds	Range of Error, arc-seconds
120	± 29.9	29.9	± 32.4	31.6	± 56.5	36.8	±4	2.8 to 4.2
160	± 39.7	39.4	± 42.9	42.0	± 76.8	42.6	±4	2.6 to 4.2
200	± 58.9	48.5	± 50.9	50.9	± 87.8	46.6	±4	2.7 to 4.2

In the lens design task, distortion minimization has been sacrificed for maximization of resolution to improve the information content of the exposures. Image motion compensation is also included in the terrestrial camera adding further requirements for measurement of the location of the film in the focal plane of the lens. A reseau grid and fiducial markers have been included to provide precise orientation of the film to the optical system during exposure.

A detailed analysis of the camera system derived a 1.6-micron error contribution from lens, color, and mechanism effects. With regard to camera resolution, performance will be desirable at low sun angles; therefore, a 2.3-micron residual was estimated for the 30 lines per millimeter performance on the EK 3400 film. Additional analyses have determined the values of the remaining component errors in the total system.

The net effect of these errors are tabulated below:

	Magnitude microns
Film distortion	±1.5
Camera mechanism errors	±1.6
Camera calibration	±1.5
Resolution and pointing error	±2.3
Comparator calibration	±0.5
Refraction	±0.6
RSS	±3.6

1.2.3.4 Overlap Optimization

The basic objective of this program is to determine the optimum percentage overlap between consecutive exposures. This was accomplished by considering five sets of three consecutive photographs, in which the percentage overlap increases by increments of 5 percent from a minimum of 55 to a maximum of 75 percent. Ground control points were selected in the stereo-model such that the optimum geometric strength was afforded in each case. It was concluded that the most efficient overlap compatible with accuracy and film requirements was 67 percent.

1.2.3.5 Mapping Capability

The mapping capabilities of the GOPSS photography indicate that horizontal accuracies can be met for mapping on scales of 1:50,000 and smaller (see Table 1-6). Elevation accuracies are sufficient only for mapping at a scale of 1:75,000 or smaller, unless additional elevation or supplementary high resolution photography is incorporated into the mapping system. This high resolution photography should have a ground resolution in the order of 8 feet to meet the contouring and information content requirements for 1:50,000 scale map making.

1.2.4 Data Reduction Plan

The concept to be employed in the data reduction scheme is that of simultaneously adjusting data from all sensors. This approach may not appear to be justified when the precision of orbital positions obtained from Doppler alone are considered, since these data indicate that the orbit determination can be effected with only range rate data within the position tolerances specified in this program. For this reason, the Doppler tracking data is considered to be the prime means for

Table 1-6 — Landmark Locations

Orbit Error Scale Factor	Auxiliary Data	Altitude, nautical miles	Cross-Track Error, feet	In-Track Error, feet	Elevation Error, feet
0		160	40	43	77
100		160	49	180	190
1	Altimeter	160	39	42	43
1	Altimeter	200	49	51	48
1	Ground control	160	25	32	43
1	Ground control plus altimeter	160	24	28	28
1	(Orbital extension 15th model)	160	26	30	49

orbit determination. The orbit determination analyses conducted did not include simultaneous adjustment of all possible sources of error. Therefore, results may be somewhat optimistic since they require that air drag and higher degree gravitational harmonic coefficient uncertainties be almost negligible. These assumptions were based on the inclusion of a sufficiently sensitive and highly reliable accelerometer in the orbiting vehicle, and a sufficient distribution and density of high quality tracking observations for a variety of inclined orbits. The further insurance obtained from a computer program which permits simultaneous adjustment of data from all sensors is therefore desirable.

With Doppler and accelerometer data being immediately available from a mission, this program is so designed that a preliminary orbit determination can be accomplished long before any photogrammetric data is available Altimeter data could then be added on a limited scale, and its contribution to the total adjustment evaluated.

The program illustrated by the accompanying flow diagram, Figure 4-60, performs a rigorous least squares adjustment of observation data from all system sensors—range, range rate, altitude, retarding force, and photogrammetric. The parameters to be adjusted are of five types:

1. Orbital parameters
2. Geodynamic parameters
3. Bias parameters
4. Landmark positions
5. Datum shifts

The first two types of parameters fall into the group that are not dependent on a particular tracking station or landmark. The reason for making this distinction between parameters which are station dependent and those which are not is that the two types will be handled differently in the formation, solution, and inversion of the system normal equations.

The flow diagram of the program shows that the system of equations is solved at each iteration, the inversion being performed only once, after the final solution has been completed.

All observations of or from a particular station must be grouped together on the data tape, preceded by a station record which contains data pertaining to the station itself. The end of such data can be recognized by the presence of a new station record. Each observational record will contain:

1. The time of the observation
2. The observed data
3. A covariance matrix of the observation
4. Any required auxiliary data

The observing time is used to compute the position of the vehicle which is a function of time. Various pre-computed perturbations are applied to the vehicle position. The partial derivatives of vehicle position with respect to orbital parameters, geodynamic parameters, and some of the bias parameters are computed in exactly the same manner irrespective of the type of observation being processed. The partial derivatives of the observation equation with respect to the vehicle position, station position, and remaining bias parameters are then formed according to observation type. The product of these two matrices of partial derivatives is the set of partials of observation equations with respect to parameters. It is this product that is required for the formation of the system normal equations.

The data reduction program is designed to utilize the vast amounts of observation data available to compute the most precise orbital ephemerides, geodynamic parameters, and landmark positions possible. Data from all vehicles in this series and all observing systems employed will be combined in a rigorous least squares adjustment for the above parameters. A special partitioning is then applied in order to take advantage of the zeros in this matrix so that the formation, the solution, and finally the inversion can be accomplished by present day computers.

1.2.5 Orbit Planning

The objectives of the orbit plan are to specify a group of orbits which optimize the acquired data necessary to achieve the objectives of the GOPSS. Basically, the orbit or group of orbits will be planned so that the ground swaths swept out by the camera's field of view will cover all land areas of the Earth. Each vehicle will have approximately a 10- to 15-day observational lifetime and at least 5 percent sidelap on adjacent passes. The following paragraphs summarize the major considerations in the orbit plan.

1.2.5.1 Inclination

Valuable constraints on the calculated orbit will be obtained using data obtained from intersecting orbits (Q Data) when the camera observes the same point on the Earth at different times. If possible, the observations should be from orbits where ground tracks are inclined with respect to each other at approximately 90 degrees. In addition, the inclination on at least two flights will have to be in the neighborhood of 90 degrees because of the mission requirement that all land masses, including the Arctic and Antarctica be observed. The remaining flights should be inclined several equally spaced inclinations to aid in determining geodynamic parameters.

1.2.5.2 Cloud Cover Considerations

At any given time, about half of the land masses of the earth are covered by clouds. Average cover is greatest near the Arctic and Antarctic circles, near the Equator, and near some mid-latitude continental shorelines. It is lowest around latitude 30 degrees where air is dried by descent. Diurnal maxima can be expected in early afternoons in the tropics and probably in the morning and evening in temperate latitudes subject to heavy fogs. Yearly minima in temperate latitudes generally occur in summer, but there is a great deal of variability. Storms move primarily from west to east. These factors indicate the following:

1. Redundant coverage of high latitudes in desirable (and inevitable with orbital inclinations near 90 degrees).
2. Summer flights are most apt to give good coverage.
3. Westward diurnal motion of the ground swath is desirable to prevent observing clouds from a given storm for several days.
4. Orbits crossing the equator before noon and higher latitudes around noon are more apt to be free of cloud cover.

1.2.5.3 Launch and Recovery

The combination of cloud cover and illumination conditions presently indicate the following launch and recovery conditions.

Launch times about 10 AM at Vandenberg are probably acceptable for launches near summer and winter solstices. These orbits should be polar or nearly polar. The morning launch both gives acceptable solar angles at the latitude of the sun and improves the chances for minimum cloud cover in the tropics. If there is any departure from a polar orbit, it should be retrograde near June 21, and direct near December 21 to provide better cloud cover conditions in the hemisphere of importance.

Launch times about noon at Vandenberg with southern retrograde orbits are probably best for vehicles launched near the equinox. In these orbits, the equator will be crossed in the morning, while northern latitudes will be crossed somewhat later in the day.

Recovery will be made in the area of Hawaii on a south-going pass in the daylight, at least two hours before sunset. The recovery area is wide enough to ensure at least one appropriate pass in the area each day. One recovery package will be recovered on each of two successive days.

1.2.5.4 Solar Radiation Effects

Solar storm activity may influence the GOPSS in two ways: (1) to increase drag forces and (2) to increase the base fog level of the film through radiation. The 1968 to 1970 era will be the peak period during the present 20-year cycle and prediction of solar activity will be of primary concern. At present, it can be shown that the probability of an event during a 10-day period is over 10 percent. A radiation shield of 5 grams per square centimeter will provide adequate protection to the film; however more accurate prediction, or lower activity allows less of a weight penalty to be incurred.

1.2.5.5 Three Illustrative Orbit Plans

During the feasibility study, Itek generated three orbital plans to aid in comparing the results of orbital parameter choices. The first plan's objective was to provide polar coverage during the summer solstice; the second plan provides a greater redundancy of northern hemisphere coverage, without polar redundance. In addition, it provides the inclined orbit necessary to gather geopotential data and stronger east to west photogrammetric ties. The third plan was generated simply to check effects on coverage overlap or interlacing as a result of higher altitude. Table 1-7 is a list of the particulars of each plan.

It may be concluded that a minimum of two of the planned five GOPSS missions will have to be launched in polar orbits, a month prior to the winter and summer solstice. This would leave a month or more for a second launch during a solstice period in case of failure. Other missions planned with inclined orbits would be necessary to maximize coverage and redundancy in the northern hemisphere where most of the land masses are located and to allow for removing ambiguities in the determination of geodynamic parameters.

Table 1-7 — Particulars of Three Orbital Plans

Plan	1	2	3
Date	22 May to 21 July	22 May to 21 July	18 June
Longitude	120° W	120° W	120° W
Time	Local noon	Local noon	Local noon
Altitude, nm	160	184.57	234.14
Inclination	5° retrograde	25° retrograde	5° retrograde
Nominal velocity, ft/sec	25,354	25,268	25,001
Launch direction	South	South/West	South
Camera duty cycle	13 percent	16 percent	12 percent
Frames per orbit	34.7	37.1	22.8
Number of orbits	257 or 273	193 or 209	172
Number of TRANSIT network sightings	712	556	731
Number of SCF sightings	334	263	336
Period, minutes	90.37864	91.24458	93.1815

1.3 DATA COLLECTION SYSTEM

The data collection system provides the satellite and ground-based instrumentation required to implement the data gathering phase of the GOPSS program.

The photographic satellite system consists of an Agena D orbiting control vehicle (OCV), a data collection module (DCM), and a recovery section (RS). The DCM and the RS have been treated as a single integrated structure which is properly interfaced with the orbital control vehicle. The satellite system is supported by ground-based tracking networks which consist of the Navy TRANSIT Doppler Navigational System and the Air Force Space Ground Locating System (SGLS).

The OCV provides the required on-orbit propulsion, satellite stability, payload power, and mission control. The OCV sensors provide the signals from which the vehicle is stabilized in roll and yaw, and pitched at a controlled rate. The OCV programmer operates the subsystem equipments through the use of mode signals in any one of four data gathering modes. Two additional photosensor signals, V/h and exposure (t_e), are also supplied from the OCV.

The DCM is connected directly to the front of the OCV and contains the photosensor system, radar altimeter, TRANSIT transmitter, and system clock. The DCM also houses the film supply cassettes. The DCM bay is a cylindrical structure of monocoque design, which is thermally insulated and contains fore and aft fiberglass bulkheads for thermal and light-sealing purposes. The payload electronics, radar altimeter, and TRANSIT transmitter are packaged as modular units and mounted to the DCM structure. The radar altimeter antenna is mounted below the film supply cassettes with its axis pointed down along a yaw axis.

The RS is attached to the forward end of the DCM structure. This section contains the recovery vehicles (RV), each with a recoverable film payload. Two RV configurations were developed; the first has the RV's inline along the roll axis, while the second has each RV "canted" 60 degrees from horizontal and aft. The canted configuration eliminates the necessity of adjusting the pitch of the vehicle prior to recovery. Each RV contains a recoverable payload consisting of a takeup cassette with spools for 9½-inch wide terrestrial film and 70-millimeter stellar film, and a recorder for electronic data storage. A combination cutter and seal is mounted on the bulkhead of each RV to cut the film path and seal the RV to ensure a watertight compartment.

The photosensor system consists of a terrestrial photogrammetric camera, and a twin stellar camera which mounts directly to the lens cell of the terrestrial camera, to provide a precise attitude reference for the photosensor system (see Figure 1-2).

The terrestrial camera consists of the Itek-designed, 300-millimeter focal length, f/6.0, wide-angle lens, shutter, IMC drive, platen assembly, film transport assembly, and connecting structure. The twin stellar camera, constructed as a single unit, uses two 250-millimeter focal length, f/1.8 modified Wild Falconar lens assemblies, and is bolted directly to the terrestrial central cell section with the rigidness required to maintain the calibrated knee angles between all three lenses. The stellar lenses are 90 degrees apart, ±45 degrees from the roll axis; they are pointed forward and are elevated 10 degrees with respect to the horizontal.

Lens and camera design factors and environmental factors were analyzed to determine photogrammetric accuracy predictions from all contributing sources. These errors are reflected in an overall system performance estimate.

The detailed photo-optical analysis of the camera system performance indicates that a minimum resolution of 40 lines per millimeter will be maintained at a 20-degree sun angle on EK 4404 and that 30 lines per millimeter will be maintained at a 5-degree sun angle with EK 3400.

The auxiliary equipments required to implement the GOPSS operation are configured into the overall payload package. These equipments are the TRANSIT transmitter for Doppler tracking, radar altimeter, low-g accelerometer, precision clock, and mission data recorder.

Inclusion of TRANSIT transmitter equipment in the GOPSS package provides an all weather means of precise orbit determination. Basically, this unit consists of an extremely stable oscillator which transmits continously two radio frequencies. The generated radio frequencies, modified by the Doppler shift, are received by tracking stations at known locations, and are used to compute, predict, and update GOPSS orbital parameters.

The desirability of placing accelerometers aboard the vehicle stems from the necessity to obtain as much direct information as feasible on the action of nongravitational forces on the vehicle motion. Greater accuracy in the knowledge of these factors yields a greater accuracy in separating the geopotential effects in the data reduction. The accelerometer system selected for this application is a three-axis, miniaturized electrostatic accelerometer (MESA) developed by Bell Aerosystems for NASA. This instrument provides an accurate measurement of vehicle accelerations from 10^{-4} through 10^{-8} g.

The radar altimeter, designed by Space Craft, Incorporated, is a complete on-board tracking system which augments ground-based tracking systems. It provides an accurate measurement of altitude where little or no coverage exists. Altitude measurement to an accuracy of 10 meters provides needed information to control the photogrammetry and to determine geoid undulations over the surface of the oceans.

The mission data recorder stores time, altitude, and other mission data which will serve as inputs in the overall data reduction scheme; it has the capability to collect a large quantity of information in small increments.

The system clock provides the precision timing reference by which all pertinent events can be referred to absolute time. It provides an absolute time reference of less than 1-millisecond error which will be maintained over the entire mission.

Details of the characteristics of the photosensor system, auxiliary sensors, and the ground tracking networks are given in the following subsections.

1.3.1 Photosensor System Characteristics

To establish the required photogrammetric capability, a wide-angle lens has been designed for the camera system and is in fabrication. Lens design progressed through four versions of a 300-millimeter focal length, 80-degree field system. The final selected configuration has three aspheric surfaces, and will yield a 70-line per millimeter AWAR at 1.6:1 contrast on EK 3404 film.

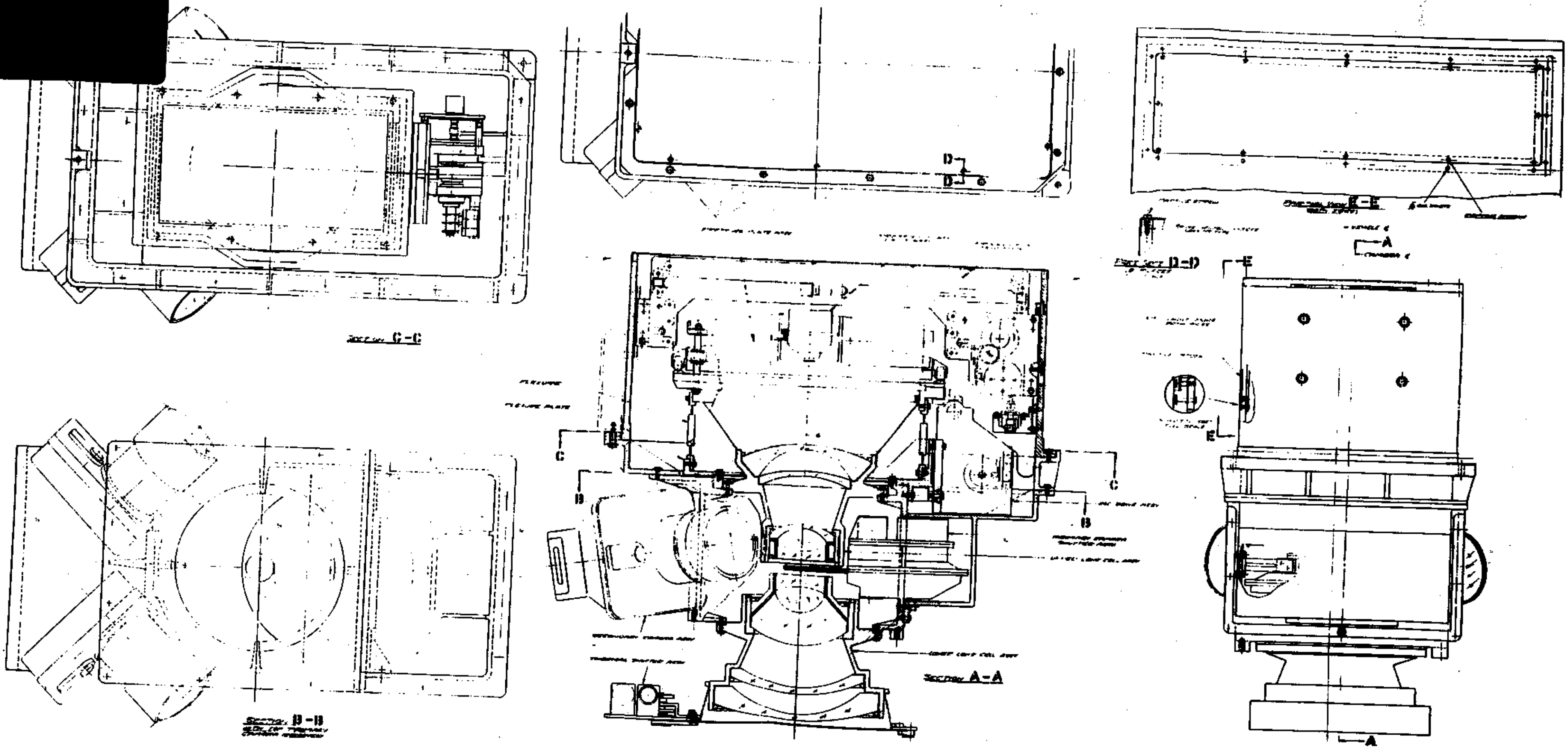

Fig. 1-2 — Primary and secondary camera assembly

SECRET [redacted]

The metric capabilities of the GOPSS are dependent on the resolution of the resultant photography and the ability of the camera system to maintain its geometric fidelity. In the course of the lens design, secondary lateral color blur was found to be proportional to the square of the spectral width. This blur, in addition to causing a loss of resolution, caused the centroid of the resulting imagery to shift as a function of the spectral content of the image. To minimize this effect, the operational spectrum of the system was limited to from 0.6 to 0.7 micron.

An additional benefit was derived from this narrowed spectrum in the form of increased modulation at resolution levels of 20 to 30 lines per millimeter. The characteristics of the resulting photo-optical system are listed in Table 1-8.

1.3.1.1 Resolution Prediction

The operational performance of the photographic systems encompassing the Itek lens is gated by residual image motion errors at the focal plane during exposure. The photogrammetric performance is influenced by the resolution of the photography and mechanism and alignment errors which produce shifts in the centroid of the image. The influence of these errors is accounted for in the ability of the photogrammetry to detect and measure landmark locations within the photographs. In the present configuration, the terrestrial camera resolution has been computed for the 0.60- to 0.70-micron spectral bandwidth (W-25 filter), and the predicted operational blur rates.

Figure 1-3 is a plot of film resolution versus IMC error for the two film types as a function of the on-axis and radial and tangential corner resolutions. Film selection is primarily dependent on the sun angles under which optimum photographic results are to be obtained. Computations indicate that EK3404 is preferred down to a 20-degree sun angle and EK 3400 below 20 degrees.

The resolution across the format at a 160-nautical mile altitude using EK 3400 is plotted in Figure 1-4, as a function of the distance from the center of format. A minimum ground resolved distance of 80 feet is predicted at maximum blur rate conditions in the corners with 42 feet on-axis.

1.3.1.2 Image Position Errors

Metric discrepancy between what is presented to the camera and what the camera records on the undeveloped film was analyzed for the camera systems. Geometry changes likely to arise because of the launch and thermal environments were predicted and the residual position errors after the on-orbit calibration have been estimated. The effects of uncorrectable secondary lateral color error in the lens at wide field angles and film/platen contact irregularities were estimated analytically and experimentally, and the total image position error from these sources was computed as the root-sum-square error of the individual errors.

Calculated results show a one-sigma image position error of 1.6 microns or less at all points in the format. These errors become contributors to the 4-micron error limitation assigned to the metric photography.

1.3.1.3 Photo-Optical System Conclusions

To satisfy the photogrammetric requirements, three fundamental operational characteristics must be satisfied by the photo-optical system. These are:

1. The minimum resolution of the terrestrial camera system must exceed 23 lines per millimeter.

Table 1-8 — Photo-Optical System Characteristics

Characteristic	Final GOPSS Lens Design
1. Focal length	300 millimeters
2. f/number	f/6.0
3. Format	230 by 460 millimeters
4. Total field angle	80 degrees
5. Spectral region	0.60 to 0.70 micron
6. Glass reseau plate	flat
7. Maximum distortion	0.055 inch
8. Minimum relative illumination	40 percent
9. Elements (without reseau plate)	10
10. AWAR on EK 3404	
1.6:1 contrast	70 lines per millimeter
1000:1 contrast	100 lines per millimeter

Conditions:
- 160-nautical mile altitude
- 20 and 5-degree solar elevation
- 1.6:1 contrast in ground scene
- 3400 and 3404 films
- W-25 filter

Curve Designations:
- OA = on axis
- R = radial
- T = tangential
- 45° = 45 degrees to radius

(R, T and 45°: at format corners)

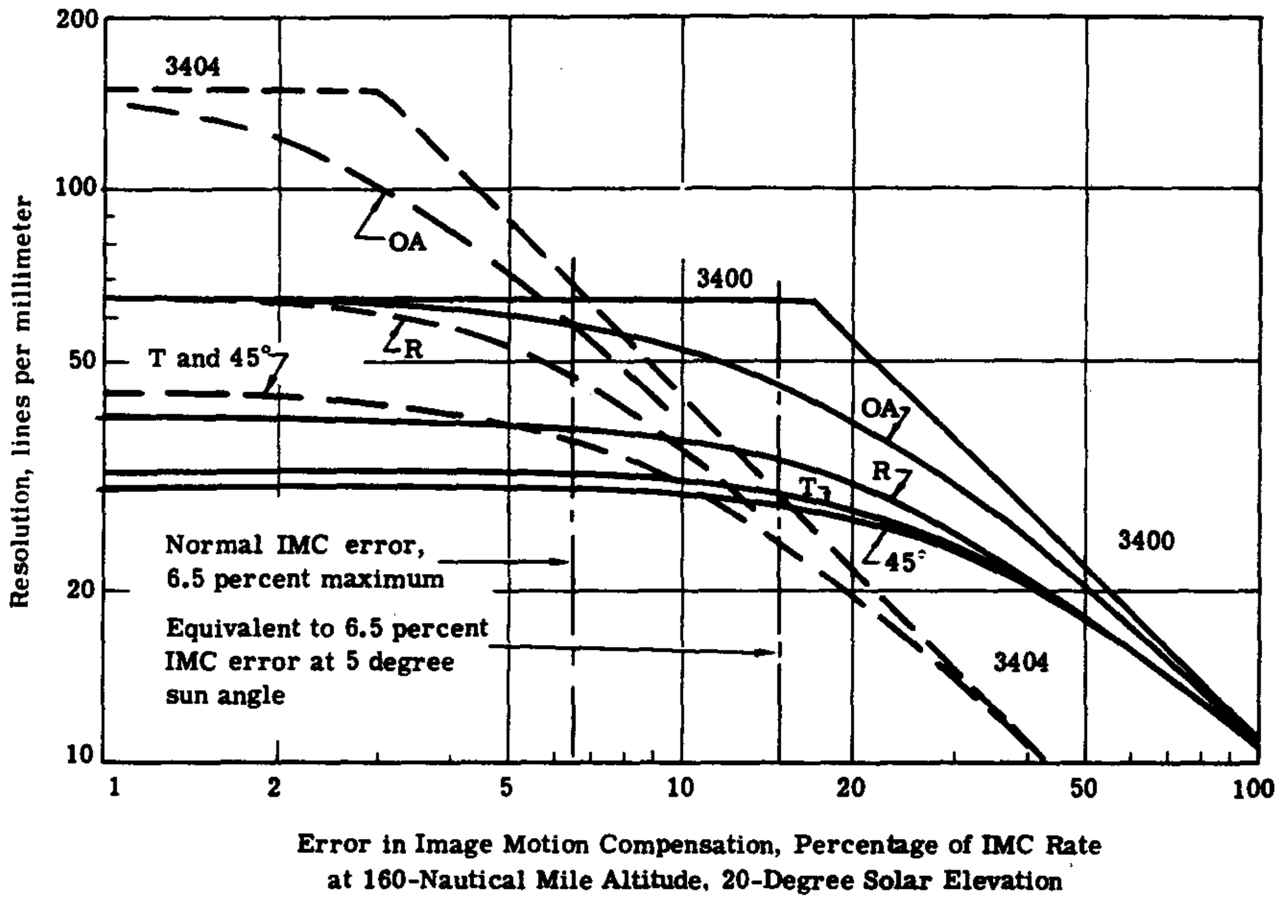

Fig. 1-3 — Resolution versus blur

2. Image motion errors must not exceed 8.5 microns over the exposure period.
3. Image position errors due to mechanism, lens effects, and color must be significantly less than ±4 microns.
4. The stellar cameras must define the pointing accuracy of the terrestrial camera to a tolerance of ±5 arc-seconds.

The terrestrial camera operating with EK 3400 film provides a minimum resolution in the corners of 30 lines per millimeter including predicted image motion errors. The predicted 1-σ blur for the system is 4.3 microns along-track and 5 arc-seconds pointing error, based on the recorded star population, mechanical alignment, and thermal shifts. As previously noted, the camera system performance is based on the use of EK 3400 film. If resolution at low sun angles is not considered imperative, then the use of EK 3404 film will provide a minimum operational resolution of 40 lines per millimeter over the entire format.

1.3.2 Auxiliary Sensors and Ground Instrumentation

To enhance the orbit determination computations and provide additional data on the forces which affect the satellite motions, auxiliary instrumentation (radar altimeter, precision clock, accelerometer) has been evaluated for use with the GOPSS. Error budgets and measurement capabilites of these sensors are summarized in the following paragraphs.

1.3.2.1 Radar Altimeter (Space Craft, Incorporated)

The radar altimeter provides altitude control for the metric photography and determines geoid undulations over the surface of the oceans. Analysis of the reflected radar pulse at an X-band has shown that a variation of 20 decibels in signal will result from the various terrains encountered as shown in the following tabulated data.

Normalized X-band Radar Cross Section

Desert: -12 decibels
Meadow: -15 decibels
Forest: -10 decibels
Sea: +5 decibels

The major error contributors to the altimeter system may be summarized as follows:

Counter gate errors		±5 meters
AFC jitter		±1 meter
Echo pulse rise time degration		±7.5 meters
Least significant bit		±3.5 meters
	RSS	±9.7 meters

The proposed sampling rate for the altimeter is one sample every 15 seconds where transmission occurs for approximately one second. The information bandwidth is sufficient for mapping of the geoid and this mode of operation minimizes the energy storage requirements.

1.3.2.2 Accelerometers

Nongravitational forces (see Figure 1-5) such as air drag (10^{-5} to 10^{-8} g) and vehicle stabilization (10^{-8} g) introduce significant errors into the orbit determination if not measured and accounted for in the computations. The proposed BELL MESA three-axis, low-g, accelerometer configuration provides in a single assembly the capability for measuring these forces through the entire range of interest. This unit is an electrostatically suspended and electrostatically pulse-rebalanced accelerometer. The following is a tabulation of the principle characteristics which would affect the GOPSS mission.

Dynamic range — 10^{-4} to 10^{-9} g
Accuracy — 10^{-8} g
Sampling period — 0.1 sample/second

1.3.2.3 Precision Time Standard

A Sultzer precision clock provides to the system a prediction time standard which can be calibrated prior to launch and will maintain the time standard to an accuracy of one millisecond over the entire 15-day mission.

Clock frequency	5×10^6 cycles/second
Stability	5×10^{-9}
24-hour deviation	0.5 millisecond
15-day deviation	1.0 millisecond
Precision	0.1 millisecond

The accuracy of this clock will be checked by inflight interrogations, so that the necessary corrections can be analytically applied in the post flight data reduction.

1.3.2.4 Navy Doppler Navigation System (TRANSIT)

The Navy Doppler system provides to the GOPSS program near real-time orbit determination and a permanent record of the satellite motions as observed by the ground tracking network. Orbit determination is established by precise measurement of the Doppler frequency from two transmitters located on the satellite. Major errors and characteristics contributing to the computations are tabulated below:

Station Location Error

X, Y, Z — 15 meters/50 feet

Effective velocity error — 1.3 feet/second

Velocity measurement error

Present — 0.5 feet/second

Predicted — 0.05 feet/second

Sampling rate — 0.5 samples/second

Observation angle — 10 degrees above horizon

Number of stations — 16 utilized in computations

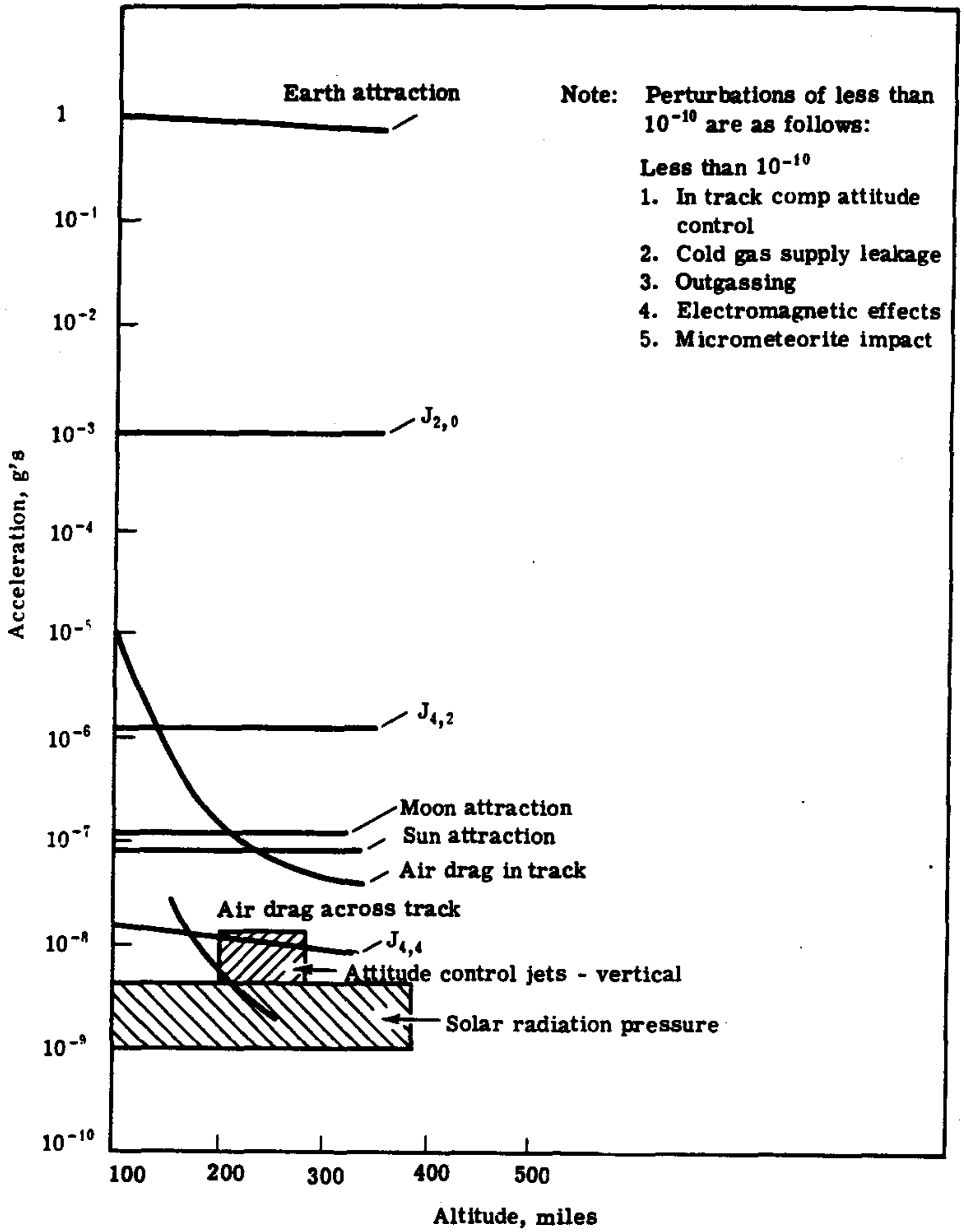

Fig. 1-5 — Relative magnitude of perturbations

1.3.2.5 Space Ground Locating System (SGLS) Radar Network

This network is an improved and expanded version of the Satellite Control Facility network planned to be operational when the GOPSS program is operating.

Tracking Capabilities

Range	±60 feet
Azimuth and elevation	±0.05 degree
Range rate	±0.1 foot/second
Coverage	10 degrees above horizon
Number of stations	7 (well distributed)

The range rate measurements from this network are most significant and provide the most favorable means of determining the orbit from this sensor system.

1.4 PHASE II THROUGH V PROGRAM PLAN

The Phase II through V Program Plan describes the implementation of the results of the Phase I software feasibility study into an operational payload configuration to accomplish the objectives of the GOPSS program. Figure 5-2 is a family tree of the payload configuration.

The various segments encompassed in this task are design breadboarding, fabrication, integration, testing, and field service, all of which are woven into an efficient flow by strict management control. Best engineering practices are reflected in this plan to design and construct the advanced equipment necessary to gather the required data. Design tasks are strengthened by breadboarding during the design phase. Test procedures have been developed for comprehensive debugging during fabrication and assembly. Integration test programs facilitate orderly system integration with formal qualification and acceptance tests programmed to make the most economical use of test facilities during the short schedule. In general, all program events follow a sequential order which permits design modifications that result from testing to be implemented without schedule slippages. This order is reflected in the division of the program into four phases following the presently concluded feasibility phase. Although these phases are separately defined, many requirements are interwoven among the phases to ensure total program accomplishment. However, these four phases have the necessary separation of effort to permit efficient program management and control of funding allocations. A Phase II through V schedule is shown in Figure 1-6.

Phase II is devoted primarily to the design of the GOPSS payload and the breadboarding of critical designs. Included are designs for the cameras, DCM structure, and film transport system, generation of auxiliary sensor specifications, and a preliminary design of the recovery section. Support to this design function includes a configuration control effort, necessary interface liaison, construction of a mockup, design of Phase III special tooling, formal test program specifications, and the initiation of the reliability program. Breadboarding is started immediately using Phase I design information. Sufficient notification of the choice of recovery vehicle will permit design of the recovery section during the 10 months of Phase II. All design tasks during this phase terminate in complete drawings and specifications for all of the GOPSS except the recovery section.

Procurement of glass blanks for lens manufacture is an initial requirement of Phase III, which is primarily devoted to the fabrication, assembly, and qualification testing of a complete photosensor system. Phase III effort is actually initiated during Phase II to allow immediate fabrication of photosensor parts. During Phase III, tooling and test equipment is fabricated, the final recovery section design is completed, and AGE design and MAB layout are accomplished.

Phase IV, which runs concurrently with Phase III, requires the fabrication, assembly, integration, and qualification testing of one complete GOPSS payload. The phase is scheduled so that system qualification testing follows Phase III qualification testing to permit design modifications, if needed, and judicious use of test facilities.

Phase V effort consists of the fabrication of three complete GOPSS payloads, the fabrication of a fourth to mate with the refurbished "qual" photosensor system, and acceptance testing of these four systems plus the refurbished "qual" system as the fifth deliverable flight system. Fabrication and test of AGE, MAB, construction liaison, and field support of launch site efforts are additional tasks under Phase V.

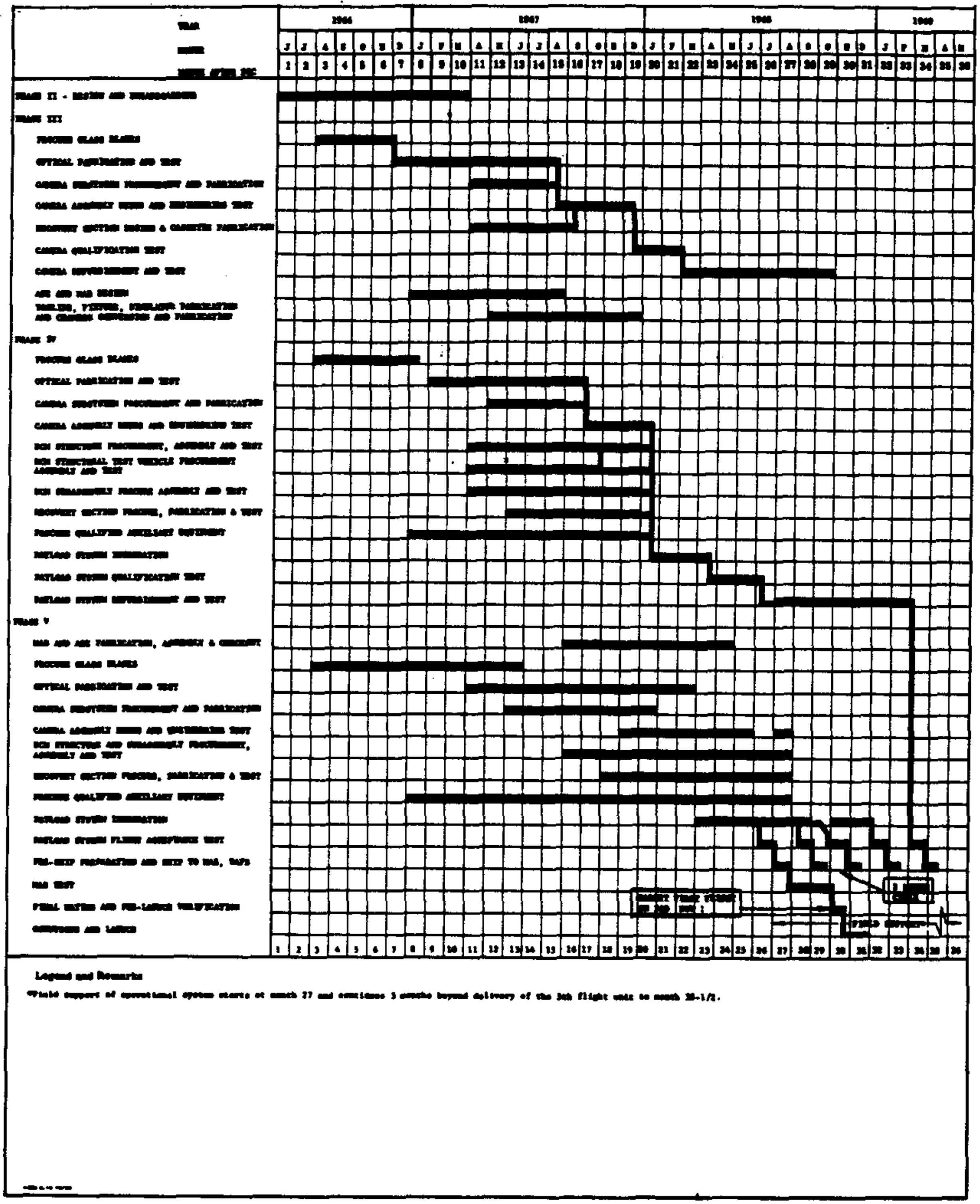

Fig. 1-6 — Phase II through V schedule bar chart

NOTE: This schedule also appears in Volume 5 as Fig. 5-3.

1.5 CONCLUSIONS

It is concluded that the GOPSS concept for the determination of landmark locations and geodynamic parameters, based on the information gathered by the proposed satellite sensor system supported by ground based tracking data, is feasible. With a reasonable geographical distribution of tracking data of reasonable quality and density, the satellite system can be located with an accuracy within the 200-foot horizontal and 40-foot elevation requirements.

These results are achieved by the incorporation of the TRANSIT tracking network to effect precise orbit determination, the Itek camera system to obtain the metric photography from which the landmark can be identified and located from the known satellite positions, the ability of the sensor system to measure atmospheric drag effects with an accelerometer system, and the proper treatment of the gravitational potential in the analytical procedures.

The achievement of landmark location specification is dependent on the ability of the photosensor system to obtain the metric photography from which landmark coordinates can be adequately measured. Computational results (shown in Table 1-5) indicate that the station coordinates can be determined to a spherical error not exceeding 43 feet at the 160-nautical mile altitude and 51 feet at the 200-nautical mile altitude.

The proposed data reduction scheme will provide to the system a method for treating the various sensor data inputs simultaneously. It is anticipated that the incorporation of these data into the proposed reduction scheme will provide significant improvements in the overall system performance, thereby realizing the desired 40-foot elevation specification.

Recommendations for further work are given where applicable in the text of the final report. However, the two following areas should also be considered for future study. Absolute positioning can be increased proportionally to the increase in the accuracy of timing. With a more accurate timing device and the same tracking data, the orbital parameters can be more accurately determined so that the absolute positioning over unknown areas will be increased considerably more than according to a linear function. The effects of timing errors, both relative and absolute, have not been discussed in depth in the final report; this is an important investigation that should be performed.

Orbits of near-earth satellites are influenced by the gravitational field of the earth. The usual manner of expressing this is to expand the potential field in terms of spherical harmonics, through the use of the generalized Stokes formula and the theory of Somigliana. According to the "new theory" of physical geodesy, a correction term due to topographic variations which ranges from 10 to 50 mgal should be additionally applied. Arnold has shown that the influences of a mean 5-mgal anomaly over a 10- by 10-degree square perturbs a satellite at 500 miles by a 20-meter tangential shift. These perturbations can be used to evaluate gravity anomalies in unknown areas. However, the point that should be made is that local gravity anomalies can significantly affect the orbits of close-earth satellites, and may seriously affect an orbit description if they are not accounted for. It would appear that the inclusion of known gravimetric data into the data reduction scheme could alleviate this situation, and should be considered as a future study.