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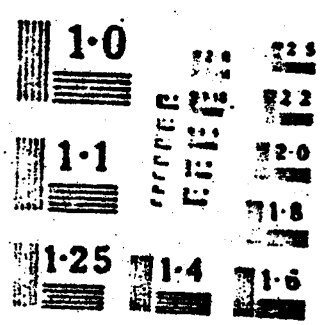

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LMSD-6034

WS 117L

ADVANCED SYSTEM DATA PROCESSING FOR SUBSYSTEM G = 'MIDAS SATELLITE SYSTEM

CONTRACT AF 04 (647) -97

LOCKHEED AIRCRAFT CORPORATION
MISSILE SYSTEMS DIVISION
SUNNYVALE, CALIFORNIA

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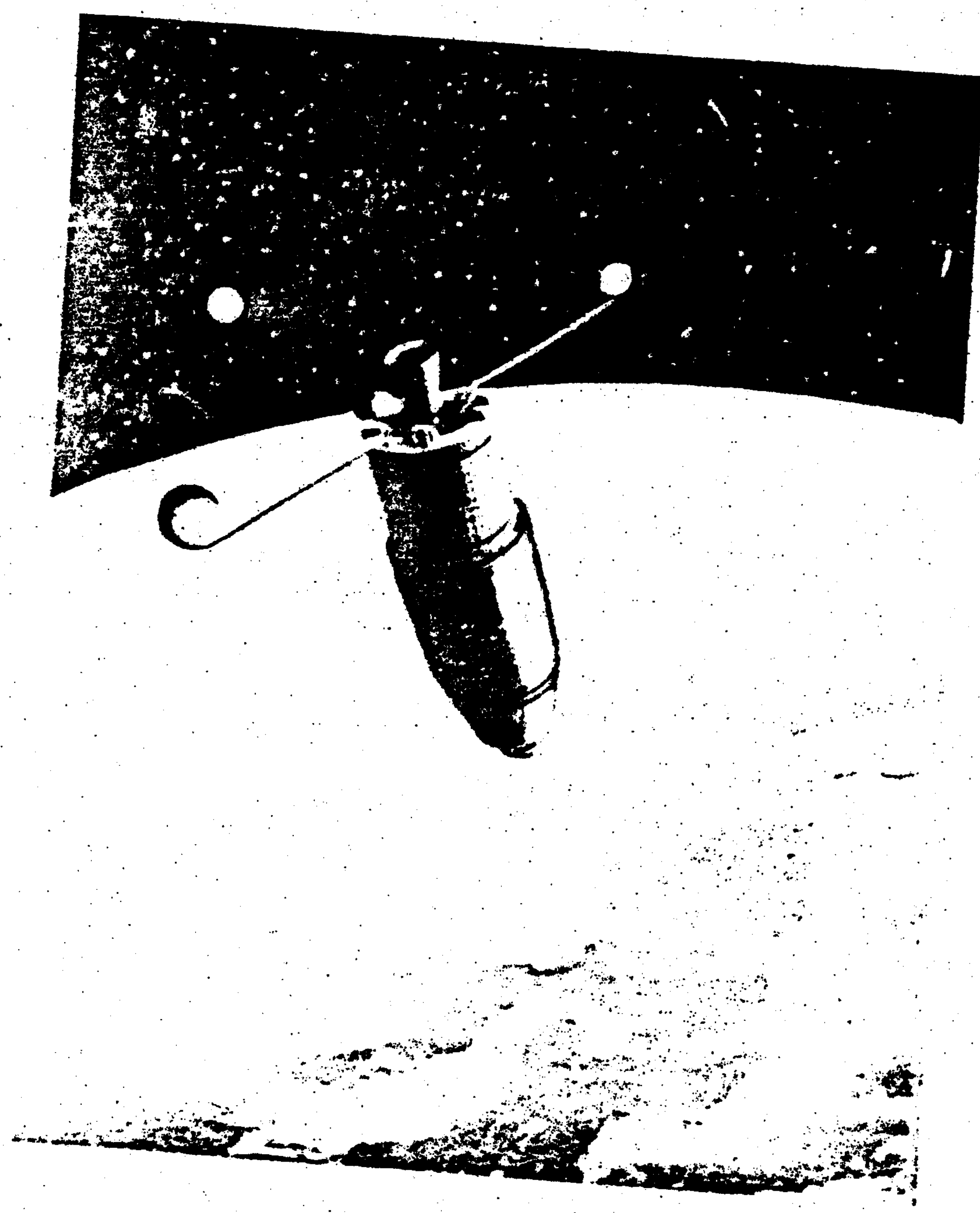

FOREWORD

This report presents the results of a study conducted by D. D. Aufenkamp of the Applied Mathematics Department, LMSD Research and Development organization. The work is being done in support of the WS-117L Project under Contract AF 04(647)-97.

The report reflects many of the ideas and opinions and much of the general philosophy that have evolved in consultations with people in LMSD's Preliminary Design Department, Data Control Department, and Subsystem C Department.

The study is part of a continuing effort, and additional reports will be forthcoming as significant progress is made.

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SECTION 4 QUANTITATIVE EVALUATION OF THE COMPUTER FACILITY

SECTION 5 CONCLUSION

PREFACE

This report is predicated on the performance of all data processing by ground-based equipment, and a discussion is made of requirements which arise from this assumption.

Subsequent to the completion of LMSD-6034, but prior to its formal release, numerous advantages became evident in the area of limited satellite-borne data processing -- as opposed to the exclusively ground-based approach undertaken in the study. As stated on Page 1-2, "... By making suitable assumptions the computer requirements can be simplified considerably over those resulting from a different set of assumptions. In fact, some apparently very difficult computer problems appear to be avoided almost entirely by appropriate equipment design...." Such major gains appear possible by, among other means, transferring part of the data-processing load to relatively simple equipment on board each satellite.

Despite the advantages of limited satellite-borne data processing, information contained herein is useful and valid in its own right under the assumptions made in the study. The report is published at this time without revisions, so that it may be available for study at the earliest date. The study will be extended, and a future LMSD report will be published on a system comprised of both satellite-borne and ground-based data-processing elements.

WS-117L ADVANCED SYSTEM DATA PROCESSING FOR SUBSYSTEM G

SECTION 1 DESCRIPTION

1.1 PRELIMINARY REMARKS

This report investigates the data-processing facility required for the proposed Subsystem G ICBM precision tracking-prediction system. Such a study is particularly appropriate as a logical successor to the investigation described in LMSD Report 29..6, WS-117L ICBM Tracking Prediction Accuracies from Angle-only Measurements (Ref. 1). That investigation is concerned with the feasibility of using earth satellites equipped with infrared detectors for tracking ICBMs during their burning phase in order to obtain the burnout conditions of the missile with sufficient accuracy to permit a reasonable prediction of its free-flight path.

The precision tracking-prediction system envisaged consists of a network of satellites, each carrying an infrared search mechanism and several infrared trackers for the detection and precision tracking of ICBMs, together with appropriate ground data-processing equipment. The completed system will have a number of functions. Three basic ones are as follows:

(1) Detection of enemy ballistic missiles by the search (acquisition) gear as the missiles rise above the lower atmosphere.

(2) Tracking of each missile thus detected during its burning phase with two or more satellite-borne infrared trackers to obtain precision angular tracking data.

(3) Calculation of the position and velocity of each missile at burnout in order to predict its resulting free-flight trajectory.

A number of other functions can also be incorporated into the system depending upon the sophistication desired. For example, it may be necessary to follow the predicted free-flight path of each missile with infrared trackers in order to detect an additional thrust applied after initial burnout has occurred Such a function would surely complicate the proposed system in general and the associated computer facility in particular. We shall defer temporarily a detailed study of this and other possible functions of the system.

In order to carry out an effective evaluation of the magnitude of the computer facility required for the proposed system, it is necessary to make certain assumptions concerning the equipment and techniques to be employed as this phase of the development is in an early stage of formulation. It should be emphasized that this investigation is a feasibility study and that suitable solutions to many problems await further study.

The computer facility associated with such a system must necessarily be a very high-speed data-processor. The sophistication depends to some extent on the functions required of the facility. On the other hand, however, given a desired set of functions to be performed, the complexity of the associated computer depends strongly on a number of factors, such as the satellite reference system; the nature of the search and, especially, of the tracking mechanism; the particular mathematical formulation used, etc. By making suitable assumptions the computer requirements can be simplified considerably over those resulting from a different set of assumptions. In fact, some apparently very difficult computer problems appear to be avoided almost entirely by appropriate equipment design. A more detailed discussion will follow. This report emphasizes the techniques which offer considerable simplification in the data-processing, and, at the same time, are within the general philosophy of the infrared precision tracking-prediction system. Where alternatives in procedures have been studied, their advantages and/or disadvantages are also pointed out. Although, in general, the computer facility probably should not determine the development of the satellite-borne equipment, any contributions that might be made in this way to improve the overall system should be carefully considered.

The data-processing facility will be evaluated relative to the IBM STRETCH computer to the extent that this is possible in order to give a better indication of the magnitude of the problems involved. Some information on STRETCH appears in Par. 4.5 although many of the details of its development have not yet been released by IBM.

An introduction to the operation of the system is given in Par. 1.2. This introduction is followed by a detailed discussion in Section 2 of the various assumptions made in connection with the satellite reference system, search gear, infrared trackers, etc. A functional block diagram of a tentative data processing system is given in Section 3, and each major block is discussed in detail. After this qualitative discussion, the proposed computer facility is evaluated in terms of the STRETCH computer (Section 4). The report concludes with a general discussion of the work (Section 5).

1.2 OPERATION OF THE PRECISION TRACKING-PREDICTION SYSTEM

Consider a network of satellites with each carrying the above indicated search and tracking mechanisms and capable of communicating through a data-link system to the data-processing equipment on the ground. The system is illustrated in Fig. 1. The number of satellites needed for satisfactory performance will depend largely on such factors as the following:

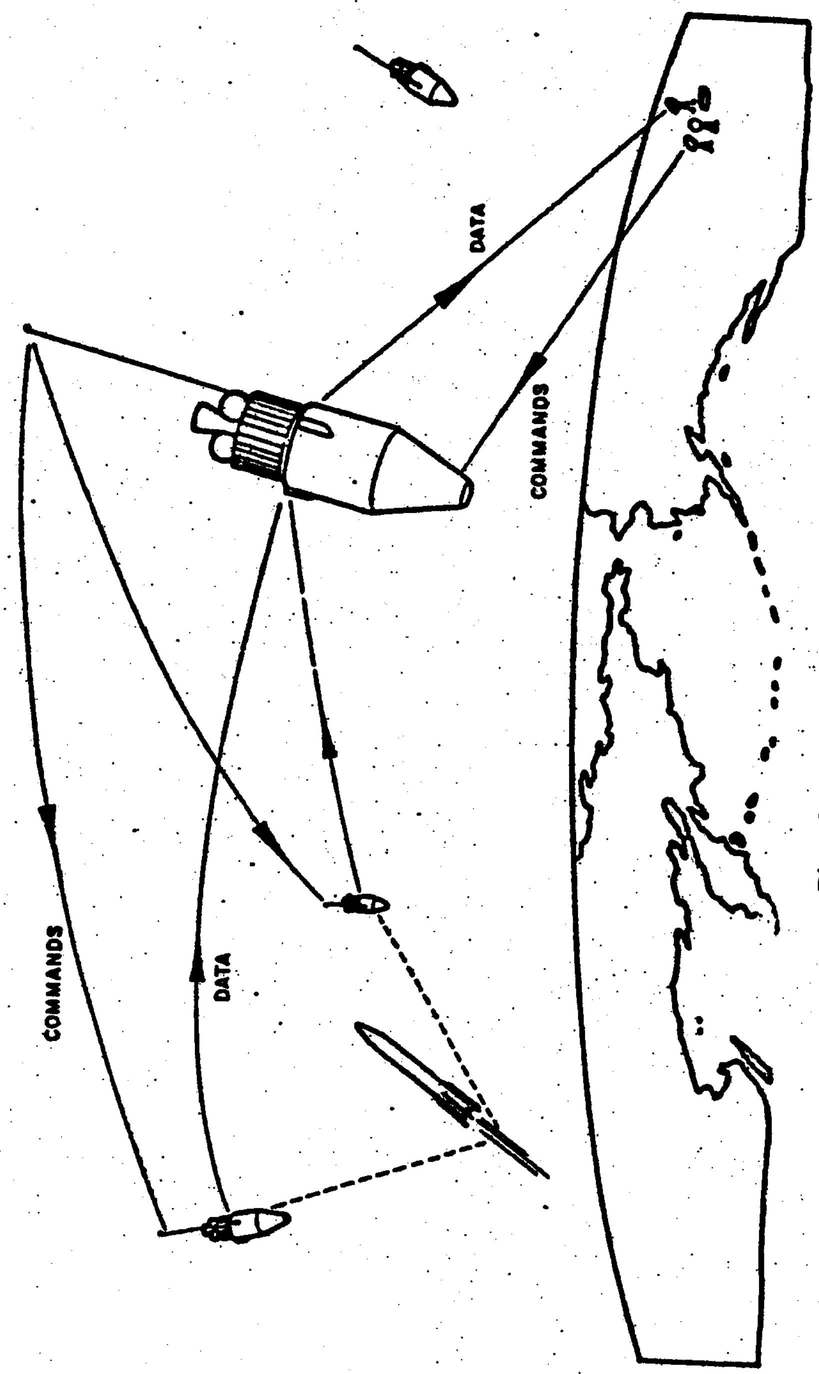


Fig. 1 Data Relay Concept

(1) Altitude and orbits of the satellites.
(2) Data-link network, including location of readout stations.
(3) Number of trackers per vehicle.
(4) Average number of trackers to be assigned to a target.
(5) Average time that a given target must be tracked.
(6) Estimated "maximum" rate of ICBM launchings in the event of an all-out enemy attack.

The "maximum" rate of ICBM launchings is defined to be the average rate of launchings during the period of maximum enemy activity in a time interval equal to the average tracking time per missile. This rate can be expected to increase as Russia's capacity develops for producing and launching missiles--especially when a solid propellant ICBM becomes operational.

In the standby state (i.e., when no heat sources are under observation) it would suffice to have only enough search gear in operation to give continuous coverage of the region of interest. The infrared trackers will be idle; however, some technique must be employed to ascertain whether or not the trackers as well as the other vehicle-borne units are in satisfactory operating condition.

Subsystem H will be tracking satellites to obtain precise present and future positional data. A very accurate attitude sensing device also must be developed to establish a satellite reference system with respect to which the high-resolution tracking measurements are given. Whether or not the attitude sensors must be functioning in the standby state will probably depend upon the procedures used. This point is developed in Par. 2.2.

When a heat source appears, as illustrated in Fig. 1, one or more search scanners will observe it and send an alarm through the data-line network to the ground master computer. The master computer analyzes the search data to determine whether a missile has been observed. If this is so, a suitable action must be taken. For example, after certain staging information is obtained, and/or after an appropriate time lapse, the computer could direct two or more vehicle-borne trackers from different observing satellites toward the heat source. The tracking data obtained is relayed to the master computer for processing. When burnout of the missile is detected, the master computer calculates the resulting ballistic trajectory so that appropriate defensive measures can be taken.

SECTION 2 BASIC ASSUMPTIONS

2.1 PRELIMINARY REMARKS

As stated in Par. 1.1, it was necessary to make a number of assumptions concerning the techniques and equipment to be used for collecting and processing data in order to carry out an effective evaluation of computer requirements. In part, use has been made of assumptions in a forthcoming report, LMSD-2889, First Annual Report: Feasibility Study of a Data Relay Network for the WS-117L Project, Subsystem G (Ref. 2). However, the nature of the tracker mechanism has been changed in view of a considerable simplification of the data-processing techniques concerned. With reference to the complexity of the overall data-processing facility, two general factors which should be kept in mind are as follows:

(1) The sophistication of the system with reference to the functions it must perform.

(2) The extent to which techniques--mathematical, procedural, and other--are developed to simplify the data-processing for a given set of required functions.

It is clear that the data-processing becomes much more complicated as the number of missiles to be tracked in a given time increases. A computer facility that would handle, say, ten missiles simultaneously would be considerably more complex than one designed to process only one missile at a time. It is difficult to estimate the maximum rate at which the system would have to process data on enemy missiles; however, for the purposes of this evaluation, the basic assumption is made that the infrared precision tracking-prediction system will have to process missiles at a rate of 30 per minute. This rate would represent a portion of an all-out attack in which, say, 450 ICBMs were successfully launched at random during a 15-minute interval.

It is of the utmost importance that the rate of processing missiles be approximately equal to the rate at which they are launched. If, for example, 450 missiles were launched in 15 minutes, and if it took an average of four seconds to process a given missile instead of the two seconds assumed above, at least 30 minutes would be required to process all 450 missiles. Therefore, some of the missiles would already be approaching their targets before any calculations could have been made.

With reference to the satellite configuration, the model assumed in the data-link feasibility study will generally be used in this report. In particular, a network of 96 satellites will be considered, with five infrared trackers per satellite, distributed on selected orbits. The orientation of the various orbits is not critical for the present evaluation. If it is required that trackers follow the predicted free-flight paths of missiles, the total number of trackers needed increases considerably. The data-link report reasoned that a configuration of 50 satellites would be able to handle missiles at an average rate of 30 per minute. This conclusion is based in part on the assumption that each vehicle-borne tracker will be in a position to view two missiles simultaneously. This assumption is not made here for reasons given in Par. 2.3.

2.2 SATELLITE REFERENCE SYSTEM

The infrared precision tracking-prediction system envisages tracker mechanisms whose precision is such that the angular accuracy of the overall system is to within 1.4 x 10[illegible] radians. Such precision is of little value unless the measurements are given with respect to a satellite reference system whose orientation relative to the ground is known very precisely. If the attitude of the vehicles were known perfectly, there would be no problem Since, in practice, this will not be the case, some technique will be required for determining carefully a reference system for each satellite.

It is assumed for the present evaluation that an applicable technique exists. The particular method used is of concern in this study to the extent that computer specifications are involved. One possible realization of a satisfactory reference system from the computer viewpoint is taken as a basis for discussion in this report. It is assumed that the satellites will ordinarily be well stabilized although some long-term drift may be present. The satellite's position is assumed known on the ground from Subsystem H calculations. Two reference directions are determined by assigning two star trackers to track different known stars. These two directions are sufficient to establish a unique coordinate system; hence the angular measurements of each tracker can be given with reference to these two directions. If these two directions correspond to coordinate axes, a third axis can be determined by a given cross product of the two associated unit vectors. While the two star trackers are occupied, a third star tracker will be ordered from the ground to seek out a third known star in order that a reference system moving with the vehicle can be provided at any time.

Since the motion of the star trackers relative to the vehicles will probably be somewhat restricted, communication must be maintained between the satellites and the associated star trackers so that any long-term drift of the satellites' orientations can be detected and corrected. It might be necessary, in this scheme, to have continuous star tracking from the time the vehicle is placed in orbit to insure that the reference system can be maintained at all times since otherwise even a small unknown change in satellite attitude could make the problem of seeking out assigned stars extremely difficult. It is assumed in any event that the resulting angular accuracy of the overall infrared tracking system, including any errors in the reference system, is 1.4×10^{-4} radians.

Further, it is suppoed that either Subsystem H or the master computer calculates the transformation matrices between the satellite reference systems and the inertial coordinate system used on the ground.

2.3 THE SEARCH GEAR

One area in which considerable effort is needed is in the design of appropriate search and tracking equipment for the proposed tracking-prediction system. The need for a data-processing facility that is as completely automatic as possible to handle the large number of missiles assumed implies that techniques be used which can be mechanized for a computer. Decisions that might be easy for a human operator to make can be very difficult for a computer. The search gear to be utilized could be basically the same as that proposed for the ICBM Attack-Alarm System. A complete description of this equipment is given in LMSD Report 2939, <u>WS-117L Subsystem G Engineering Analysis Report, Attack-Alarm System</u> (Ref. 3). There are certain difficulties in connection with this search mechanism from the computer viewpoint if complete automation of the data-processing is desired. However, this design will be used with the understanding that a refinement will probably evolve for use in the operational infrared precision tracking-prediction system.

Briefly, the ICBM Attack-Alarm System provides for a rotary radial scan of the region limited at the outer edge by 4 degrees above the horizon and at the inner edge by the locus of points 25 degrees from the vertical axis of the vehicle. The fact that this scanner does not observe targets in the conical region directly below the vehicle would be a disadvantage at times in the infrared precision tracking-prediction system, but it is assumed that a complete coverage can be provided. The normal angular scanning rate is 12 degrees per second, or, in other words, the scanner moves through a full 360 degrees in azimuth every 30 seconds. Twenty-seven detectors are used which allows all elevation angles at any one azimuth to be observed almost simultaneously. An angular accuracy of about 5 by 7 minutes of arc (1.5×10^{-3} by 2.0×10^{-3} radians) is obtained in azimuth and elevation, respectively. In addition, the relative intensity of the infrared signal is observed. In Ref. 3 it was assumed that eight intensity levels can be observed. In this way, some staging information is obtained. Knowledge of staging is particularly important if infrared trackers are to be placed on targets at appropriate times for obtaining the required data.

There exists a provision for sector scan in the ICBM Attack-Alarm System in order that a particular sector of interest can be examined in more detail. If, for example, a 45 degree sector were being scanned, information on a given target would be available about every 4 seconds instead of every 30 seconds. The scan direction on each sector scan is reversed each time the sector is traversed. The detection unit is also designed so that approximately the same signal-to-noise ratio is obtained for targets at all ranges.

2.4 THE INFRARED TRACKERS

It has already been assumed that the infrared tracking system has an overall angular accuracy of 1.4×10^{-4} radians, independently of the techniques used to obtain such precision. The nature of the tracking mechanism has a considerable effect on the complexity of the associated computer facility as is shown in the cases which follow.

Two basically different types of infrared trackers have been considered informally so far in connection with this precision tracking-prediction system.

(1) The first is essentially a search-type mechanism which scans a very narrow field, probably on the order of 1/4 degree. This type of tracker would be capable of collecting and relaying data on all targets within this field of view. If more than one target were present, then, presumably, it would be programmed to follow, for example, the center of mass of the configuration. This is essentially the tracker assumed in the data-link feasibility report.

(2) The second type of tracker considered is one with a field of view similar to the one above that locks on a given heat source and ignores all other targets. The orientation of the tracker would thus determine the line of sight to the target.

The former type of tracker has the advantage that data is recorded on all targets within its field of view which might help to reduce somewhat the total number of trackers needed. If the field of view were on the order of 1/4 degree, at 2500 miles a right cross-section of the conical region under observation would have a diameter of approximately 10 miles. Thus, depending on the arrangement of firing pads and the launching pattern, it appears that two or more missiles could easily be observed by a single tracker. On the other hand, when multiple targets are present, a serious difficulty arises if a high degree of automation is desired in the data-processing. (A similar difficulty arises in connection with the search system.) Presumably, in this type of tracker, there would exist a number of cells (forty is one number that has been considered) which would be examined in some order for the presence of infrared signals. Briefly, the problem is as follows: How is the data obtained on successive scans to be associated? In other words, some technique is required for providing a continuity of data on each target present. If the number of targets viewed by a given tracker were relatively small, a human operator could probably supply this continuity rather easily by observing an appropriate visual presentation. However, a high-speed mechanization of this process appears to be difficult with respect to a computer. The motion of the satellite in its orbit, the continual need for redirecting the trackers, and the likely gradual separation of the missiles in space would all contribute to the complexity of the problem. There would be no guarantee, for example, that two missiles would remain in the field of view of a given observing tracker. Any difference in launching times alone would bring about an increasing separation because of the accelerations involved.

Essentially, a computer would have to associate on the basis of some criterion of "closeness" the directions to a given target that were determined on successive looks of a tracker. This closeness is somewhat difficult to define for computer mechanization. One possibility is that as long as the same cell were indicating a heat source on successive looks it could be assumed that these directions were all associated with the same target. This assumption will be generally the case at the tracker data rate assumed. (The argument does not extend to the assumed search gear because of the much lower scan rate.) In fact, this problem is simplified as the data rate increases. At 144 looks per second, which is the data rate assumed in the data-link study and in this report, a target would ordinarily appear in the same cell for a number of looks, at least ten, and often for a considerably longer time depending on the relative motion of the observer and target. Therefore, checks must be made on how to associate the data only when a target has moved into a different cell. Presumably, a new target would be easy to recognize, and the probability that two targets would change angular locations simultaneously is small under ordinary conditions; even so, a satisfactory check would not be difficult.

A redirecting of a tracker to follow its targets would cause an abrupt change, the effects of which would have to be carefully calculated in order to preserve the data continuity, and there would not be much time for these computations. Difficulties also arise (1) in calculating where to point the trackers if two or more targets are present and (2) in determining what to do when it is no longer possible to keep all targets within view of a given tracker. Further, if a target not in the set under observation by a given tracker sweeps across the field of view, there are other problems. The data taken would be sent automatically to the ground along with the other data, which would complicate considerably the data-processing, since extensive checking would be necessary to determine how to use this information.

In the apparently rare event that two missiles were on the same line of sight there would be a problem for either type of tracker. A check on the relative infrared signal intensities might offer a solution to the data-continuity problem in this case.

The second type of tracker, which is assumed for this investigation, is ideal as far as the data-processing system is concerned, although a larger number of trackers might be needed in this case. This tracker might be designed so that when it has been ascertained that the desired target has been found, the tracker's field of view narrows considerably. If the tracker is always centered on a target under observation without appreciable error (i.e., the overall angular accuracy is to within the assumed 1.4×10^{-4} radians), it suffices to relay only the magnitudes of the two angles between the line of sight to the target and the two reference directions plus an indication of the target's location relative to the plane of the orbit. This information, assuming the satellite's position is known, determines a unique line of sight in space.

The data-link feasibility report assumed that no infrared signal strength data was received from-the trackers. It is assumed to the contrary in the present study that signal amplitude is also observed and relayed to the ground. If this is feasible, the trackers as well as the search gear can provide staging information.

The rate at which observations are made will affect the precision of the results of the subsequent calculations, as will the length of time that data is recorded on a given target. The size of the high-speed storage unit also depends upon the data rate. The data-link study assumed a rate of 144 looks per second. It is assumed that a missile is tracked for a minimum time of 40 seconds. Since burnout cannot be accurately predicted, trackers may generally be tracking targets for more than 40 seconds. Sufficient information should be available on enemy ICBMs so that burnout can be predicted to within 20 seconds. The total tracking time would thus be on the order of a minute. It is assumed specifically that burnout can be detected by the trackers even at maximum range. The intelligence to be obtained from the system diminishes considerably if this is not the case.

The number of trackers per satellite has been taken as five although there seems to be no reason why this number could not be increased. If further study indicates that this is indeed the case, the total number of satellites needed could be reduced accordingly.

It is assumed as in the data-link report that there is a clock in the vehicle which sends a synchronization pulse every 7 microseconds. This is approximately the time for the search scanner to traverse 5 minutes of arc. The 144 looks per seconds of the infrared trackers is also based on this 7-microsecond pulse. On the ground the data received is decoded on the basis of its arrival relative to this pulse. According to the data-link report, a considerable bandwidth advantage is obtained by this procedure.

2.5 THE DATA-LINK NETWORK

For this evaluation the single-relay data-link network described in Ref. 2 is adopted, although it is not used extensively. (Ref. 2 emphasizes that the data-link network described represents only a first look at the problem.) The reader is referred to Ref. 2 for a complete analysis; however, the important characteristics from the viewpoint of the present study are as follows: The data-link network studied calls for one or two ground readout stations in a northern location. The data received at the readout stations is relayed immediately to the master computer.

With regard to the satellite configuration, a subnetwork concept is introduced in which a single satellite within range of a readout station acts as a relay for data from, and commands to, a set of approximately seven other satellites. Each satellite is equipped to act either as a relay or as an observer. The rationale is that about one-eighth of all the satellites in a given hemisphere, whose pole is at the readout station, are on a line of sight to the readout station, assuming a uniform distribution of satellites around the earth. Under this subnetwork concept, each subnetwork reports its information to the ground station through its own readout vehicle. The various satellites are programmed to become part of the network or to be removed from the network as they change position. The observing vehicles will transmit their data to the readout vehicle using a narrow-beam antenna directed in both azimuth and elevation toward the readout vehicle. The readout vehicle will receive this information on an omni-azimuthal antenna having restricted coverage in elevation. The readout vehicle also serves as an observer. Commands for the activation and deactivation of a satellite for a particular subnetwork will be transmitted to the vehicle when it is within range of the ground station and stored for subsequent use. The required commands for positioning the transmitting antenna beams and for positioning the infrared trackers while within the subnetwork will be relayed to the observing vehicle by the readout vehicle. If there were 96 satellites in all, those in the northern hemisphere would form six subnetworks.

2.6 SUMMARY OF ASSUMPTIONS

a. General System Assumptions
   - (1) The overall processing rate is 30 missiles per minute.
   - (2) Subsystem H or the master computer provides present and future positional data on the observing satellites and the coordinate transformation matrices at a rate equal to the data rate of the infrared trackers.

b. Satellite Configuration
   - (1) 96 satellites are distributed in appropriate orbits at an altitude of 1000 miles.
   - (2) One search scanner and five infrared trackers are on each vehicle.

c. Satellite Reference System
   - (1) The reference system is provided by three star trackers, of which at least two are locked on known stars at all time.
   - (2) Commands for the positioning of star trackers originate on the ground.
   - (3) There is a provision for the correction of any long-term drift of each satellite's orientation.

d. Search Gear
   - (1) A rotary-type scanner is provided which sweeps out that region below the vehicle limited by 4 degrees above the horizon.
   - (2) The angular scanning rate is 12 degrees per second.
   - (3) A provision is made for sector scan on command.

(4) The angular accuracy is 5 by 7 minutes of arc (1.5×10^{-3} by 2.0×10^{-3} radians).

(5) Eight infrared intensity levels can be detected.

(6) There is a vehicle clock providing a synchronization pulse with respect to which the data received on the ground is decoded.

e. The Infrared Tracker

(1) The trackers are basically the lock-on type.

(2) There are five trackers per satellite. (This number will be increased, if possible.)

(3) The data rate is 144 looks per second.

(4) The angular accuracy of the overall system (including the reference system) is 1.4×10^{-4} radians.

(5) Infrared signal intensity is observed.

(6) Burnout can be detected even at maximum range.

f. Data-Link System

(1) The subnetwork concept is used in which there are approximately seven observers to one readout vehicle, hence a maximum of six subnetworks in the northern hemisphere for the satellite configuration is assumed.

SECTION 3 FUNCTIONAL BLOCK DIAGRAM OF DATA-PROCESSING FACILITY

3.1 PRELIMINARY REMARKS ON DATA PROCESSING PROCEDURES

In addition to the many assumptions made concerning the nature of the search and tracking mechanisms, data-link network, etc., it will also be necessary to postulate certain procedures by which the data is processed on the ground in order to complete this intended evaluation. These procedures will affect the general organization of the computer facility to a considerable extent. Many problems in this area need to be studied thoroughly with reference to the functioning of the entire system and, in particular, from the standpoint of simplifying the complex computer routines. Many questions will undoubtedly resolve themselves as designs are formulated for the search and tracking gear, but this present study should indicate what is desirable relative to the data-processor.

There are two procedural problems of particular interest which need considerable attention. The first is to find a satisfactory procedure for assigning a given infrared tracker to a given target. The second refers more to the philosophy involved in making the assignments.

With reference to the first problem, what is an effective procedure by which the vehicle-borne trackers can be assigned to targets for the search and tracking gear described in the preceding sections? Is it feasible to make this process completely automatic, or must human operators assume the responsibility for making the assignments?

With reference to the second problem, it is assumed in Ref. 1 that trackers would be assigned to targets relatively late in the burning phase yet early enough to include the last 40 seconds of powered flight.

An alternative plan, however, could be the following: Trackers would be assigned relatively early in the burning phase to determine the plane of motion at which time only a single tracker need follow the missile to burnout. It is important to find effective procedures which are attractive from the computer's viewpoint. There will also be "logistics" problems in the assignment of trackers. How does the computer handle them?

3.2 A PROPOSED FUNCTIONAL BLOCK DIAGRAM

In order to organize better the many factors which occur in the data-processing, they will be related to the functional block diagram in Fig. 2. This block diagram as formulated may not be applicable to all data-processing procedures. It does apply, however, to those described in this report. First, a brief description is given for each major block in the master computer. A more thorough analysis follows.

The decoder is essentially a sorting device. As the search, tracking, and other data are relayed through the data link network to the master computer, the decoder identifies the type of information and sends it to the appropriate place.

The satellite-earth reference system computer computes the coordinate transformation matrices between the satellites' reference systems and the coordinate system used on the ground.

The monitor-computer (M-C) has a number of functions which are largely supervisory in nature. Examples are as follows: The M-C will monitor the infrared signal strength data relayed by the search and tracking gear to look for staging information, especially burnout. The M-C decides when trackers should be assigned to targets and so notifies the tracker assignment computer. It will be the responsibility of the M-C to address

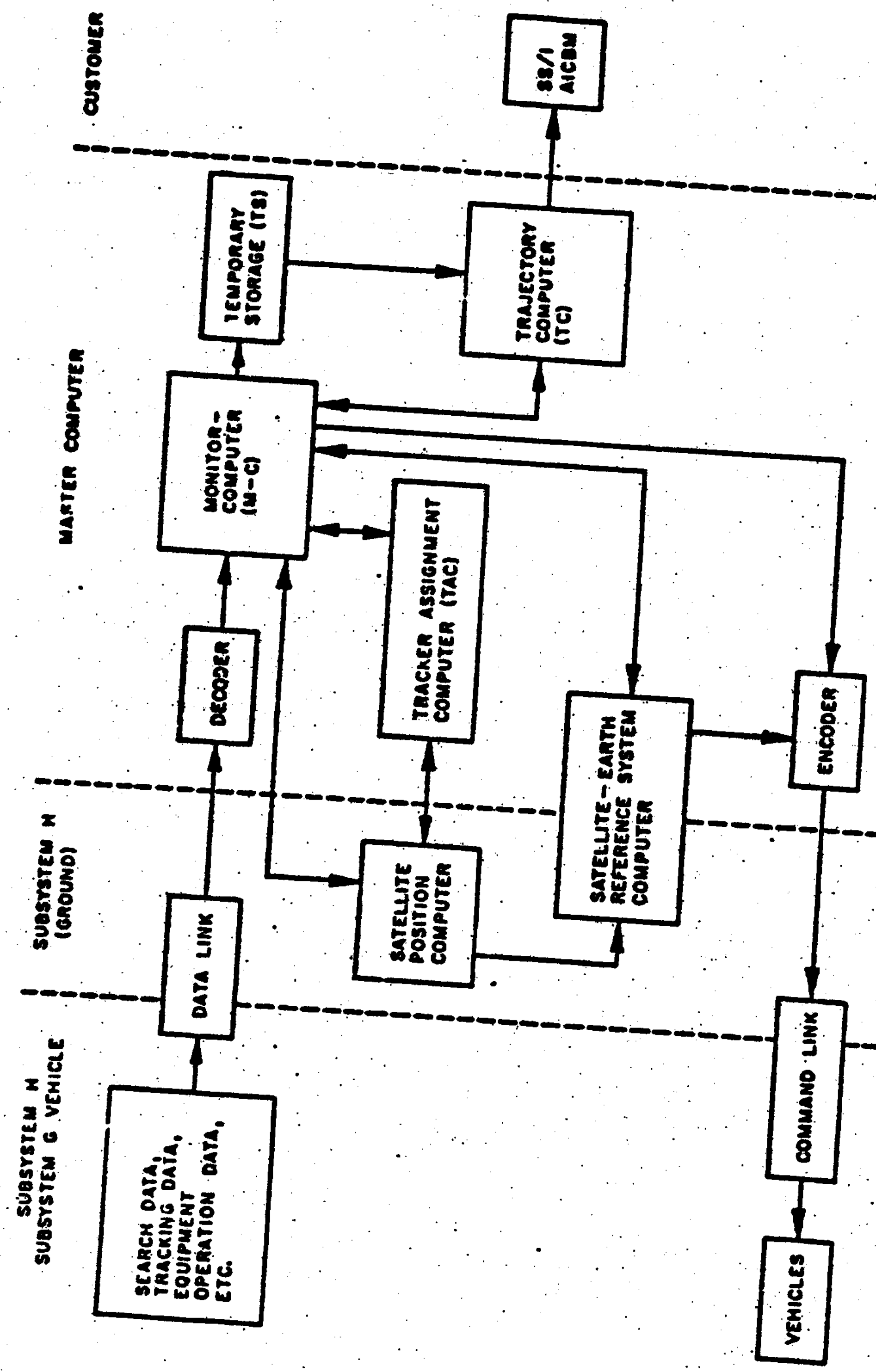


Fig. 2 Functional Block Diagram

the incoming infrared tracking data on the observed targets and send it to the temporary storage. When data is needed for subsequent calculations, the M-C orders the information from the temporary storage.

<u>The tracker assignment computer</u> (TAC) has the responsibility for making satisfactory tracker assignments. Its complexity will depend upon the degree of automation desired. Three possible realizations of a TAC are considered later in the report. Of these three the last two are of particular interest.

<u>The temporary storage</u> (TS) would likely be a high-speed, random-access memory in which the infrared and Subsystem H tracking data are stored until needed. The organization of the TS will depend upon the procedures developed for the data-handling.

<u>The trajectory computer</u> (TC) has the responsibility for most of the computing in the data-processing system. In view of the large number of missiles anticipated in an all-out attack, the TC must be capable of working at very high speed to obtain maximum intelligence from the system. The calculations to be made by the TC would be a function of the sophistication desired in the overall system; however, some basic ones would be as follows:

(1) Positional computations during the burning phase.

(2) The fitting of an appropriate curve to the results of these positional computations to obtain the burnout position and velocity.

(3) The predicted impact point, as well as certain intermediate points on the trajectory.

The results of (3) will be especially valuable for AICBM activities. Additional computations that might be considered essential would include, for example, the programming of infrared trackers to follow the free-flight paths to detect the application of any additional thrust.

3.3 THE MONITOR-COMPUTER (M-C)

Each of the major blocks with the exception of the decoder and the satellite-earth reference system computer will be discussed now in detail. The decoder is essentially a sorting device and requires no special attention at this time. The satellite-earth reference system computer could be a part of either Subsystem H or the master computer. In either case the function of this computer is clear. An estimate of the number of computations involved in computing the coordinate transformation matrices is given in Par. 4.4.

When a heat source is observed by search gear, the corresponding azimuth and elevation data from all observing vehicles are relayed through the data-link network to the ground. The decoder recognizes that search information is present and, in turn, relays the data present to the M-C. The M-C will first have to determine whether the information indicates the presence of a new heat source or whether it is another look at a target previously observed. This problem involves remembering the number and angular location of targets seen on the preceding scan and comparing the two sets of data.

Since the configuration of missiles may change considerably from scan to scan the problem is far from trivial, especially if the process is to be mechanized (particularly so if a scan rate as low as the presently assumed 12 degrees per second is used). A human operator watching an appropriate presentation unit would be capable of making rapid and accurate decisions if the total number of targets were relatively small; however, this association problem is much more difficult for a computer to handle. Since a number of satellites may be observing the same missile, an approximate triangulation is possible from the search data, and this fact may be of interest to the M-C. There exist necessary conditions that the search data on each missile must satisfy which will help to provide the needed continuity of data on a given target. (This development is only partially completed and has not been included in this report.) It appears that a satisfactory procedure for identifying and analyzing the above search data can be developed. This problem may be simplified by an appropriate design of the search mechanism. The intelligence obtained from the infrared signal intensity will also help in discriminating between missiles, and, say, cloud returns or noise.

The M-C must determine without delay whether a given heat source under observation could be a missile. Since an ICBM such as the Atlas has only about 3-1/2 minutes of its powered phase above the atmosphere, it is clear that a rapid decision is necessary. Action should probably be taken after only a few looks from a given search scanner. Generally, a number of different observing satellites will have contributed information on the target concerned in this time interval. If it is determined that a missile may be present, the action taken will depend upon the procedures developed for the data-processing. The system should be flexible enough to permit changes as it becomes operational. Any intelligence obtained from the system on enemy missile tests such as characteristics of the powered flight, for instance, can be used to improve the functioning of the data-processing facility.

Two alternative data-processing procedures were mentioned earlier in Par. 3.1.

I. Trackers are assigned to targets relatively late in the burning phase yet soon enough to include, say, the last 40 seconds of powered flight (or whatever period is finally selected). Since burnout times cannot be predicted accurately it would be prudent to assume that the average tracking time is on the order of a minute.

II. Trackers are assigned relatively early in the burning phase and the plane of motion is determined, at which time only a single tracker need follow the missile to burnout. (This procedure may not be effective if more sophisticated launching techniques are developed.)

The mathematical formulation of techniques based on procedure I appears in Ref. 1 and a detailed statistical analysis is also given. The corresponding formulation for II, although it can readily be obtained from Ref. 1, has not been specifically formulated. Should the latter procedure also be applicable some flexibility is offered over the former, and it might be developed in such a way as to reduce the total number of infrared trackers needed.

The procedure that is eventually used will be determined by the requirements placed on the system as it becomes operational. A relatively recent suggestion calls for the launching of antimissile missiles from appropriate bases before an ICBM has burned out so that interception can be made soon after the ICBM enters the free-flight path. If such defensive measures were employed, it would be essential that information on the approximate path of the ICBM be obtained as early as possible. In this case it would be advisable to put two or more trackers on each missile as soon as they were detected and to use the data received to make a number of successive approximations to their ballistic paths. No major change is required in the block diagram of Fig. 2 to account for the additional function. Probably a larger number of infrared trackers and an expanded computer facility would be needed, however.

Since the mathematics for procedure I has been developed, that procedure together with the suggestion in the next paragraph, summarized under procedure III below, will be used as the basis for the data-processing model in this report.

A primary responsibility of the M-C is to determine when infrared trackers should be assigned to targets. Any information received from the search equipment relative to when the missile was first observed, and/or to possible staging, will be essential to this determination. In order to support the M-C in this function, it is suggested that the M-C assign one tracker to each heat source from an observing vehicle as soon as it has been determined that a missile may be under observation. Procedure III is the following general plan for data-processing assumed as a model for the remainder of this report:

> III. When the M-C has determined from the search data that a missile may be under observation, a tracker is assigned to the target from one of the observing satellites. Additional trackers are assigned at an appropriate time as in procedure I in order to obtain angular tracking data on, say, the 40 seconds prior to burnout.

How the trackers are actually assigned is the responsibility of the TAC; this is described in Par. 3.4.

When the TAC notifies the M-C that a single tracker has been directed to the indicated target, a check must be made by the M-C to ascertain as well as possible whether the tracker is locked on the correct target. If it is not, the M-C must advise the TAC accordingly. An advantage of assigning a tracker to each target immediately is that as each observing search gear reports to the ground, the line of sight so indicated can be compared approximately with the line of sight determined by the observing tracker to see whether they appear to intersect. Such a procedure would also help to provide the continuity of search information relative to a given target.

When the time comes for the assignment of additional trackers the M-C notifies the TAC. The TAC in turn informs the M-C of the satellites and trackers involved when the assignments have been completed. Upon receiving this information the M-C runs through the following steps immediately:

(1) A check is made to ascertain whether the trackers assigned to presumably the same target are actually observing a common target. (The search gear may not have resolved two or more heat sources approximately on the same line of sight.) This check could be simply a consideration of calculations of the distances between the various lines of sight from the two or more observing trackers. If discrepancies exist, the M-C must be designed so that appropriate action can be taken. More trackers may be needed, for example, or the given trackers may need to be reassigned.

(2) Subsystem H information is processed to obtain satellite positional calculations for the vehicles concerned and the transformation matrices between the satellites' reference systems and that used on the ground at a rate equal to the infrared tracking data rate. (These calculations may have already been initiated due to a previous tracker assignment.)

(3) An appropriate block of the temporary storage is reserved for the incoming Subsystem H and infrared tracking data and the coordinate transformation matrices.

If the M-C determines that a sufficient number of trackers are on a given target, the vehicle positional data, the coordinate transformation matrices, and the infrared tracking data are sent to the TS. All data from a given tracker are stored under one heading; the same applies to all Subsystem H data and coordinate transformation matrices on a given satellite.

The M-C's monitoring of the infrared signal strength data to detect staging will be an additional check on the accuracy of the tracker assignments, since staging would most likely not occur simultaneously for two missiles. The missile burnout will be a final check on tracker assignments. Ordinarily, the M-C can associate those trackers with a common missile which indicate simultaneously the burnout of a missile.

The vehicle tracking data and the coordinate transformation matrices may be needed in connection with as many vehicle-borne trackers as are on a given satellite since the infrared trackers may be tracking different missiles. Therefore, the same Subsystem H results, for instance, may be used in subsequent calculations more than once. The total number of observations required from a given tracker for the subsequent computations will depend upon the mathematical procedures to be used. In this report, it is assumed that 5760 looks (144 x 40) are desired from each observing tracker prior to burnout. Since trackers will generally be observing a given target for more than 40 seconds, the following procedure is suggested: As trackers are assigned to targets, the M-C reserves a block of storage sufficient to hold only the data for 5760 observations from each tracker plus similar memory blocks for the Subsystem H data and the coordinate transformation matrices on each satellite concerned. The M-C addresses the data from a tracker in such a manner that when the 5760 memory locations have been filled the data from the next observation is sent to the spot first filled; hence only the last 5760 observations are retained. If a missile burns out before the desired number of observations has been made, the procedure used should be sufficiently flexible so that the required computations can be made on the basis of the information received.

When burnout of a missile is detected by the M-C, the infrared tracking data, the Subsystem H satellite positional data, and the coordinate transformation matrices associated with that missile are ordered from the TS into the trajectory computer. The M-C informs the TAC that certain trackers are available for reassignment, and notifies Subsystem H that the precise positional data is no longer needed on the satellites involved, provided all other trackers on each satellite are also idle. Similarly, the coordinate transformation matrices may no longer be needed.

If trackers must follow each missile's ballistic trajectory to detect any additional application of thrust ("jinking"), the M-C must remember what trackers are involved, and, most likely, be prepared to interrupt any normal calculations in progress to give priority to computing the effects of an additional thrust.

Another function of the data-processing facility to be considered would be to extrapolate the powered portion of each missile's trajectory backward in time to obtain an approximate location of the launching pads for appropriate countermeasures. Such a function would add little complexity to the computing system, in general, or to the M-C, in particular.

3.4 THE TRACKER ASSIGNMENT COMPUTER (TAC)

The primary function of the TAC is to assign infrared trackers to heat sources when so directed by the M-C. Its complexity with respect to computer requirements will depend largely upon the degree of automation desired. Three possible realizations are given in this section for discussion purposes:

A. A visual presentation of the search data (basically that system described in Ref. 3) in which human operators assign trackers to targets according to indications viewed on a two-dimensional, ground-stabilized display. A relatively small associated computer would be needed in this case.

B. A completely automatic TAC which assigns trackers on request from the M-C.

C. A three-dimensional scale model presentation with a visually interpreted, real-time simulation of the search and tracking observations which permits human operators to make the proper tracker assignments. (Some of the functions of the M-C are included here.)

Each proposal will now be discussed in turn. The first realization is presented chiefly to point out that a more sophisticated TAC will be needed for the operational system. The second realization, if feasible, would surely be the most desirable system of the three in view of the complete automation. The third system offers a number of advantages in reducing the complexity of the computer facility; however, human observers are needed at all times. A combination of the last two proposals would provide perhaps a very practical solution for a TAC. The three-dimensional visual presentation would indicate how an attack was developing and would permit a manual override of the associated computer, if necessary.

A. The visual presentation developed in connection with the ICBM Attack-Alarm System, together with a relatively small associated computer, would be satisfactory for the precision tracking-prediction system, provided the rate at which missiles were launched was not large, for example, five to ten missiles per minute. In this presentation the targets would be indicated on a ground-stabilized, two-dimensional display on which the predicted orbits of all observing vehicles (obtained from Subsystem H) could also be shown. Operators would make the necessary tracker assignments on the basis of this information. The remainder of the data processing would be completely automatic.

That a more sophisticated procedure for tracker assignment will be required in the operational system is evident from the following discussion . If the average launching rate of 30 missiles per minute is assumed, as many as 120 missiles could be in the powered phase at a given time. Hence, as many as 120 indications of targets could be on a display at a given time during an all-out attack (and it is possible for all of these indications to appear on a single display should each vehicle have its own display unit). It would be necessary to assign trackers at an average rate of one to two per second in this case. These considerations together with other complications arising out of the presence of many missiles at one time support the contention that a more sophisticated TAC will be needed.

B. A completely automatic TAC also presents a number of difficult problems, especially if a large number of targets must be handled simultaneously. One of the major problems is the labeling problem discussed in connection with the M-C in Par. 3.3. Since an average of 15 additional indications of new targets could appear on each revolution of a search scanner, the M-C must label each target carefully so that continuity of information is maintained on a given target.

A second problem can be described with the supposition that there are five trackers on a given satellite and that this particular vehicle is observing a number of missiles of which, say, six must be assigned trackers immediately. It does not appear difficult to command the vehicle to assign one tracker to each of five of the six targets. However, the sixth missile must be assigned a tracker from some other observing vehicle. The problem is this: How does the second vehicle involved know which of the missiles indicated by its scanning equipment is the one in question? Calculations of the distances between the line of sight to the sixth missile from the first vehicle and each of the lines of sight from the second missile would ordinarily indicate which target under observation by the second vehicle is the one in question. The problem is not trivial, especially if a number of targets are in the same general area.

A third problem is to formulate an effective procedure for directing a given tracker to a given target using the search information. Essentially, this means directing the tracker along the last line of sight to the target indicated by the search gear. Some refinement is necessary, however, as the search information may be several seconds old. It may be that the investigation mentioned earlier (in Par. 3.5) of conditions on the search data for a target to be an ICBM will yield results which can be applied to this particular problem.

In order to make satisfactory tracker assignments, the TAC must determine which observing satellites will be within sight of their respective targets until burnout occurs. This means that Subsystem H will have to supply information on demand concerning the orbits of possible observing vehicles. This information should be readily available since the satellites will presumably already have been programmed with reference to the constantly changing satellite subnetwork configuration. A possible procedure for selecting infrared trackers would be simply to use trackers on those satellites closest to the target. These satellites would be indicated roughly by an examination of the elevation angles of the targets at the various observing vehicles. This procedure is probably an oversimplification, however, as problems in the assignment of trackers will arise as system saturation is approached. A careful analysis of the situation is needed to determine the number of trackers required. If the supply of trackers were sufficient, many of the above problems would be essentially solved in that trackers could be assigned immediately to targets as they come into view and could follow the missiles to burnout and beyond, if necessary.

C. The third suggested realization for a TAC could be used by itself or in conjunction with the automatic version just described. The proposal calls for a three-dimensional, scaled, satellite-earth configuration which simulates in real time the observations made by the infrared tracking-prediction. The lines of sight between satellites and observed targets are indicated by beams of light.

If a scale of 10 miles per inch were used, the U.S.S.R. and her satellite neighbors would appear as a portion of a spherical surface with a radius of approximately 33 feet. The portion in question would measure approximately 50 feet by 20 feet on the spherical surface. Any topographical features desired concerning the U.S.S.R. could be indicated on the model. Certainly, known and suspected missile launching sites should be marked. Orbiting vehicles at an altitude of 1000 miles would trace out paths on a near spherical surface of an approximate radius of 41 feet in this scale model (8 feet above the model's surface). Since satellites at an altitude of 1000 miles could be scanning enemy territory from a considerable distance away, nearly a hemispherical surface would be needed in this simulator to display the entire region from which orbiting vehicles could observe activity over Russia. If other areas of the earth were also to be scanned, for example, to guard against ICBMs, the model would have to be enlarged correspondingly.

Simulation of the orbiting vehicles to present their activity in real time may require ingenuity. For each satellite in a position to observe Russian-controlled territory there could correspond a projector whose simulated orbital motion were determined from Subsystem H calculations. The satellites would move at a rate of approximately 30 inches per minute. The projectors would have to be designed to emit beams of light corresponding to the lines of sight determined by the respective search and tracking mechanisms when heat sources were present. If the completed scale model presentation system were situated in a dimly lighted room, and if a fine powder were present in the atmosphere, the light beams would be clearly visible. Colored filters could be used to help in distinguishing between search and tracking beams, if necessary, or even between different trackers. Observation points would have to be constructed so that no interference occurred in the operation of the system. A number of operators would be needed, each watching a preselected region. Perhaps more than one presentation could be provided to give each observer at least two views of his particular region of interest to provide more complete close-up information. Each operator would also have before him a panel indicating which satellites were in a position to scan his assigned region and whether each associated tracker were idle or busy. Since a given vehicle would probably be indicated on more than one operator's panel, a problem could arise among the various operators in assigning trackers if system saturation were approached. A master control with an override provision might be a solution to this difficulty.

A plausible procedure to be used in operating the above system in event of an attack is the following: As a target in a given operator's region is picked up by search scanners, one tracker is immediately assigned from one of the observing vehicles. An ICBM would appear about an inch off the surface of the model, and burnout would probably occur roughly 15 to 20 inches from the surface. A convention would have to be agreed upon to establish jurisdiction over a missile which was first sighted in one region and passed into another region before trackers were assigned although such an event would ordinarily be rare. The three-dimensional presentation should make the task of a single tracker to each heat source as it appears reasonably uncomplicated. If a given heat source were a cloud, this fact should not be difficult to establish by the operator, and the assigned tracker would be released. If the heat source were, in fact, a missile, an indication would be given to the operator at a predetermined time. Two or more trackers would then be assigned to the target by the operator. For greater flexibility the number assigned should be variable. The tracking light beam would be a steady beam, while the search indications would probably consist of short flashes. It should not be difficult, however, to pick out immediately other satellites observing a given target in order to make satisfactory tracker assignments.

It is believed that the proposed or a similar three-dimensional visual presentation would enable operators to make rapid and accurate decisions concerning tracker assignments. The complexity of the problems of the associated mechanized portion of the TAC is greatly reduced from that existing for a completely automatic TAC. In the event that an automatic TAC is developed, the above visual display would still be of considerable value in making a quick check on the functioning of the system.

3.5 THE TEMPORARY STORAGE (TS)

Briefly, the TS is a high-speed, random-access memory unit in which the Subsystem H and infrared tracking data, including the satellite-earth coordinate transformation matrices, are stored until needed. The M-C has the responsbility for sending information into and out of the TS. Precisely what information is stored, and how and when it enters and leaves the TS, will depend upon the data-processing procedure finally selected. With reference to the model assumed for this report, e.g., procedure III of Par. 3.3, the data would be stored until burnout at which time the M-C would order that the appropriate data be sent to the trajectory computer.

The access speed required of the TS is to some extent a function of the overall system design; however, it appears that in any event a memory unit on the order of a magnetic core storage will be needed to provide the desired speed and access flexibility.

The size of the TS is, again, a function of the data-processing procedures used. Relative to procedure III, the TS would have to be large enough to store all the information on the estimated maximum number of missiles to be launched during a time interval approximately equal to that during which data is required on each missile prior to burnout.

3.6 THE TRAJECTORY COMPUTER (TC)

The majority of computations in the proposed data-processing facility are made in the trajectory computer. Hence, the TC is basically a very high-speed computer. The organization of the data-processing facility as outlined in the functional block diagram is such that much of the editing of the observational data will have been done prior to the time data reaches the TC. For instance, after procedure III of Par. 3.3, all the Subsystem H and infrared tracking data and coordinate transformation matrices are stored in the TS until needed. When a missile burnout occurs, the M-C orders the data associated with that missile into the TC, thus permitting all computations on a given missile to be made at one time. Such a procedure offers many advantages over procedures in which computations on a number of missiles are in progress at the same time.

The computations to be made by the TC will depend upon the functions required of the overall system; however, they would probably include some or all of the following:

(1) Successive positions of each missile during the burning phase.

(2) The smoothin · of the above infrared data on each missile to obtain the burnout position and velocity.

(3) Determination of the plane of the free-flight path.

(4) Prediction of the impact-point and any desired points on the ballistic trajectory.

(5) Prediction of the location of the launching pads.

(6) The programming necessary in order for infrared trackers to follow the ballistic trajectory.

(7) Estimation of the effects of applying additional thrust.

(8) Coordinate transformations whenever needed.

A thorough analysis of the first four items relative to procedure I of Par. 3.3 appears in Ref. 1. Mathematical procedures are formulated in that report for effectively using the precision tracking data. Considerable attention was also devoted to investigating the quality of the results obtained. The reader is referred to the original report for a complete discussion. In this report only the aspects which pertain directly to the TC are considered.

Two techniques were developed in Ref. 1 for estimating missile positions in space during the powered phase using the precision tracking measurements. If there were no errors in the infrared tracking-prediction system, the intersection of the lines of sight determined by the infrared trackers would coincide with the missile's position. In practice there will be errors, in the tracker measurements, in the reference system, in the Subsystem F tracking of the vehicles, etc., and it is unlikely that an intersection of the lines of sight would exist. Therefore, some estimate of the target's position is required. One choice is to take as an estimate that point, the sum of whose distances from the lines is a minimum. This procedure, called the "least squares" estimate, will be considered in order to continue the intended computer evaluation.

In this method the missile's position in space at any time during powered flight is given by the following matrix equation:

$$(R) = (K)^{-1} \sum_{n=1}^{N} (K_n)(R_n), \qquad (1)$$

$$(K) = \sum_{n=1}^{N} (K_n),$$

$$(K_n) = \left[I - (Z_n)(Z_n)' \right],$$

and N is the number of trackers assigned to the target. (R) is a 3 x 1 matrix which gives an estimate of the target's position relative to an inertial coordinate system. (Z_n) and (R_n) are also 3 x 1 matrices which contain the observational data supplied by the infrared trackers and the Subsystem H satellite trackers, respectively, transformed to the same inertial coordinate system. The elements of (Z_n) and (R_n) would be the equivalent of, say, bounded five decimal digit numbers. The value of N would probably be variable in the operational system for greater flexibility. From the standpoint of the number of calculations involved, it is desirable to keep N small, say, two or three; however, it has been shown in Ref. 1 that the estimate of the target's position improves considerably with N. On the other hand, the number of trackers available per missile in the event of an all-out attack may not be so large as would otherwise be desired.

There would necessarily be coordinate transformations involved with the infrared observational data (the elements of (Z_n)), since this data is taken in the satellite's reference frame. The Subsystem H tracking data (the elements of (R_n)) could probably arrive at the master computer in the desired form, i.e., given with respect to the inertial reference system used.

When the above computations have been made for the required number of target positions, the burnout position and velocity can be determined. The tracking data are to be smoothed in some way to estimate these burnout conditions. Two methods of smoothing are indicated in Ref. 1. The technique employed in the ICBM prediction problem involves fitting a polynomial to the tracking data. The degree of the polynomial used may not be determined until after burnout occurs. Once a suitable polynomial has been fitted to the data, the estimates of burnout position and velocity are found by evaluating the polynomial and its derivative at the burnout time. These estimates are given respectively by

$$(Y(T)) = \sum_{i=0}^{p} (A_i) P_i (M-1) \qquad (2)$$

and

$$(Y'(T)) = \frac{M-1}{T} \sum_{i=0}^{p} (A_i) P_i' (M-1), \qquad (3)$$

where

$$(A_j) = \frac{\sum_{n=0}^{M-1} (X_n) P_j (n)}{\sum_{n=0}^{M-1} P_j^2 (n)} .$$

Here, the prime (') indicates differentiation with respect to time; M is the number of data points; p is the degree of the approximating polynomial; and T is the burnout time. The matrix (X_n) represents the successive estimates of the missile's position, and the $P_i(n)$ are a known set of orthogonal polynomials. The burnout conditions obtained could be checked at this time to determine whether they have the rangesof missiles which require defensive action.

The plane of the free-flight path of the missile is readily and accurately determined by the center of the earth and either the successive positions obtained along the powered path or the burnout conditions. Assuming that sophisticated launching techniques are not developed (that is, assuming the missile moves in such a plane for the latter portion of its powered phase),-then as was shown in Ref. 1, the use of the positions along the powered portion of the flight, obtained from equation (1), give the better estimate of the plane of motion. Knowledge of the plane of motion will be particularly important for effective ICBM defense measures.

Consider a coordinate system whose origin is at the center of the earth. If the plane of motion is not normal to one of the axes, say, the X axis, it has the equation

$$X + aY + bZ = 0 \tag{4}$$

The least-square estimates of the parameters a and b were derived in Ref. 1 and are respectively:

$$\hat{a} = \frac{(\Sigma X_i Z_i \, \Sigma Y_i Z_i - \Sigma Z_i^2 \, \Sigma X_i Y_i)}{(\Sigma Y_i^2 \, \Sigma Z_i^2 - (\Sigma Y_i Z_i)^2)}$$

and

$$\hat{b} = \frac{(\Sigma X_i Y_i \, \Sigma Y_i Z_i - \Sigma Y_i^2 \, \Sigma X_i Z_i)}{(\Sigma Y_i^2 \, \Sigma Z_i^2 - (\Sigma Y_i Z_i)^2)}$$

where the summation in each case ranges over the data points 0, 1, 2, . . . , M-1. The X_i, Y_i, and Z_i represent the coordinates of the target observed at the successive positions along its powered path.

The equations for the prediction of the missile's free-flight trajectory will be revised from time to time as more is learned about the trajectories of ballistic missiles. No particular problems are anticipated in these computations although it is to be expected that they will become more complicated as the precision increases.

One possible procedure in connection with this function is as follows: The TC would calculate the burnout conditions and the impact point. If a given ICBM were seen to be a threat, the initial conditions for the ballistic trajectory, including burnout time and possibly the plane of motion, would be sent immediately to an appropriate anti-missile missile site.

At this remote station a smaller special purpose computer, probably an analog device, would supply the necessary extrapolation of the free-flight path for defensive action. Since a number of outlying stations would likely be available, the computing load at any given one should not be excessive.

In this report certain equations of motion that have already been programmed for an existing computer will be assumed as a basis for evaluation. These equations do not give, at present, the precision that will be required in the operational system; however, they suffice for obtaining the estimate of the number of calculations needed in Par. 4.4.

The computations required for programming the infrared trackers to follow the ballistic trajectory have not yet been studied. Certainly, a considerable amount of computing is involved. For example, Subsystem H would be called upon to provide precise information on the orbits of appropriate satellites. It may be that this function should be also delegated to a computer separate from the TC.

Few additional complications would occur in the TC if the powered portion of the trajectory were extrapolated backward in time to determine the approximate location of the firing pad. More accurate results would be obtained if trackers were assigned to targets immediately upon detection by the search gear. Such action would imply a larger supply of trackers than that called for by procedure III alone as well as additional high-speed memory. On the other hand, if anti-missile missiles are to be launched before burnout occurs, trackers would have to be assigned as early as possible for satisfactory operation. Hence, little additional complexity would be introduced in this case.

Calculation of the effects of applying additional thrust after burnout should not present any serious problems beyond those already implied by the programming of the infrared trackers and the considerable increase in the number of trackers needed.

The transformation of coordinates for the tracker data, from the satellites reference system to the inertial coordinate system used on the ground, will also require considerable computing. Basically, a 3 x 3 matrix of the transformation is required between the stellar system of the satellite and the ground reference system. It may be advisable to make these calculations in advance with another computer, as has already been mentioned, and to send the results to the master computer along with the Subsystem H satellite tracking data. This can be done since the stars being tracked and the satellite positions would be known in advance.

SECTION 4 QUANTITATIVE EVALUATION OF THE COMPUTER FACILITY

4.1 PRELIMINARY REMARKS

The preceding qualitative discussion of the data-processing facility required for the infrared tracking-prediction system is developed in this section in a more quantitative form. Such questions as the size of the high-speed memory, the estimated total number of computations involved, the data-processing rate, etc. will be examined under the many assumptions previously made.

To present a more distinct picture of the magnitude of the problems involved, Par. 4.6 indicates how the IBM STRETCH computer might be used in the proposed data-processing facility. Although this particular computer may not be used, it is believed that a machine with at least the capabilities of STRETCH will be required. Most of the important features of STRETCH relative to this study have been taken from a paper by S. W. Dunwell entitled "Design Objectives for the IBM STRETCH Computer," (Ref. 4) to which the reader is referred for additional information. It is emphasized that the numbers and other characteristics given regarding STRETCH are design objectives and that some changes may be expected in the operational system. A more complete evaluation of its applicability to the infrared tracking-prediction system will be possible when the appropriate information is released by IBM.

4.2 THE MESSAGE STRUCTURE OF THE VEHICLE-ORIGINATED DATA

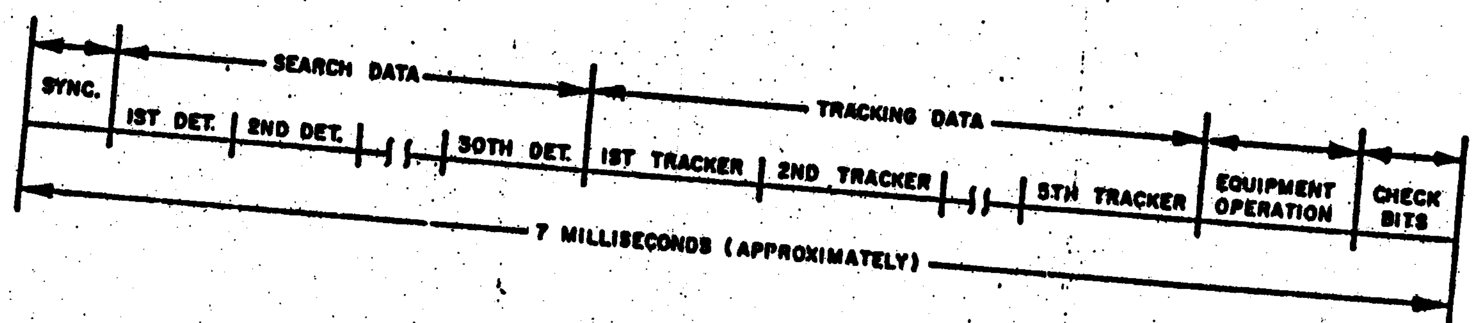
In the data-link network assumed for this evaluation a synchronization pulse provided by the vehicle clock is sent every 7 milliseconds, and the data is decoded on the ground on the basis of its time of arrival relative to this pulse. Using this assumption, an outline of a possible message structure, similar to one given in the data-link study, can be made. In a 7 millisecond interval the assumed search equipment would traverse 5 minutes of arc, that is, the angular accuracy in azimuth. During this time each of the 27 acquisition detectors is sampled and the magnitude of any signal is noted. Also within this same time interval the complete orientations of the five trackers, as well as the magnitudes of the signals observed, are given. In addition, data is transmitted on the current operating status of the equipment and for whatever message redundancy is needed. An e- -- -- of the number of binary digits involved in such a message is obtained in the following manner. A four-digit binary number provides the synchronization pulse and indicates at the same time the satellite identification.

Three binary digits suffice to indicate any one of eight intensity levels for each of the 27 detectors in the search gear. Two 15-digit numbers (5 decimal digits each) indicate the angles between the line of sight to the target and the two directions determined by the star trackers. Another digit gives the general orientation of each tracker with respect to the plane of the satellite's orbit. Three digits give the infrared signal strength observed by each tracker. Perhaps four digits are needed for indicating the current operating status, and another six are used for message redundancy as suggested by the data-link feasibility report. This gives a total of 265 binary bits that it might be necessary to transmit during each 7 millisecond interval for each observing vehicle

If no targets were under observation, for instance, the number of bits actually transmitted could be correspondingly reduced. An illustration of the message construction is given in Fig. 3.

Since as many as 50 satellites could be reporting during an all-out attack, nearly 2,000,000 bits per second could be arriving at the master computer for processing from the satellites. When targets are being tracked, there will also be satellite tracking data and coordinate transformation data arriving at the master computer. Each satellite positional calculation would involve 3-five-decimal digit numbers or a total of 45 binary digits. The nine elements in a coordinate transformation matrix [illegible] roughly 16 binary digits each for a total of 144 bits. Consider, for example, that trackers from 20 satellites were actually tracking targets. Then, approximately an additional 500,000 bits of information would be arriving at the computer each second which makes a total of 2.5×10^6 bits per second.

It is clear then that a highly efficient data-handling facility is required. The decoder and monitor-computer are responsible for the majority of this data-handling. The decoder will recognize the various parts of each message, search data, tracking data, equipment operation information, etc. and will send each part along with the satellite identification to the appropriate unit in the M-C. The M-C will have many decisions to make concerning the disposition of this incoming data which will involve a modest amount of computing. A considerable portion of its efforts, however, will be devoted to sending the infrared and Subsystem H tracking data and coordinate transformation matrix calculations and from the temporary storage.



SYNCHRONIZATION AND SATELLITE IDENTIFICATION	4 BITS
SEARCH DATA	81 BITS
TRACKING DATA	170 BITS
EQUIPMENT OPERATION	4 BITS
CHECK BITS	6 BITS
	265 BITS TOTAL

Fig. 3 Message Construction

4.3 THE TEMPORARY STORAGE REQUIREMENTS

If a data-processing procedure similar to III were used, a considerable amount of data must be available for processing at missile burnout. The size of the high-speed memory unit needed can be estimated by determining how much information must be stored. Such information would include the following:

(1) Infrared tracker angular measurements.

(2) Subsystem E satellite positional data.

(3) Satellite-earth coordinate transformation matrices.

Under procedure III, this data is required for the 40 seconds prior to burnout, i.e., for a total of nearly 6000 observations at 144 looks per second. Each infrared tracker measurement would consist of two angles and the tracker's general orientation relative to the plane of the satellite's orbit. Approximately 32 binary bits are needed for this. As in Par. 4.2, each satellite positional calculation would involve a total of 45 binary bits, and each coordinate transformation matrix would require a total of 144 bits. Since a given satellite will have trackers on as many as five missiles, the amount of data to be stored is not just a function of the number of missiles tracked. An upper bound to the data to be stored will occur as system saturation is approached when all available trackers (and satellites) are occupied. If, for example, 90 trackers from 20 satellites were in use (tracking, say, 30 targets), and if the data rate were 144 looks per second, then, during a 40 second interval, approximately 40×10^6 bits ([(90) (32) + (20) (45) + (20) (144)] (5760)) would have to be stored. This amount of data can be stored by the IBM STRETCH computer, according to the design objectives (see Par. 4.5); however, it is considerably beyond the high-speed, random-access storage capacity of any machine presently in operation.

4.4 ESTIMATE OF THE NUMBER OF COMPUTATIONS

Next, an estimate is obtained for the number of calculations (additions, subtractions, multiplications, and divisions) that must be made by the trajectory computer on a single missile after burnout occurs (assuming that, under the data-processing procedure used, the observational data is stored until burnout). Such an estimate will help to indicate approximately the size of the computer needed. No distinction is made between additions and subtractions nor between multiplications and divisions in this estimate.

There are also numerous computations to be made by the M-C in connection with processing the incoming data. These computations were discussed in Par. 3.3 in a general way. Since a computer program has not yet been developed for handling the 2.5×10^6 bits of information that could arrive every second, no attempt will be made to give an estimate of the number of calculations and logical decisions involved. A general indication of the computer facility necessary to handle the functions of the M-C can be made, however, and a discussion of this point appears in Par. 4.6.

With reference to the TC, the number of individual computations required will depend strongly upon what functions are performed and on the programming of the data-processing procedures for the computer. For the present evaluation consideration will be given to the necessary computations for the following:

(1) Transforming the infrared tracking data from each satellite's reference system to the inertial reference system used on the ground.

(2) Determining the numerous position points along the powered portion of the flight.

(3) Calculating the burnout position and velocity.

(4) Determining the plane of the missile's free-flight path.

(5) Computing the impact point and, perhaps, a few points on the ballistic trajectory.

No specific estimate is made of the number of calculations needed for determining the location of launching pads; for programming trackers to follow the free-flight path; or for computing the effects of an additional period of thrust. With respect to percentage, the first and third of these tasks would add little to the number of computations needed. The second function has not been studied from this point of view.

The approximation to the number of computations required was obtained simply by estimating the number of additions and multiplications involved, and no attempt was made to consider logical operations or to develop any "shortest" program. The following list of symbols is used:

N = Average number of trackers assigned per target

M = Number of data points needed on the powered path (product of the data rate and the time interval throughout which data is required)

P = Degree of the approximating polynomial to be fitted to the above data points

K = Number of points to be determined on the free-flight path.

Using this notation, the approximate number of calculations required for the above five functions are as follows:

Function	Number of additions	Number of multiplications
(1)	12 M	12 M
(2)	(27 N + 5) M	(18 N + 48) M
(3)	6 M p	6 M p
(4)	5 M	5 M
(5)	850 K	860 K
Total	(27N + 6p + 22) M + 850 K	(18N + 6p + 65) M + 860 K

if, for example, N = 3, p = 3, M = 5760, and K = 20, approximately 714,000 additions and 806,000 multiplications are required. It is re-emphasized that the missiles must be processed at very nearly the launching rate; therefore, under the assumptions of this report, over 1,500,000 calculations must be made in the 2 seconds allowed just for this portion of the data-processing on a single missile. Approximately 70 percent of the additions and of the subtractions in the previous example are used in the determination of the 5760 positions along the powered path. Changing N by one, for instance, (i.e., increasing or decreasing by one the average number of trackers per missile) makes a difference of 150,000 additions and 100,000 multiplications.

If M could be halved without materially affecting the quality of the results, a saving of one-third would be obtained in the number of calculations needed. The effect on the probable error in the burnout velocity can be estimated as follows: This error in burnout velocity is proportional to

$$\frac{1}{\sqrt{RT^3}}$$

where R is the infrared tracker data rate and T is the time tracked (from Ref. 1). Thus, if the data rate were divided by 4 and T were left unchanged, i.e., M is divided by 4, only a factor of 2 would occur in the estimated error of burnout velocity. The problem is not quite this simple, however, since a number of factors must be considered. If the trackers employed were not of the lock-on type mentioned earlier, to mention one such factor, a relatively small data rate would make the problem of providing data continuity on a given target much more difficult. It is apparent that a suitable compromise will have to be made.

4.5 DESIGN OBJECTIVES OF THE STRETCH COMPUTER

The STRETCH is a very versatile general-purpose computer whose estimated operating speed on typical technical applications will be on the order of 100 times that of the fastest general purpose computer now in use. The system will consist of two major computer sections, both communicating with one multi-sectional memory. The two computer sections are an input-output section to maintain communication with the various input-output units and a high-speed arithmetic unit.

The input-output section will include such devices as the following: a magnetic disk memory of one million words capacity capable of communicating with the computer at a rate of one word each 4 microseconds; high-speed magnetic tape units; paper tapes, etc. The system will be capable of operating on-line with numerous analog and digital devices.

The arithmetic unit is a very high-speed device. The basic time for addition and subtraction in floating point form is 0.6 microsecond. Multiplication and division will take 1.2 microseconds. Approximately 0.2 microsecond must be added to each of these times for each data word transferred between the core memory and the arithmetic unit. The word length is considerably greater than that of most existing computers.

Two classes of ferrite memory will be used. One class will be provided in units of 8192 words and will have a full cycle time of 2 microseconds. The second class will be provided in units of 512 words and will have a full cycle time of 0.5 microsecond. When reading from these two memories a word will be ready in 0.5 and 0.2 microsecond, respectively. Multiple sections of each class are planned so that each section can operate concurrently with the others. Ultimately, the design objectives of the STRETCH system call for a random-access memory of one million words capacity and an external memory in the form of magnetic disks and tapes with a total capacity of up to 100 million words.

There are many details concerning this computer which have not yet been released by IBM and which would be of considerable interest in view of the possible applications of STRETCH to the data-processing facility described in this report.

4.6 APPLICATION OF STRETCH IN DATA-PROCESSING FACILITY FOR INFRARED TRACKING-PREDICTION SYSTEM

In view of the considerable data-processing required for the tracking-prediction system, the use of any computer currently in operation is precluded. For example, consider a very recently developed computer, the IBM 709. Additions and subtractions require approximately 24 microseconds; multiplications and divisions require approximately 240 microseconds. Over 200 seconds would be needed to perform the calculations on a single missile that must be made after burnout occurs. If the data-processing that must be done prior to burnout is also considered, for the assumptions of this report (chiefly, that 450 missiles are anticipated in 15 minutes) perhaps an average of one IBM 709 computer for every two missiles would be required or over 200 computers in all.

The IBM STRETCH computer, according to its design objectives (which it appears are being met), offers a possible solution to the physical realization of the data-processing system. The number of these computers needed will depend largely upon the missile processing rate desired, assuming that the required functions to be performed have already been specified and that the data-processing procedures have been formulated. Under the assumptions of this report it appears that the data-processing capability of approximately two STRETCH computers would be required. The reasons for this conclusion follow.

The data-processing conveniently falls into two general areas under data-processing procedure III--that which must be done on a given missile prior to burnout and that which must be done after burnout occurs. Assuming the basic rates of addition and multiplication stated for the STRETCH, a single computer could probably perform only the calculations required on a single missile after burnout occurs. If 100 percent efficiency were assumed, 1.7 seconds would be required. In practice, an efficiency of 75 to 85 percent is probably more realistic for the STRETCH. The computing time required could probably be reduced somewhat by a careful analysis of the mathematical formulation as well as by decreasing the number of position points required on the path of the missile prior to burnout (provided the quality of the results is not significantly decreased).

Processing the incoming data is also a large task. This processing includes analyzing the search data; assigning trackers to targets; sending the tracking data to the temporary storage; interpreting the equipment operational data; and performing the other functions mentioned in connection with the TAC and M-C.

It was estimated in Par. 4.2 that, under the assumptions of this report, 2.5×10^6 bits per second would be arriving at the computer facility for processing. Almost half of this data, 10^6 bits per second, would be sent directly to the temporary storage. There should not be any difficulties in recognizing this data (e.g., infrared tracker angular measurements, satellite tracking data, and the coordinate transformation matrices) and in sending it to the TS. The rate at which data must be stored and the amount involved (assuming data-processing procedure III) are both well within the capability of a STRETCH computer even with the other processing considered. The time required for storing, say, 10^6 bits depends on the type of memory concerned; however, even if the magnetic disk storage were used not more than perhaps 80 milliseconds should be needed.

The processing of the search data will involve some computing, but there appear to be no serious problems. If, for example, each of as many as 30 satellites were observing the assumed maximum number of ICBMs, which would be in the burning phase at a given time (approximately 120 for this report), an average of 120 indications per second would be arriving at the computer for processing. Any necessary computations and decisions could be made readily in the time allowed.

Although the role of Subsystem H in the assignment of trackers has not yet been fully specified, no computer difficulties are anticipated in this phase of the data-processing from the standpoint of a STRETCH computer. Little attention has been devoted to the processing of information on equipment operation thus far; however, no computer problems are expected in this function either.

Hence, it is believed that a single STRETCH computer could handle the data processing, other than the computations required after burnout occurs, for the system outlined in this study. A more detailed estimate must await further study.

Thus an arrangement of two STRETCH computers could serve as the basis of a data-processing facility for the infrared precision tracking-prediction system under the assumptions of this report. One computer would perform the functions of the trajectory computer while the other would do the remaining processing. The two machines would be connected through the input-output units. One of the important design objectives of the STRETCH calls for the operation of the computer on-line with other analog and digital devices.

If sufficient ferrite storage were not available for use as the temporary storage unit, it might be possible to use the magnetic disk memory for this purpose. The access speed and capacity are satisfactory; however, problems would arise if there were not a sufficient number of reading and writing heads. When a missile burns out, the associated data must be made immediately available to the TC for the subsequent calculations. If, as according to data-processing procedure III, only tracking data from the 40 seconds prior to burnout were required, it would be difficult to use the storage offered by magnetic tapes for the temporary storage since tracking would ordinarily be carried out over a longer period, and the tape usually reads in one direction only. Disk memory from its physical construction alone would permit the retaining of only the data taken during the desired time interval.

As an approximation, it is estimated that one STRETCH computer is needed in the data-processing facility of the infrared tracking-prediction system to give a missile processing rate of one missile every 4 seconds. If the average missile launching rate were, say, one a second, approximately four STRETCH computers would be needed. It should be emphasized that these estimates depend to a great extent on many factors such as (1) the functions required; (2) the formulation of optimum data-processing procedures for these functions; (3) the extent to which Subsystem H is coordinated with the computer; (4) the operational characteristics of STRETCH as compared to the design objectives.

SECTION 5 CONCLUSION

5.1 SUMMARY OF AREAS REQUIRING FURTHER STUDY

In this section a list is presented of some of the more important problems and comments relative to the data-processing facility for the infrared precision tracking-prediction system. Most of the items were discussed in the report and all require additional consideration.

(1) If use is made of a search mechanism whose general characteristics are similar to those assumed in Par.2.3, what is an effective procedure for processing the data received when a relatively large number of targets are present? In particular, it is important to provide a continuity of data on each target under observation.

(2) If the infrared trackers are not of the lock-on type, a situation exists which is similar to the one described in problem (1). The data-processing problems are more complicated in this case because of the high data rate and the necessity of directing the trackers to follow targets.

(3) Considerable attention must be devoted to the development of a suitable satellite reference system. The one suggested in Par. 2.2 would be satisfactory with respect to computers; however, it might not be acceptable for other reasons.

(4) If an automatic tracker assignment computer is used, a procedure must be developed for making satisfactory tracker assignments. The procedure should be flexible enough to solve any "logistics" problems in assigning trackers that might arise as system saturation is approached.

(5) The computer facility used for supervision of the intersatellite network requires study. Under the data-link system assumed in this report, satellites must be programmed to become part of the various subnetworks or to be removed from them, and the transmitting and receiving antennas must be correctly positioned.

(6) If trackers must follow the free-flight path a somewhat more sophisticated data-processing system will be required in view of the probable increase in the number of trackers needed and the additional data-processing involved.

(7) The mathematical formulation of any data-processing procedures used must be carefully analyzed from the computer standpoint to reduce the processing time whenever possible.

(8) It was assumed in this report that all data-processing is done on the ground. An alternative under investigation calls for smoothing the infrared tracking data on orbit using satellite-borne computers and sending only appropriate data to the ground. A considerable saving in the complexity of the ground-space communications is achieved with this method. A preliminary study indicates that this data-processing procedure would simplify the required computer facility considerably.

(9) When the infrared precision tracking-prediction system becomes operational, information should be available from missile tests, which, if properly evaluated, could be used to improve the functioning of the overall system.

(10) Since the full capacity of the data-processing facility in the operational system will be used only if an all-out attack occurs, some attention should be given to the possibility of using the computer facility for Subsystem E, Subsystem F, or other applications.

(11) Many of the questions arising in this report could be considered in a better perspective if a number of plausible models were formulated of how an actual ICBM attack might evolve. These models would have to account for many factors, for example:

a. Satellite configuration and location of readout stations.
b. Characteristics of the search and tracking gear used.
c. Type of tracker assignment computer used.
d. Location and characteristics of ICBM launching sites.
e. Number of ICBMs available for attack and the anticipated launching pattern.
f. Characteristics of the burning phase, including staging and guidance.
g. Whether or not trackers must follow the free-flight path.
h. Location of targets in the U. S.

Such an investigation is in progress, and it should prove extremely valuable for developing insight into the entire problem of infrared detection and precision tracking.

5.2 CONCLUDING REMARKS

The feasibility of a data-processing facility for the infrared precision tracking-prediction system has been established. Although the sophistication of the operational system depends upon many factors, as evident in this report, an indication of the order of magnitude of the problems involved has been obtained. The solutions to many problems must certainly await further study and, in particular, the preliminary design of the vehicle-borne equipment.

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