Preparations for Tracking Artificial Earth-Satellites at the Vanguard Computing Center

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Introduction

IT is considered appropriate to remark at the outset that part of the computer programming system subsequently to be described has been used extensively in performance of tracking calculations for artificial earth-satellites. This operational use commenced with the tracking at the Vanguard Computing Center, Washington, D.C., of the first Russian satellite last October 5, the day after the satellite was launched, and has continued during the interim.

To perform with great speed the calculations which would be required in the tracking of any artificial earth-satellites launched during the period of the International Geophysical Year ending December 31, 1958, an IBM Type 704 Electronic Data-Processing Machine was installed at the Vanguard Computing Center. The purpose of this paper is to describe the flow of operations and calculations performed using the programming system developed to handle these tracking calculations on this stored-program 704 computer.

Various stages involved in the data processing will be discussed; stages commencing with receipt of raw observational data and extending to provision of computed orbital information specifying the predicted future motion of a satellite, and extending eventually to provision of a comprehensive history of its past motion. Deadlines pertain to processing observational data and to distributing predicted positional information.

It is emphasized that the only calculations considered in this paper pertain to satellite tracking and orbit determination. It is the preparation for such calculations only—not for calculations pertaining to satellite or launching-vehicle structural design, not to launching-vehicle trajectories, and not to studies of the earth and its atmosphere—that the Vanguard Computing Center has been responsible. Furthermore, the Vanguard Computing Center, which is owned, staffed, and operated by the IBM Corporation under a contract with the Navy, is largely concerned with problems involved in processing positional information obtained from a satellite's continuous radio transmission. Problems involved in acquisition and processing of optically or visually obtained observations of a satellite, enabling continued use of new observational data for orbit determination if the satellite outlasts the life of the batteries which power its radio transmitter, are primarily the concern of another group, also using a 704 computer, and located in Cambridge, Mass. Naturally, however, both the Cambridge and Washington groups are interested in using observations obtained by both radio transmission and optical or visual methods.

The responsibility for establishing the orbit computation procedures rests with the working group on orbits which includes: Dr. J. W. Siry and J. J. Fleming of the Naval Research Laboratory; Dr. Paul Herget, Director of the Cincinnati Observatory; Dr. G. M. Clemence and Dr. R. L. Duncombe of the Naval Observatory. The detailed mathematical formulations were developed chiefly by Dr. Herget with assistance from Dr. Peter Musen, formerly of the Cincinnati Observatory.

The author of this paper has had responsibility, together with those working under him in New York, N.Y., for planning and preparation (synonymously "programming") of the system of instructions used by the 704 computer for accomplishing the desired orbital calculations, and for the programming of certain special calculations. These special calculations were performed during the development of the mathematical formulation, and guided the course of this development.

IBM staff members of the Vanguard Computing Center, assisted by the New York system development group, will handle the operation of the programming system on the 704 computer. The operation of the system is highly automatic, with many minor decisions being made by the computer according to rules provided to it. Nevertheless, from the processing of raw observations, to the computation of orbital characteristics and predicted positional information, the operation permits certain major alternative techniques to be used at various intermediate stages of the calculations. Decisions regarding some of these major alternatives can be supplied in advance to the computer, enabling its subsequent automatic handling of the desired choices of these alternatives. However, if these decisions are not made in advance or if it is desired to alter any of these decisions during the course of the calculations, the programming system is designed to make this conveniently possible by manual intervention. On hand to assist in any such decisions and to interpret the calculated results will be Dr. Herget and others responsible for the formulation.

General Description of Programming System

A very general description of the structure of the programming system will now be given before discussion of mathematical techniques employed and of their flow of operation. From the outset of the planning, it became apparent that the system should be designed to permit convenient choice not only in the methods of computation

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used, but also in the order of their use. To enable great flexibility in these respects, it was decided to make the system card-controlled. That is to say, the choice and arrangement of control cards in an input deck would, barring manual intervention, govern the choice and ordering of any operations subsequently performed by the computer. The terminology "macro-operation" was adopted to denote a collection of subroutines linked together to perform a broad orbit-computation function.

The component parts of a macro-operation were frequently needed in other macro-operations. Any such commonly-needed component part was then usually written as a subroutine with sufficiently general specifications to enable its use in the various macro-operations in which this type of operation was required. This frequently-adopted practice of programming by subroutines, rather than directly by macro-operations, had several significant advantages. Not only would this practice eliminate much duplication of programming effort which would otherwise have occurred, but also it would tend to keep localized, perhaps to a single subroutine, effects of a minor change in formulation. It may be remarked that for a research endeavor in a new field, such as the establishment of the formulation for tracking artificial earth-satellites, some changes in the formulation should not be unexpected.

It was decided to assign one auxiliary storage magnetic tape of the 704 computer to serve as a system tape, each block of information on this tape comprising instructions, constants, and control information required by just one macro-operation. Thus each control card (the contents of which are fixed) possibly followed by one or more input-data cards (the contents of each of which are variable) correspond to one macro-operation. In general, when a macro-operation control card is read at the card reader, a system subroutine retained in high-speed magnetic core storage causes (with a minimum of tape motion) the appropriate macro-operation information to be read from the tape into high-speed storage immediately prior to its use. In general, the complete set of instructions required for each macro-operation consists not only of those instructions transferred for the macro-operation from magnetic tape to high-speed storage, but also of utility subroutines (*e.g.,* input-output subroutines) commonly needed by various macro-operations, and retained in the high-speed storage. The auxiliary magnetic drum storage is used to store certain input parameters which are subject to change, and also output of certain macro-operations which may serve as input for one or more subsequent macro-operations. Comparatively small amounts of output are directly printed and/or punched on cards. Larger amounts of output are written in binary-coded-decimal form on magnetic tape for subsequent printing on a magnetic tape-to-printer peripheral device not connected to the 704 computer, and operated independently of it. In particular, one such tape, called a "log tape," was assigned to preserve a detailed chronological history of calculations performed, including not only input and output quantities but also many intermediate results. The system is designed to enable the observational data, subsequent to its preparation in decimal punched-card form, to be supplied as input to the computer, optionally from these punched cards directly, or from binary-coded-decimal tape prepared on a card-to-tape peripheral device. To check for occurrence of random machine error, the internal calculations are generally performed in duplicate with comparison of check sums, while transference of information between high-speed magnetic core storage and auxiliary magnetic tape or magnetic drum storage is checked by check sums, and special checks are made for input-output operations. In addition to the printer, magnetic tapes, and card punch, the use of which has already been indicated, the cathode-ray tube display and cathode-ray tube recorder are available as output devices. Programming has also been done to enable optional use of these devices to provide plotted output in direct-visual and/or filmed form.

Flow of Operations and Computational Methods

The flow of operations performed in processing the data will now be discussed, together with brief descriptions of the computational methods involved. As a starting point, suppose that some of the continuous radio transmission from a satellite has just been received by one of the specially-designed receiving stations, called "Minitrack stations," during a single transit of the satellite over the station. This transmission is subdivided at the Minitrack station into individual observations, up to about thirty in number and evenly spaced in time. Each observation then consists of phase-difference readings, one for the east-west-oriented radio antenna of the station, and one for the north-south-oriented antenna, both corresponding, after small adjustments, to a single instant of time. A typical time interval for these observations is one second. The associated information, comprising the phase-difference readings, first and last times for the readings, and certain information identifying and specifying characteristics of the observing station, will for convenience be called a "message." Each message is transmitted in triplicate to a control center at the Naval Research Laboratory, and thence, still in triplicate form, via teletype to the Vanguard Computing Center. A device at the Vanguard Computing Center automatically converts the teletype tape to decimal punched cards.

This message is then ready to be processed by one of the macro-operations of the programming system for the 704 computer. This macro-operation, which is always the first macro-operation to process any of the messages, includes four principal subroutines. The first subroutine is designed to load the message into the high-speed storage of the computer, transforming information from compact form on the input-data cards (or, optionally, input binary-coded-decimal tape) into a more suitable form for its subsequent use. The second subroutine performs an editing function, comparing the triplicate items of the message for exact agreement. This second subroutine reduces the size of the message if permissible when, for a given item, at least two out of three of the corresponding items do not agree exactly. The third subroutine performs several adjustments to the data due to certain characteristics peculiar to the Minitrack station which received the data, due to passage of time during the recording of a single observation, due to radio refraction, and in order to convert the phase readings to directional information. Then, each adjusted and converted observation provides the approximate direction of the satellite from the observing station at a certain instant of time. It is to be noted that no direct measurement of the distance of the satellite from the observing station is yet available. In fact, satellite distances will be derived as output of orbital calculations. Only after such calculations, shortly to be discussed more specifically, does such a distance serve as an input quantity. The processing, thus far, also checks to assure that at least three individual observations remain so that the fourth subroutine may have reasonable assurance of being able to perform its function. This function is to fit a least-squares parabola to each of the two sets of direction components which were derived collectively from east-west and north-south phase-difference readings. The principal output of this macro-operation, then obtainable, consists of a single "smoothed" direction of the satellite from the observing station, expressed in a local coordinate system and corresponding to an instant of time. This instant of time is centrally located with respect to the time range of the set of raw observations which, it is recalled, were obtained from a single Minitrack station during one transit of the satellite over this station. This principal output is provided in both punched-card and printed form. Certain subordinate output quantities, such as any discrepancies between the triplicate messages and standard errors of the least-squares parabolic smoothing operations, also are printed. Also, as in the operation of all macro-operations, a detailed record of input, intermediate output, and output is preserved on the log tape. In the subsequent discussion of the flow of calculations, it will be understood that preservation of information on a log tape, and printing of output information which is required for more rapid surveillance, are included in all macro-operations, whether or not explicitly mentioned (see Fig. 1).

Several methods have been programmed in order to enable computation of a preliminary orbit from such observations. (Here, and subsequently, the qualification "parabolically smoothed" is understood when referring to an observation.) One of these methods makes use of two observations which, roughly speaking, are suitably widely spaced in time, to obtain a preliminary circular orbit. Other available methods develop a preliminary elliptic orbit from three or four observations which are neither too closely nor too widely spaced in time. If the observations were too closely spaced in time, inaccuracies in the observations could seriously reduce the accuracy of the result, while the particular methods used would be invalidated in the case of observations spaced too widely.

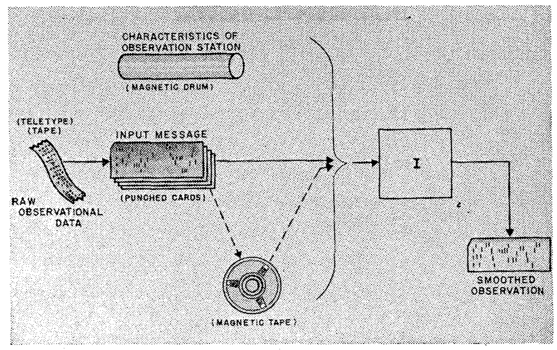

Fig. 1—Processing of Minitrack (or Minitrack-simulated) input. Macro-operation I.

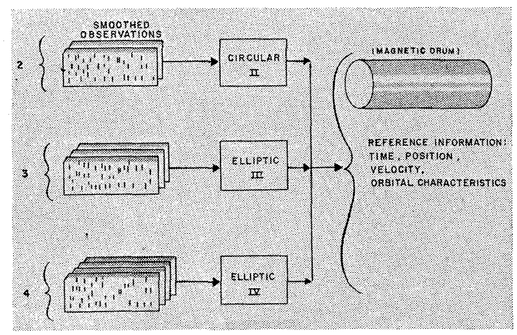

Fig. 2—Preliminary orbit determination. Macro-operations II, III, IV.

These methods are based on iterative techniques due to Gauss, and are applied after transformation of coordinates of observations, expressed in their original local systems, to an inertial coordinate system. In each case, a reference position vector, and a corresponding velocity vector, are obtained for the satellite at some instant of time. Then, from this reference time and corresponding position and velocity vectors for the satellite, the programming provides for computation of certain quantities serving to characterize the orbit in question in different ways. For example, such computed quantities are the period of the satellite's revolution, the inclination of its orbit plane, and, in the case of the elliptic orbits, also such quantities as the semimajor and semiminor axes of the orbit, and the perigee (*i.e.*, closest to earth) position of the satellite. The programming for each of these preliminary orbit computation methods constitutes a separate macro-operation (see Fig. 2).

After having obtained a preliminary approximate orbit, other methods have been programmed to enable its improvement and, as the orbital characteristics would constantly be subject to change, also its updating. One macro-operation consists primarily of a procedure for numerical integration of the differential equations relating, by Newton's law, the components of forces acting upon the satellite, to the components of its acceleration. Each of the three force components contains an expression for the force on the satellite due to gravitational attraction of the nonspherical earth, and an additive term for force due to an admittedly fairly rough estimate of atmospheric-drag force acting upon the satellite. As is well known, one of the reasons for launching artificial earth-satellites is the desire to gain further information about the structure of the upper atmosphere. Until more is learned about the upper atmosphere, in particular about variation of atmospheric density with altitude, the components of drag force in these differential equations may be subject to significant inaccuracies. The other contribution to the force components, due to gravitational attraction of the earth, may also introduce significant error because of our inadequate knowledge of local variations in the earth's gravitational field. There are, of course, further errors in the numerical integration procedure caused by inaccuracy in initial values of the satellite's position and velocity, due to replacement of derivatives by finite differences, and due to growth of error during the numerical integration computations. Though its accuracy is limited by such errors, this numerical integration macro-operation is expected to be very useful, not only because its output consists of predicted positions of a satellite spaced in time by an arbitrarily-chosen time interval, but useful also, in combination with a method of differential correction, for orbital improvement and updating (see Fig. 3).

The macro-operation for this differential correction method obtains corrections to position and velocity vectors corresponding to a reference time which may be periodically updated. These corrected vectors may be used, as before, to obtain new orbital characteristics. The input for this differential correction procedure consists of observations (preferably including, because of changing orbital characteristics, the latest available) and predictions, at the same observational times, obtained from output of numerical integration by 6-point Lagrangian interpolation. So-called equations of condition are computed, one set for each observation, after making an improved adjustment to the observations for refraction. The differential corrections are then readily obtained from least-squares solution of these equations of condition. The processes of prediction by numerical integration and differential correction may be performed iteratively in attempt to bring predictions and observations in close agreement (see Fig. 4).

A more complicated alternative technique, which is also planned to be used for prediction and orbital adjustment, is based upon three further macro-operations. In brief, one of these macro-operations uses a modification of Hansen's lunar theory to compute Fourier series representations of orbital characteristics, including perturbations due to the oblateness of the earth, in terms of a variable representing time. A second macro-operation treats separately drag perturbations in these orbital characteristics by numerical integration. By evaluations of these Fourier series and additive perturbations, adjusted orbital characteristics and, thence, derived predicted positions, may be

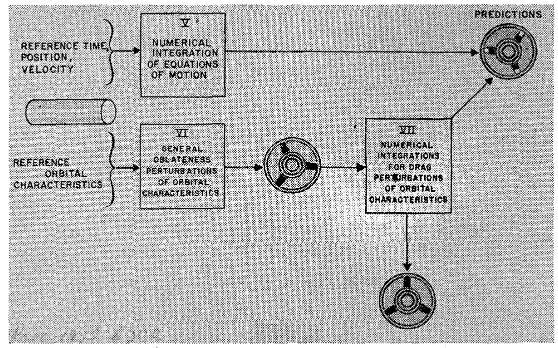

Fig. 3—Predicted positions (inertial vectors). Macro-operations V, VI, VII.

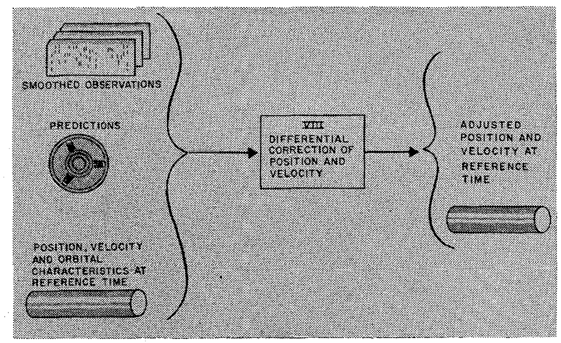

Fig. 4—Orbital adjustment (improvement and/or updating). Macro-operation VIII.

obtained. The third macro-operation computes differential corrections to the orbital characteristics by a technique similar to that used for correcting the reference position and velocity vectors. This technique for prediction and orbital adjustment, using these macro-operations iteratively, is expected to be a valuable alternative until the later stages of a satellite's "life." Near the end of the flight of a satellite, the drag force would become large enough to invalidate the method used for the oblateness perturbations.

At such time, it is planned to continue predicting and orbital adjusting by the first-described techniques for numerical integration and differential correction (see Figs. 3 and 5).

Two separate macro-operations are available for transforming predictions from the inertial-vector form into forms more convenient for use by the general public. One of these macro-operations provides as output, for each prediction of a specified time span, the time, latitude, and longitude for the subsatellite position, height, and zenith-angle-acquisition information. Also provided as output is a list of any official Minitrack or optical stations to be alerted due to the satellite's proximity, but, in the case of an optical station, only if the favorable observation condition of twilight exists. The other of these macro-operations provides, as output, positional information for a specified set of times and relative to a specified station (see Fig. 6).

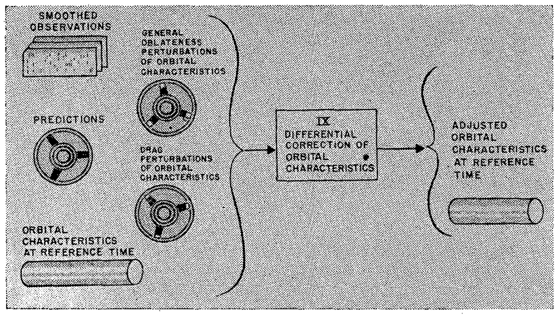

Fig. 5—Orbital adjustment (improvement and/or updating). Macro-operation IX.

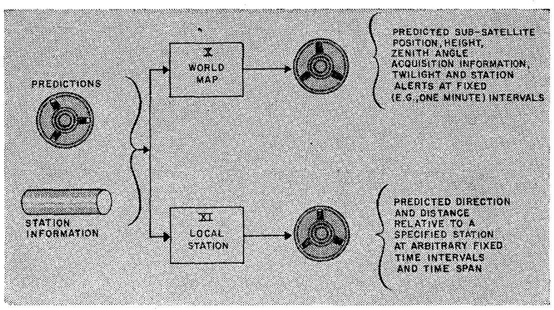

Fig. 6—Predictions (transformed for convenient use). Macro-operations X, XI.

Conclusion

Several remarks seem appropriate at this point. It was earlier stated that certain deadlines pertain to processing observational data and to distributing predicted positional information. Satellites, of the types presently being considered, would complete a single revolution around the earth in approximately an hour and a half. Allowing for communication and distribution delays in incoming data and outgoing predictions, the speed of a satellite's motion requires very rapid calculations to be performed in order to enable use of the methods described in providing, sufficiently in advance, alerts and predicted positional information to observers around the world. A machine with significantly slower speed or significantly smaller storage than the 704 computer would not have been able to do the same job adequately. In particular, in the very early stages of a satellite's flight, the Vanguard Computing Center will be concerned with developing and distributing orbital information within a matter of minutes of the receipt of observations which first enable preliminary orbit determination. However, until at least one revolution of a satellite has occurred, observations may be so sparse that better than a rather inaccurate determination of the satellite's actual motion would be prevented.

The magnitude of the programming system's development, and of associated programming for special calculations, may be measured by an estimated expenditure of between 6 and 7 man-years of work involving the writing of approximately 25,000 instructions. The size of the programming system is a result of a complex mathematical formulation whose programming included many different types of Fourier series manipulations, and a result of the system's flexibility in enabling convenient use of alternative computing techniques. To guard against possibility of machine breakdown at an inopportune time during a satellite's flight, another IBM center with a 704 computer will be kept prepared with operational information by means of a transceiver and telephone on an emergency stand-by basis.

Acknowledgment

The author wishes to express his appreciation to those whose efforts and assistance have made possible the development of the programming system. These persons include Dr. G. E. Collins and R. T. Mertz, who have been associated with this project from the beginning of this development, and also Miss L. Y. Chang, Mrs. N. G. Copeland, Israel Krongold, A. R. Mowlem, J. B. Secrist, Jr., Dr. R. W. Southworth, and N. R. Wagner.

Bibliography

[1] Herget, P. "The Computation of Orbits." Published privately, 1948.
[2] Herget, P. and Musen, P. "General Theory of Oblateness Perturbations for Vanguard Satellites" (memorandum), March 23, 1957. Presented by Dr. Herget in abstract form at the American Mathematical Society Symposium on Orbit Theory, April 4, 1957.

Discussion

It should be noted that these answers were taken from the latest technical information available through March 26, 1958.

Chairman M. Rubinoff (Philco Corp., Philadelphia, Pa.): Is a triangulation system used or planned to be used to increase accuracy of observation? This question is by E. A. Keller.

Mr. Quarles: In attempting to answer this question, I shall restrict my attention to the standard Minitrack receiving units being used by the Navy in performance of radio-tracking responsibilities. The disposition of these stations was aimed at providing a very high probability of receipt of transmission from a United States satellite by one station during each earth-circuit of the satellite. At originally expected altitudes for such a satellite, this disposition provided an expectation that simultaneous observations by two or more stations would be exceptional rather than usual. Consequently, there was an expectation of being able to triangulate simultaneous observations from these stations only comparatively rarely. The occurrence of higher than originally expected altitudes has made somewhat less exceptional the recording, and expectation for future, simultaneous observations. It is planned to investigate accuracy by triangulation of any such simultaneous observations, possibly leading to increased accuracy of observation. However, on the basis of these considerations, triangulation does not occupy a very significant role in the present operational use of the Minitrack system.

The method of obtaining a directional observation inherent in the Minitrack recording involves what might be termed "triangulation" from displaced antennas, based upon phase difference. I assumed that the intent of the question was to gain information about "triangulation" in the usual sense of this word.

Chairman Rubinoff: L. Elrod of Westinghouse asks, "will it be possible to modify the program while actual tracking is in process?"

Mr. Quarles: It is expected that modifications to the program will probably only be made after studying the results obtained and would not actually be made during the course of one continuous operation on the machine. However, it is possible to exercise a number of programmed options by manual positioning of sense switches, and to modify the arrangement of macro-operation control cards and content of data information to be used at a later stage, during calculation.

Chairman Rubinoff: The third question is, "Is there any provision in the subject program for using observational data from sources other than official tracking stations such as amateur optical or radio measurements?"

Mr. Quarles: Let me emphasize first that it is not required that the observational data be from the Minitrack stations. On the first slide it was noted that the data could be either Minitrack data or simulated Minitrack data.

To go one step further, it wouldn't even be necessary to enter the data in simulated Minitrack form if one had sufficiently reliable data obtained by whatever means. For example, one could bypass the whole operation of the first macro-operation which edits and smoothes the data, and simply enter as a smoothed observation the direction of a satellite from an observer at a certain time, if one had such information. So, it is quite flexible as to the types of data that could be used and in fact several kinds of data have been used. However, the qualification "sufficiently reliable" stated above makes virtually necessary what might be termed professional electronic or optical equipment and professional operating personnel, and seriously limits the usefulness of amateur measurements. Of course, in the absence of professionally obtained data, amateur measurements take on increased importance.

Chairman Rubinoff: A question from R. Isaacs of Philco, "What reports, if any, of the programming system are available?"

Mr. Quarles: The first actually published report of the programming system will be this paper as presented, supplemented in publication by questions and answers. Later, I expect there will be more detailed reports of the programming system available.

Chairman Rubinoff: A question by Mr. Sumpter of the Department of Defense, "Why use cards for input to the computer? Why not go directly from teletype tape to magnetic tape, then into the computer?"

Mr. Quarles: As described in my paper, there is an option of providing input observational data to the computer either directly from punched cards or from magnetic tape prepared on a device which operates independently of the computer. This option of the use of magnetic tape was provided in order to enable more rapid computer processing in the event that a large volume of input data were to be supplied to the computer at any one time. Whether or not this option is exercised, the preliminary preparation of cards has an advantage of enabling, together with the printed triplicate messages also produced from the teletype operation, convenient partial editing, selection, or rearrangement of the data prior to the more extensive editing and processing performed by the computer.

Also, there isn't presently, so far as I know, a commercially available device for converting directly from teletype tape to magnetic tape. Furthermore, there has not seemed sufficient need for such a device in this computer application to render it an important consideration. More rapid provision to the computer of this input data does not at present seem important. Using either of the options described, the operation typically requires a small amount of time for supplying the input data to the computer in comparison with times for calculation and for development of output data on magnetic tape. In particular, the maximum possible time saving due to bypassing preliminary preparation of punched cards by using a hypothetical teletype-tape-to-magnetic-tape device would not under present, or presently expected, conditions of operation seem to justify the sacrifices of conveniences of cards described above.

Chairman Rubinoff: From D. J. Nemanic of Remington Rand Univac, "Can unknown factors such as density of the atmosphere be estimated from the differential corrections to the predicted orbit?

Mr. Quarles: Yes, it certainly is possible to estimate some of these factors on the basis of the orbital calculations in general—not only from the differential corrections. One of the main purposes of the whole project is to make improvements in our knowledge about the atmosphere by examining and studying the deviations of the predictions from the actual observations.

In particular, the calculations have indicated that the density of the atmosphere is greater than originally had been expected at the altitudes attained by the artificial earth-satellites. However, much study of orbital calculations is expected to be required before reasonably reliable information about density variation at high altitudes is known.

B. Zendle (National Bureau of Standards): Has it been possible to determine the mass of the Russian earth satellites, thereby verifying the mass values announced by the Russians? If so, how, and to what degree of accuracy?

Mr. Quarles: Though I have not been concerned with this question, it is my understanding that the presently limited information about the density of the atmosphere, and consequently about the drag acting upon a satellite, would have prevented any independent, accurate verification of the masses announced by the Russians. Later, when it is possible to determine atmospheric drag with greater accuracy, such independent verifications should be possible with reasonably good accuracy from the laws of motion of a satellite which depend upon both the drag and the mass.

S. M. Selig (Chemical Corps Eng. Command, Army Chemical Center, Md.): What are the computer facilities that the Russians have set up equivalent to Minitrack?

Is the accuracy of their predictions for Sputnik I due to more sophisticated equipment than the IBM-704, or to better programming and better fitting or Fourier series and other essential computations that you mentioned?

Mr. Quarles: I do not know the answer to this question. However, on the basis of any predictions by the Russians which I have seen, I do not have reason to believe that they are using anything but comparatively unsophisticated techniques.

M. A. Hyman (Philadelphia, Pa.): Approximately how many points were calculated by numerical integration for each elliptical trajectory? What can be said about the accumulation of errors during calculation of an average trajectory? How long did the computer require for each trajectory?

Mr. Quarles: The typical time interval in the numerical integrations performed to date is one minute, and hence the order of one hundred steps per earth-circuit. A thumb rule which may be applied to estimating the accumulation of errors by the method of numerical integration which has been programmed is that the error is approximately the three halves power of the number of steps, divided by eight, units in the last place of the digital precision employed. The programming of the numerical integration enables optional use of single- or double-precision floating-point calculations, providing precision equivalent approximately to eight or sixteen significant decimal digits, respectively. Including binary-coded-decimal tape output as well as binary-tape intermediate output, the single-precision computation requires approximately six minutes per day of predictions using a one-minute time interval, whereas the double-precision computation requires about six times as long. Both of these computations are reduced by about four minutes per day of such predictions at the sacrifice of the binary-coded-decimal tape output.

W. H. Jenkins (ElectroData): You mentioned 25,000 instructions. Does this complete the program? Are these operations debugged? If so, you should have some accurate times for the processing from the input cards or tape until the final result of "where to look."

What are the limits of these times? (For example, three to five minutes, or ten to thirty minutes.)

Mr. Quarles: The figure of 25,000 instructions was intended to cover completed instructions and modifications which were in progress. It is expected that some additions and modifications to the system will be planned and developed later due to the research character of the project.

With the exception of some current comparatively minor modifications, all of the macro-operations described are debugged and all are in use. In view of the great variety of ways in which the macro-operations have been combined in actual operation, permitted by the flexibility of the design of the programming system, it is very difficult to give meaningful over-all time figures without extensive qualification. Even for individual macro-operations there usually are several modes of operation with