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FINAL REPORT

CONTINUING SERVICES TO THE 496L SPO
SYSTEMS ANALYSIS AND INTEGRATION, PROGRAMMING,
ORBIT DETERMINATION AND MAINTENANCE

TECHNICAL DOCUMENTARY REPORT NO ESD-TDR-62-341

November 1962

496L SYSTEMS PROGRAM OFFICE
ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
L.G. Hanscom Field, Bedford, Mass.

Prepared under Contract Nr AF 19(604)-7375
by
Aeronutronic
A Division of Ford Motor Company
Newport Beach, California

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Contractor's Report
Number U-1927

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FOREWORD

This report represents work accomplished by the Astrodynamics Department of Aeronutronic, A Division of Ford Motor Company. This report has been assigned an Aeronutronic publication number of U-1927.

ABSTRACT

This report is a summary of the principal accomplishments in the prescribed and related areas of endeavor of the contractual work statement of contract AF 19(604)-7375. In order to present the material in a logical manner, this report contains, in individual sections, restatements of the several tasks described in the work statement along with the associated status and accomplishments. A list of technical reports produced under this contract are listed with their abstracts for reference.

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SECTION 1

INTRODUCTION

This report is a summary of the principal accomplishments in the prescribed and related areas of endeavor of the contractual work statement of contract AF 19(604)-7375. In order to present the material in a logical manner, this report contains, in individual sections, restatements of the several tasks described in the work statement along with the associated status and accomplishments. In response to requests subsequent to the publication of the work statement, a number of additional tasks have been conducted and are described within a separate section.

SECTION 2

ON-SITE ASSISTANCE TO THE 496L SPO

2.1 SPADATS CENTER, COLORADO SPRINGS, COLORADO

2.1.1 Work Statement

Provide assistance to the 496L SPO in the introduction and final installation of the Semi-Automatic Computer Program System and in training of SPADATS personnel in the operation of the system. Contractor personnel (4 people for a three months period) for training and liaison to be stationed temporarily in Colorado Springs.

2.1.2 Work Accomplished

The assistance to the 496L SPO in the introduction and final installation of the Semi-Automatic Program System (SPADAT A-1 System) and in the training of SPADATS personnel in the SPADATS Center, Colorado Springs, was conducted in two parts. The first part consisted of the original implementation of the system of computer programs, the training of SPADATS personnel, the operational testing, and the assistance in operational usage of the system. The second part consisted of revising the system of computer programs in accordance with operational requirements determined from three months of active utilization of the programs.

The original implementation of the programs consisted of operating the entire system in a manner which would simulate actual SPADATS operations. Five satellite orbits were computed from real observations over a period of several weeks of satellite lifetime. Investigation of the operation of the computer programs and the accuracy of the results indicated the validity of the system within the SPADATS functions. Two hundred hours of formal classroom instruction was conducted during the months of October and November. On-the-job training was conducted continuously during the months of December, January, and February. All instruction was conducted in accordance with a formal training plan. During the operational testing and full scale use of the system certain modifications were made to the originally delivered set of programs to meet new operational requirements. In March 1962, the A-1 System was being operated by SPADATS personnel without direct assistance from Aeronutronic. This first period of assistance to the 496L SPO conducted at Colorado Springs is documented in Monthly Status Reports covering the reporting periods November 1961 through January 1962, February 1962, and March 1962.

The second phase of assistance to the 496L SPO with respect to the SPADATS A-1 System required two Aeronutronic employes to spend a total of ten weeks at Colorado Springs. Work accomplished consisted of evaluation of three months of SPADATS A-1 System operation, determination of changes required to the A-1 System on the basis of this operation, and the insertion of program modifications where necessary. This ten week effort was not scheduled in the contractual work statement. This period of assistance is documented in Section 2 of the Monthly Status Reports for the reporting periods of April, May, and June of 1962.

2.2 SPACE TRACK RESEARCH AND DEVELOPMENT FACILITY, BEDFORD, MASSACHUSETTS

2.2.1 Work Statement

Provide the services of three resident Aeronutronic employes to serve as liaison and direct support to th 496L SPO at Bedford, Massachusetts, for the following purposes:

(1) The familiarization of 496L personnel in the SPS and other programs at Bedford.

(2) Liaison and participation in the work of the 496L Program Task Group.

(3) Assistance for in-house effort for adapting several, as yet not included, computer programs to the SPS and the SPADATS integrated programming system.

(4) Assistance to 496L technical personnel in the area of atmospheric density research.

(5) Liaison to the Newport Beach group of Aeronutronic with regard to program checkout and computer use at Bedford.

2.2.2 Work Accomplished

During the past year, Aeronutronic has provided three employes to serve as liaison and direct support to the 496L SPO, at Bedford, Massachusetts. Work accomplished by the Aeronutronic representatives has included tasks in the following areas of activity:

(1) Establishment, at Bedford, of a duplicate of the SPADATS A-1 Computing System.

(2) Training of 496L SPO personnel in the operation of the SPADATS A-1 System.

(3) Assistance to the 496L SPO in maintaining and improving an operational backup system to the SPADATS A-1 System.

(4) Familiarization of the 496L SPO personnel in the operation of all programs and techniques developed by Aeronutronic.

(5) Liaison and participation in the work of the 496L Program Task Group.

(6) Assistance to 496L technical personnel as required.

(7) Liaison to the Newport Beach group of Aeronutronic, with regard to contractual matters, program checkout, and computer use.

(8) Conduct preliminary studies to determine the relative accuracies of special and general perturbations computational methods.

SECTION 3

DEVELOPMENT OF NEW/IMPROVED METHODS OF ORBIT DETERMINATION

3.1 EQUATORIAL ORBIT COMPUTATION

3.1.1 Work Statement

Develop and program methods of computing and correcting equatorial or near-equatorial orbits and of preparing suitable prediction formats.

3.1.2 Work Accomplished

A general perturbations method and computer program has been developed to compute equatorial and/or near-equatorial satellite orbits. The program utilizes the variations of parameters method with the basic formulation based on the F, G orbital elements which closely resemble the N, M orbital parameters now in use in the operational SPADATS computations. Details of the analytical development and of the computational program with flow diagrams have been published in the Aeronutronic Preliminary Report, Equatorial Orbit Computation, dated November 1962.

The perturbations accounted for in the formulation are only those due to the Earth's equatorial bulge and atmospheric drag. Analytical expressions describing the first order secular variations of the second harmonic of the geopotential function have been included. The long period terms are insignificant when the inclination of the orbit is small, and, therefore, have not been considered. Changes in the orbital parameters due to drag perturbations are calculated from the terms involving the "c" and "d" drag coefficients.

The programming and preliminary checkout of this program for equatorial orbit computation has been completed during the current contract period.

3.2 INITIAL ORBIT DETERMINATION FROM ANGLE OBSERVATIONS ONLY

3.2.1 Work Statement

Prepare and program methods for computing initial orbits on the basis of angle observations only, and combine this with existing programs to obtain a general initial orbit program system.

3.2.2 Work Accomplished

A computer program (IØANGLES) has been developed which provides initial elements for a satellite orbit when given three topocentric angular observations within one revolution. The core of the theory is based on Gauss's ratio of sector-to-triangle expressions. The time intervals, which are the most accurately known piece of observational data, thus become intimately involved in the problem, whereas they would not be used to full advantage in a strictly geometrical solution.

The customary series expansions used to obtain initial position vectors in the classical Gaussian orbit determination method are avoided by first fitting a circular orbit to two of the observations. Since Earth satellite orbits are of relatively low eccentricity ($e < 0.2$), the semi-major axis of this circular orbit provides a good initial estimate to the geocentric radial distances on the three observation dates. Gauss's ratio of sector-to-triangle theory and the observations then form the basis of an iterative procedure for converging upon the actual geocentric position vectors. The traditional series solution of the two sector-to-triangle relationships is replaced by an iteration. The geocentric velocity vector at the central observation time follows from the three geocentric position vectors and the time intervals. With the position and velocity vectors known, any set of terminal elements can be calculated by conventional formulas. There are no inclination or eccentricity singularities in the theory.

A large number of experimental cases have been run with the program. In nearly all instances, the preliminary orbit was found from three angular observations within one revolution with sufficient accuracy to provide satisfactory initial conditions for the differential correction. However, there still remain certain cases where the period is quite poorly determined.

The theory and program have been described in detail in the preliminary report Preliminary Orbit Determination from Angular Observations, 12 October 1962. The final report will be issued when the experimentation is completed, and a complete evaluation of program capability can be made.

3.3 INTERPLANETARY PROGRAM

3.3.1 Work Statement

Add differential correction procedures to the program developed under a previous Contract, and produce a tape containing geocentric position and velocity in a format acceptable to the look angle program.

3.3.2 Work Accomplished

During the contractual period, evaluation of the Interplanetary Program indicated the necessity of modifying the research program to apply to SPADATS operational requirements. Some of the changes found necessary were the simplification of the input requirements to account only for SPADATS needs, the generation of an ephemeris for use in calculating acquisition coordinates, the extension of the Interplanetary Ephemeris Tape, and the re-documentation of the program to account for these changes. All of these tasks have been accomplished and the revised program has been delivered to SPADATS. These tasks have been discussed in Section 8 of the Monthly Status Reports for the reporting periods of June and August.

The work done on this program and in other areas (see Section 6) not originally specified in the statement of work did not allow the completion of the insertion of the differential correction into the program. Work is currently being conducted to incorporate this additional feature.

SPADATS use of the Interplanetary Program has led to additional requests for program modification to further change the research program to fit military requirements. Some of these modifications will be inserted into the program at the same time as the insertion of the differential correction routine.

3.4 GENERAL PERTURBATIONS

3.4.1 Work Statement

Develop general perturbation expressions for lunar and solar attraction and solar radiation pressure, and introduce them into existing programs where required and deemed advantageous.

3.4.2 Work Accomplished

(1) Luni-Solar Gravitational Attractions

Aeronutronic Report U-1830, entitled Luni-Solar Perturbations of the Orbit of an Earth Satellite, dated 15 September 1962, contains a comprehensive analysis of the effects of the lunar and solar perturbations on an Earth satellite orbit.

The lunar and solar gravitational attractions on an Earth satellite result in secular motions of the nodal longitude, Ω, argument of perigee, ω, and mean anomaly, M. These secular effects are relatively small, being less than 2 degrees per year for a satellite orbit having a period of twenty-four hours, an eccentricity of zero, and an inclination of forty degrees; however, some of the long period perturbations are large. By changing perigee height, they can in turn change the drag perturbations significantly, thereby drastically altering a satellite's lifetime.

The problem differs from the well established lunar and planetary theories in that the inclination of the perturbed body's orbit with respect to the reference plane is not always small. Nor is the eccentricity of the perturbed body's orbit necessarily small. It is customary practice to neglect short period terms, that is, those terms containing the anomaly of the satellite in their arguments.

When analytically determining the perturbations caused by a third body, of mass m', it is customary to expand the perturbing function

$$R \triangleq \frac{m'}{r'}\left[\frac{r'}{|\underline{r}' - \underline{r}|} - \frac{\underline{r} \cdot \underline{r}'}{(r')^2}\right]$$

into a power series in terms of the ratio of the distances from the primary body, $\left(\frac{r}{r'}\right)$, $\underline{r}$ and $\underline{r}'$ are the geocentric position vectors of the satellite and the perturbing body, respectively. Inclusive of the $\left(\frac{r}{r'}\right)^2$ term, the perturbing function then becomes

$$R = \frac{m'}{r'}\left\{1 + \left(\frac{r}{r'}\right)^2 \left(\frac{3}{2} S^2 - \frac{1}{2}\right) + \ldots\right\}$$

where $S \triangleq \cos\,(\underline{r}, \underline{r}')$.

The ratio $\left(\frac{r}{r'}\right)$ is small for the solar perturbations and additional terms in the perturbing function would be numerically insignificant. For the lunar perturbations, it may be necessary to retain higher powers of $\frac{r}{r'}$ in the perturbing function if the satellite's semimajor axis exceeds about a tenth of the moon's distance from the earth. However, the analytical expansions then become unmanageably long, making it more profitable to turn to semianalytical methods or possibly even to numerical integration.

The general perturbations theory developed at Aeronutronic (U-1830) includes all secular and long period terms, inclusive of the

$\left(\frac{r}{r'}\right)^2$ term of the perturbing function. Terms involving the square of of the eccentricity of the perturbing body's orbit were neglected. The satellite's Ω, ω and the true anomaly of the perturbing body were regarded as variable quantities, thereby enabling the integration to cover several revolutions.

(2) Direct Solar Radiation Pressure

The analytical development of the effects of direct solar radiation on a satellite orbit has been described in Aeronutronic Report U-1357, Orbital Effects of Solar Radiation Pressure on an Earth Satellite, dated 14 September 1961. A detailed summary of the computation procedure and description of the program based on this theory is contained in the forthcoming Aeronutronic Report U-1891, General Perturbations Earth Satellite Computations Incorporating Solar Radiation, Bulge, and Drag Effects.

Although there are no secular orbital variations caused by direct solar radiation pressure, the amplitude of some of the long period terms can be large. It is essential that these effects be included in long range predictions for some satellites.

The magnitude of the force acting on a satellite caused by direct solar radiation pressure is

$$F_{\odot} = \gamma P_{\odot} A$$

where

A is the effective cross-sectional area of the satellite to radiation pressure

$P_{\odot}$ is the solar radiation pressure acting on the satellite

γ is a factor depending on the reflecting characteristics of the satellite's surface.

It is customary to assume that the direction and magnitude of this force is constant along the entire orbit, except in the earth's shadow, where the force does not exist.

When a satellite is continuously exposed to sunlight, as Echo was from its launch on 12 August 1960 to 24 August 1960, the perturbing force caused by direct solar radiation is continuous, and the integration of the perturbation equations presents no problem. More often, however, the satellite passes through the earth's shadow on each revolution, the eclipse thereby producing discontinuities in the perturbing force. The customary way of handling this discontinuity is to evaluate the perturbative variations in the elements after each revolution. The points where the satellite leaves and enters the shadow on each revolution are then the lower and upper limits of integration, respectively, in the perturbation equations. The quantities, Ω , ω , the Sun's longitude, and the eclipse points are considered constant during the one revolution interval. In order to avoid the once per revolution integration, the approach adopted by Aeronutronic regards Ω , ω , and the Sun's longitude as variables in the integration. In addition, the shadow effect is approximated on the basis that the time spent in eclipse per revolution does not change appreciably over a number of days.

3.5 THRUST APPLICATION TO ORBITING VEHICLES

3.5.1 Work Statement

Develop means to allow in existing perturbation programs for the effects of applications of thrust to orbiting vehicles. The subroutine will require specifications of time, magnitude and thrust acceleration in orbital or inertial coordinates.

3.5.2 Work Accomplished

The Six Element Special Perturbation Program has been modified to accept various vehicular thrusting terms. Basically, the thrusting term is entered as an additional input perturbative acceleration to the numerical integration subroutine and subsequently integrated. The salient features of the program modifications are described in the Monthly Status Report, August 1962.

3.6 DETERMINATION OF ARTIFICIAL ENERGY CHANGES IN THE ORBIT

3.6.1 Work Statement

Develop methods to identify artificial orbit changes and to estimate amount, time and location of thrust application, and program such methods for semi-automated use.

3.6.2 Work Accomplished

A method and computer program, Orbit Intersection Program (XRØADS), have been developed in order to determine the point at which two satellite orbits intersect. This condition may occur when one satellite is ejected from another or when a satellite changes its orbit because of the application of impulsive thrust. Because of inaccuracies in the orbital elements, and because of the finite duration of thrust application, the above problem reduces to that of finding the most likely point of intersection. This point is determined by minimizing a function of the separation in both space and time, weighted by the variances in each. Thus, if the variance in time is assumed to be zero, the problem becomes that of determining the point of closest approach.

Some of the characteristics of this program have made it useful in several areas which were not anticipated when it was conceived. Several modifications have therefore been made which make the program more versatile. It can now be used to generate geocentric ephemerides for each of two orbits which, in turn, can be used to analyze the relative motion of two satellites. The program can then be used to compute precisely the point of closest approach.

The program has been delivered to 496L and has been documented including the modifications. Aeronutronic publication U-1701(R), Orbital Intersection Program, describes the theory, formulation, flow diagrams operation and test cases for the program.

3.7 CIRCUMLUNAR (UNIFIED ENCKE) TRAJECTORY PROGRAM

3.7.1 Work Statement

Introduce rectification procedures into the lunar trajectory program (Unified Program) to make it applicable to circumlunar missions and provide for automatic rejection of bad data.

3.7.2 Work Accomplished

During the evaluation of SPADATS operating procedures, described in Section 2, modifications to the Circumlunar (Unified Encke) Trajectory Program were determined to be necessary. The primary modification was the verification and delivery of the differential correction routine associated with the operational ephemeris calculation. The experimentation indicated that the formulation must be modified to account for large errors in the initial conditions. This investigation is described in the Monthly Status Report for the reporting periods of May 1962, and June 1962. The verified differential correction routine is now operating at the SPADATS Center. All of the described modifications except rectification have been incorporated into the program and have been delivered to the 496L SPO. A further discussion of these modifications may be found in Section 10 of the July 1962 Monthly Status Report. Work on the insertion of the rectification function is continuing.

A program description with operating instructions is included in the delivered preliminary report on the program dated 15 November 1962.

SECTION 4

AREAS OF RESEARCH AND ANALYSIS

4.1 CORRELATION OF UNASSOCIATED OBSERVATIONS

4.1.1 Work Statement

Study and develop methods for selecting and correlating previously untagged observations (so-called UO's) in order to recognize new satellites and to obtain sufficient orbital data to keep track of such bodies.

4.1.2 Work Accomplished

The task of studying and developing methods for the selection and correlation of previously untagged observations has been undertaken in order to recognize and maintain the orbits of new satellites. The problem has been attacked in two stages. The first stage, the association of untagged observations with the orbits of known satellites is handled automatically by the Report Association Program (RASSN) in the Semi-Automatic SPADAT System. RASSN has several other functions among which are the monitoring of the discrepancies (residuals) of the observations from the predictions by the orbital elements currently stored by the system for known satellites and the initiation of differential correction for any satellites when these residuals exceed predetermined bounds.

The second stage concerns the treatment of those observations which are left unassociated by RASSN. These observations must be correlated so that there is a high degree of probability that the correlated observations belong to the same physical body. This is necessary because the determination of orbital elements from the observations is a fairly time-consuming process. It is therefore impossible to attempt to "fit orbits" through any great number of observation sets.

In order to treat the large amount of data to be correlated, the analysis immediately resorted to computer program techniques with the design concept of automatic operation. The result of this effort was the development of three computer programs:

(1) The Radar Observation Selection Program
(2) The Unidentified Observations Non-Rotating Earth Program
(3) The Nodal Reduction Observation Correlation Program.

A detailed description of the salient features of these programs as well as a critical evaluation of their application is contained in the Aeronutronic preliminary report entitled Correlation of Unassociated Observations, dated 31 October 1962.

4.2 RE-ENTRY ORBITS OF SATELLITES

4.2.1 Work Statement

Study numerical and analytical techniques for computing re-entry trajectories and develop computing techniques for routine use with particular emphasis on accuracy and machine efficiency.

4.2.2 Work Accomplished

The problem here considered is that of predicting the time at which a satellite with known characteristics will decay into the earth's atmosphere.

A method and computer program, Satellite Decay Prediction Program, have been developed for this purpose. The equations which are used are those which were developed by King-Hele, Cook and Walker. In order to mitigate the effect of random fluctuation in the orbital elements, particularly the direct co-efficient, c_o, some smoothing techniques must be employed. At present this smoothing is done as follows: The best estimate of the decay date is computed by averaging the decay date, which is based on the current elements only, with the previous "mean decay date" (determined in a like manner). Thus, the best estimate becomes a weighted mean where the current value is weighted 1/2; the previous one 1/4; the one prior to that 1/8; etc. The previous "mean decay date" is specified as a program input. If it is not specified, no averaging is done. For the purpose of experimentation, the program has been written to accept any number of element sets and process each one sequentially. As each new "mean decay date" is computed, it is stored as the previous "mean decay date" and used in the subsequent computation.

SECTION 5

MODIFICATION OF THE A-1 SYSTEM

Work Statement

Provide the services of two Aeronutronic programmers (from those previously engaged in programming the A-1 System) for six months to assist the 496L Program Task Group in the modification of the A-1 System to achieve an early operational date of the B System. These two people to be stationed at Bedford during the programming, and at Colorado Springs during system checkout (last four to six weeks).

Work Accomplished

Two Aeronutronic personnel were assigned to the Bedford office during the period 15 January 1962 to 20 July 1962, to provide assistance to 496L and related agencies for the purpose of modifying the A-1 System to make it compatible with the B-2 System. This work included relocation of the A-1 programs and additional modifications to facilitate the incorporation of the real time interrupt equipment.

Test cases were compiled and run on the operational system to provide a means of checkout of the new system. These test cases included six weeks of operational observations for a set of six selected satellites displaying a variety of characteristics. With this data set it was possible to run the system operationally to obtain the widest range of outputs for comparison. Liaison between 496L, 496L Program Task Group, and 496L contractors was provided for the documentation and checkout of necessary changes to the A-1 System. Technical assistance was given as necessary to all agencies at Bedford using the A-1 System.

SECTION 6

SIMULATION ERROR ANALYSIS PROGRAM

Work Statement

(1) Provide assistance to the 496L SPO in technical matters related to system studies.

(2) The contractor shall, as required by the 496L SPO for the development of simulation and error analysis studies, perform the following specific work:

a. Write a model system to analyze specific problems associated with simulation and error analysis. This model system will detail the mathematics and logic involved.

b. Carry out a preliminary investigation of the simulation problem to determine new programming requirements.

c. Rewrite specified SPS Programs so as to be self-contained, relocatable, modular, and rectify interface problems. These Programs will be compatible with any specified executive control routine. The programs to be rewritten will be determined from the preliminary analysis.

d. Write new programs to meet the requirements of the model system described in a. above.

e. Check out and deliver all computer programs, including test cases, developed under this task.

Work Accomplished

The Simulation Error Analysis Programming System has been developed to provide to the USAF 496L Systems Project Office (SPO) and RCAF Directorate of Systems Evaluation (DSE), a means of evaluating some of the problems concerning satellite detection, tracking, orbit determination, and prediction of future satellite position. The system has been programmed for the Philco 2000 computer, making extensive use of the Philco 2000 Operating System (SYS). Fulfillment of the design development and production of the computational system required the full-time effort of three men for seven months.

The primary study objectives that the Programming System has been designed to accomplish include:

(1) An investigation of the factors involved in the accuracy of the determination of the orbital elements of a satellite, and the requirements of sensors to achieve given levels of accuracy in the orbit determination.

(2) An evaluation of the accuracy with which satellite position can be predicted at times subsequent to the determination of the orbit elements.

Realization of these objectives necessarily requires the performance of a comprehensive set of functions, many of which are equally as essential as the primary task. The Programming System provides the desired versatility in executing these functions, having been formulated in program modules.

The publication of the system's documentation is scheduled for early December; however, descriptions of the major programs produced concurrently with the system development are documented in the Monthly Status Reports, April, 1962, through September, 1962.

SECTION 7

TASKS NOT SPECIFIED IN WORK STATEMENT

This Section describes tasks accomplished at the request of the contract monitor. These tasks were not included in the Statement of Work of the subject contract but were necessary due to SPADATS and 496L requirements.

7.1 A-1 SYSTEM DOCUMENTATION

Aeronutronic was assigned the responsibility of collecting information regarding changes to the SPADAT A-1 System, generating corrections to the A-1 System documentation, and issuing such changes. Since the assignment of this responsibility, two sets of revised pages for the SPADATS Operator's Handbook (Aeronutronic Publication U-1431) have been issued. A complete revision of the SPADATS Program Description Document (Aeronutronic Publication C-1339-R) was made. The resulting new publication (Aeronutronic Publication U-1690) was issued in May, 1962. Since that issuance, one set of revised pages incorporating descriptions of new A-1 System programs has been delivered.

The task of maintaining the A-1 System documentation is not specified in the Statement of Work of the November, 1962, contract (AF 19(628)-562); therefore, no additional work will be applied to this task.

7.2 BAKER-NUNN CAMERA OBSERVING SCHEDULE PROGRAM

The Baker-Nunn Camera Observing Schedule Program computes the specialized satellite acquisition and camera setting information required by Baker-Nunn stations and presents this information in a special time scheduled format. Baker-Nunn cameras are designed to track along great circles centered at the camera. The program fits one or more great circles to a series of closely spaced points along the visible portion of the orbit. A least-squares technique is employed in the great circle fitting procedure. Camera setting parameters are then computed for each of the great circle segments. The number of great circles required to fit one satellite pass is a function of the distance between the satellite image and the center of the photographic field and the speed at which the image moves across the field of view. The great circle fitting and camera setting computations are terminated at culmination. However, the program may easily be modified to fit great circles to the descending arc also.

The analytical expressions used for computing satellite position are identical with those expressions in the other programs in the Semi-Automatic Programming System. The message format that is generated (666 Message) is identical to the format that the Smithsonian Astrophysical Observatory is transmitting to its Baker-Nunn camera stations. The new program operates in the Job Schedule mode with the SPS System. One run of the program produces a listing of camera settings for observing all satellites on file by all input sensors. Other input options allow the generation of camera settings for observing selected satellites by selected sensors.

The method used to determine when a satellite will be observable from a given sensor is a combination of analytical and iterative techniques.

(1) The satellite orbit is inspected to determine if it will ever appear above the observer's horizon. If it will not, the satellite in question is ignored and the next satellite is inspected.

(2) If the orbit will be observable, the time at which apogee appears above the horizon is calculated.

(3) An iterative technique is used to determine the time at which the satellite rises above the observer's horizon. This method allows a minimum use of computer time. When a satellite passage over a sensor is completed, appropriate use of (2) and (3) to determine when the next pass occurs provide computational efficiency.

After determining that the satellite is above the horizon, discrete points along the visible path from the first visible point to culmination are calculated at one minute intervals. The values computed and stored are the horizon-system components of the vector from the sensor to the satellite. Upon termination of a pass, the stored values are used to generate one or more great circles which represent the visible path. Camera settings and tracking rates are computed for initial acquisition and for tracking along the great circles. These settings and rates are stored with other similar data for other passes. These data are then presented in a time-sorted, special message format for transmission to Baker-Nunn cameras.

The three major divisions of computations are the ephemeris and acquisition coordinate calculations, the great circle computations, and the camera setting computations. The acquisition coordinate computations are divided into several sections with various visibility tests interspersed. Judicious testing during the early stages of these calculations facilitates the early elimination of satellites that are never visible from a given station and of non-visible passes of other satellites. The fitting of great circles to visible passes and the computation of camera settings for tracking along each great circle are accomplished when a given pass is completed. The program differs here from the Smithsonian computer program (SCROGE) in that the quantities fitted are the non-dimensional direction cosines rather than relative positions.*

The formulation, flow charts, input and output formats, and operating instruction have been submitted in a preliminary program document on 20 September 1962. The revised program document will be issued when checkout has been completed.

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*The development of the Aeronutronic computer program is described in the Monthly Status Reports of March, 1962, and April, 1962.

7.3 OBSERVING SCHEDULE PROGRAM

The Observing Schedule Program (OBSERV) generates sets of acquisition coordinates for sensors that have tracking capabilities and for sensors with fixed horizontal or vertical beam surveillance devices. In the former case, acquisition coordinates for equal intervals of time and for the time of closest approach are generated for all detectable satellite passes. For horizontal and vertical fans the program computes the time and coordinates of fan penetration by satellites. The primary mode of operation is the computation of acquisition coordinates of all satellites in the current population for one specified sensor. The results of the computation are presented in chronological order. Data listed for each time point includes the identification and acquisition coordinates of the observable satellite. The program operates in the schedule tape mode with the Semi-Automatic Programming System (SPS). Computations are accomplished with the simplified general perturbations technique.

The program is described fully in a preliminary report entitled Observing Schedule Program, dated July, 1962, and was delivered to the 496L SPO in August, 1962.

The program is being modified in accordance with operational requirements specified by SPADATS and 496L SPO in October, 1962. The changed program and final documentation are scheduled for delivery in January, 1963.

7.4 CORRELATION OF OBSERVATIONS IN REPORT ASSOCIATION PROGRAM

During the initial operational use of the SPADAT A-1 System, the Report Association Program operated longer than was desired. In response to this undesirable condition, the program was improved to yield a computer time saving of approximately thirty per cent. This revision is described in the Monthly Status Reports of February, 1962, and March, 1962.

Although the improved Report Association Program operated within desired time limits, the problem of efficiently correlating observations which are not identified by the sensors remained. Since the BMEWS stations contribute about 2500 unidentified observations per day, the approach to solve this problem was oriented toward the condition of a few stations generating many unidentified observations. The first suggested improvement was a combination of the predictions of satellite positions generated by the acquisition coordinate calculation programs with the report association technique. During the process of adjusting the Report Association Program to accommodate this new data, modifications were made which allowed a thirty-five per cent reduction in the time required to process unidentified observations. Since at this time a change was made in operational procedures which did not provide the predicted satellite position data, the combination of the techniques was not effected. However, since the revision of the Report Association Program is not dependent on the combinations the desired benefit is in effect. This problem and its solution are described in the Monthly Status Reports of April, 1962, September, 1962, and October, 1962. A further discussion of problems relating to associating observational data is discussed in the preliminary report Correlation of Unassociated Observations, 31 October 1962.

7.5 ORBITAL ERROR ANALYSIS

A study of error analysis has been accomplished to develop an analytic approach to the problem which will be complementary to the simulation program developed for error analysis. The results of this mathematical analysis are given in Aeronutronic Publication U-1831, ESD-TDR-62-227, 15 September 1962, Orbital Error Analysis. Expressions are developed for the terms of a matrix, and it is shown how this matrix can be used as the estimate of the variance-covariance matrix of error in orbital parameters resulting from errors in observations. The method is compared to the simulation method.

7.6 MODIFICATION OF DRAG AND BULGE PERTURBATION CALCULATIONS

The original theoretical formulation of the general perturbations technique used to calculate positions of earth satellites had a known deficiency of not being capable of efficiently representing satellite orbits in the last stages of orbital decay, generally the last two weeks of lifetime. The original formulation contained effectively only the first derivative of period. The new formulation contains the cubic or "d" term. This additional term has been applied to actual orbits and has proven to be successful in predicting the satellite position close to the actual decay. Extensive experimentation has been conducted to verify the validity of the new formulation. This new term has been added to the calculation of satellite position in the SPADAT A-1 System. The new formulation and the results of the experimentation are described in the October, 1962, Monthly Status Report. The original plan for the insertion of this term into the SPADATS A-1 System is described in the August, 1962, Monthly Status Report.

During the evaluation of general perturbations terms discussed in Section 7.10 certain terms not included in the current general perturbations formulation were identified as being large enough to cause significant errors in predicting satellite position. Consequently, the most significant term, that due to the third harmonic of the Earth's bulge has been inserted into the SPADATS A-1 System. The manner in which the new term is inserted into the formulation is described also in the August, 1962, Monthly Status Report.

7.7 MODIFICATION TO THE INITIAL ORBIT PROGRAMS

A modification to improve the estimate of the orbital period prior to differential correction has been inserted into the Radar Track Initial Orbit Program (IØHG). It is anticipated that this modification will, in addition, be inserted into the Angles Only Initial Orbit Program (IØANGLE). (See Section 3.2) This method is described in detail in the Monthly Status Report of August, 1962. Experimentation carried out at Bedford indicates that the method has considerable value. Appropriate SPADAT System change notices were issued in September, 1962.

7.8 INITIAL ORBIT RADAR FIX PROGRAM (IØRF)

A computer program has been developed to compute initial satellite orbits from two or more independent observations of satellite position. The technique combines other observations with the initial elements by means of a differential correction scheme to obtain a corrected initial orbit. This program is contained in the Technical Documentary Report No. ESD-TDR-62-211, 1 July 1962, Aeronutronic Publication U-1758, Initial Orbit Determination from Independent Observations of Satellite Position.

Extensive experimentation indicates that appropriate selection of observations to be used in the initial computations will yield accurate orbits. This experimentation and the conclusions drawn from the experimentation are reported in the above mentioned technical report plus the Monthly Status Reports of March, 1962, April, 1962, and May, 1962. This program has been delivered to the 496L SPO.

7.9 INITIAL ORBIT-LEAST SQUARES

A method has been developed and programmed for determining an initial orbit from radar data using a least-squares approach. The mathematical formulation and results of applying the method to hypothetical data were reported in the Monthly Status Report for April, 1962. The results of hand computations applying the method to real data were reported in the Monthly Status Report for July, 1962. The method has been programmed, and the Initial Orbit Least Squares Program (IØLSQ) has been completed. This program, and certain results from its initial application, are described in the preliminary report Initial Orbit Least Squares Program, dated 12 October 1962.

7.10 EVALUATION OF GENERAL PERTURBATION TERMS

A quantitative analysis of the General Perturbation expressions describing the variations in the orbital elements due to the gravitational perturbations has been conducted and summarized in the Aeronutronic Report U-1672, entitled Numerical Value of General Perturbation Terms in Orbital Parameters. The first- and second-order secular, long-periodic and short-periodic terms of the first order have been included in this report.

In general, the second order-secular terms generated significant variations in the orbital elements over an interval of one week. Variations caused by the long-periodic effects of the third harmonic were also large. The effects of the other long-periodic terms were not found to be significant.

SECTION 8

LIST OF PUBLICATIONS

A list of Aeronutronic published reports is presented here as reference documentation for the interested reader; abstracts are included for further identification. The publications denoted as Preliminary Reports are those issued as "preliminary" drafts of the corresponding Final Reports. The Technical Report on a particular task is issued only after a critical evaluation is made of the Preliminary Report and the conclusion of the experimentation phase of the program.

Technical Reports

1. Numerical Values of General Perturbations Terms in Orbital Parameters, Aeronutronic Publication U-1672, Jeannine Arsenault, April, 1962: Numerical values of general perturbations terms associated with the earth's oblateness primarily in the orbital parameters $L = M + \Omega + \omega$, $a_{xN} = e \cos \omega$, $a_{yN} = e \sin \omega$, and $\underline{h} = \sqrt{p}\ \underline{W}$ are discussed. Results are presented of a study of the sizes and amplitudes of the secular, short-periodic, and long-periodic variations in the parameters of various orbital models to determine which of these are necessary to maintain some given accuracy in position.

2. Orbital Intersection Program, Aeronutronic Publication U-1701, Ralph Schinnerer, May, 1962: A computer program has been developed to determine the point at which two satellite orbits intersect. Because of inaccuracies in the orbital elements and because of the finite duration of thrust application, the above problem reduces to that of finding the most likely point of intersection. This point is determined by minimizing a function of the separation in both space and time, weighted by the variances in each. Thus, if the variance in time is assumed to be zero, the problem becomes that of determining the point of closest approach.

3. *Initial Orbit Determination from Independent Observations of Satellite Position*, Aeronutronic Publication U-1758, ESD-TDR-62-211, J. Evans, 1 July 1962: A computer program has been developed to compute initial satellite orbits from two or more independent observations of satellite position which may be separated in time by up to two days. The technique combines other observations with the initial elements by means of a differential correction scheme to obtain a corrected initial orbit.

4. *Luni-Solar Perturbations of the Orbit of an Earth Satellite*, Aeronutronic Publication U-1830, ESD-TDR-62-226, Paul Koskela, Jeannine Arsenault, 15 September 1962: The theory developed in this paper is based on the Gaussian form of the expressions for the derivatives of the elements, that is, three mutually perpendicular components of the perturbing acceleration are used. All secular and long-period terms inclusive of the $\left(\frac{r}{r'}\right)^2$ term of the perturbing function are included. Terms involving the square of the eccentricity of the perturbing body's orbit are neglected. The longitude of the ascending node and the argument of perigee of the satellite, and the true anomaly of the perturbing body were regarded as variable, thereby enabling the integration to cover many revolutions.

5. *Orbital Error Analysis*, Aeronutronic Publication U-1831, ESD-TDR-62-227, T. Johnston, E. Onstead, October, 1962: Partial derivatives are established for the position coordinates of space vehicles in terms of observational quantities. These derivatives are taken with respect to that set of parameters which best defines an orbit regardless of its eccentricity and inclination. It is shown how these derivatives can be combined with variance and covariance values for errors of particular sensors to form a matrix, and how this matrix can be used to represent errors in orbital elements derived from observations made by those sensors. This method of analysis is compared with an analysis by Monte Carlo methods as to the amount of computation and the information obtained.

6. *Space Detection and Tracking System (SPADATS) Semi-Automatic Center Programming Document*, Aeronutronic Publication U-1691, Revised 1 November 1962.

Preliminary Reports

1. Preliminary Orbit Determination from Angular Observations, 12 October 1962

2. Simulation Error Analysis, October, 1962

3. Correlation of Unidentified Observations, October, 1962

4. Initial Orbit Least Squares Program, 12 October 1962

5. Baker-Nunn Camera Observing Schedule Program, 20 September 1962

6. Equatorial Orbit Computation, November, 1962

7. Observing Schedule Program, 20 September 1962

8. Unified Encke Ephemeris and Differential Correction Program, 30 November 1962

Air Force Systems Command, Electronic Systems Division, 496L System Project Office, L.G.Hanscom Field, Bedford, Mass., Rpt.No. ESD-TDR-62-341
FINAL REPORT CONTINUING SERVICES TO THE 496L SPO SYSTEMS ANALYSIS AND INTEGRATION, PROGRAMMING, ORBIT DETERMINATION AND MAINTENANCE.
Nov 62, 27 p.
Unclassified Report

This report is a summary of the principal accomplishments in the prescribed and related, areas of endeavor of the contractual work statement of contract AF19(604)-7375. In order to present the material in

1. Astrodynamics
2. Artificial Earth Satellites
3. Data Processing
4. Computer Programming
I 496L SPO
II Contract AF19(604)-7375
III Aeronutronic Div. of Ford Motor Co., Newport Beach, California

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