6R-203

THE APPLICATION OF A HIGH-SPEED DIGITAL COMPUTER TO THE PRESENT-DAY AIR TRAFFIC CONTROL SYSTEM

D. R. Israel

division 6 • lincoln laboratory massachusetts institute of technology

Report R-203

THE APPLICATION OF A HIGH-SPEED DIGITAL COMPUTER TO THE PRESENT-DAY AIR TRAFFIC CONTROL SYSTEM

by

David Robinson Israel

DIGITAL COMPUTER LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge 39, Massachusetts

January 15, 1952
(Thesis Date: May 29, 1951)

Reprinted: May 21, 1956

FOREWORD (January 15, 1952)

Because it furnishes an example of the use of a large-scale digital computer in a control application of great current importance, this thesis report, which has had only limited distribution, is being issued as a Digital Computer Laboratory R-series report.

Grateful acknowledgement is made of the assistance of W. Gordon Welchman, formerly of the Division of Industrial Cooperation at the Massachusetts Institute of Technology, who carefully read the draft of this thesis and offered numerous valuable suggestions for its improvement. The cooperation of Professor William K. Linvill, thesis supervisor, is also noted and appreciated.

The task of writing this thesis was greatly simplified by the patient aid of the personnel of the Boston Air Route Traffic Control Center.

AUTHOR'S INTRODUCTION TO 1956 REPRINT

This reprint, made almost five years after original submission of the thesis, is occasioned by the current revival of interest in expanding and improving our air traffic control system. In 1951, digital computers were first becoming available for practical use, and the possibility of their application to air traffic control was highly speculative*; today the use of such equipment in a new system of air traffic control seems to be an accepted fact and major questions now relate chiefly to how soon and how much.

Considerable progress has been made in the past five years in the design and construction of digital computers, and extensive study and experimentation has been carried out in the use of such machines in real-time control systems. Specifically, the following developments are significant and should be kept in mind while reading this document:

a) improvements in computer storage systems, principally those of magnetic cores and drums, now make large, high-speed memories possible at relatively low costs. Economy of computer storage need not be a principal factor in the design of computer programs for air traffic control

b) significant advances have been made in in-out systems and techniques for transmitting data to and from computers

c) the concept of semi-automatic systems using both men and machines has developed significantly. Techniques by which the men and machines can communicate directly are many-fold and include intervention switches; displays using cathode ray tubes.

*This, to a large extent, accounts for the inclusion of Chapter III which was intended to present the fundamental notions of a computer and how it could be used for non-mathematical problems.

c) continued.

Charactrons, or similar devices; alarms; digital indicators; high-speed printers, etc,

d) computer reliability is continually being improved, and the use of duplexed or dual computer installations offers a satisfactory solution for system operation on a continuous basis.

These and other developments, together with those in the fields of communication and navigation, significantly affect much of what is contained in this report: previous estimates need revision; many former problems have disappeared; previous possibilities and speculations (see Chapter X) now seem to be realities, and new and exciting possibilities have arisen. Nevertheless, a large majority of the original ideas are valid, and the author hopes that this report, now largely historical, may serve as a useful background and as one of the several starting points for the large effort of system design and development which yet lies ahead.

My thanks is extended to the following people who have materially assisted in the preparation of this document for republication:

Anne Catalano	Frances Lapham
Barbara Higgins	Eleanor Lyon

D. R. Israel

D. R. ISRAEL

16 May 1956

ABSTRACT

THE APPLICATION OF A HIGH-SPEED DIGITAL COMPUTER
TO THE PRESENT -DAY AIR TRAFFIC CONTROL SYSTEM

by

DAVID ROBINSON ISRAEL

Submitted for the degree of Master of Science

in the

Department of Electrical Engineering

on May 29, 1951

The general purpose of this thesis has been to consider how a high-speed digital computer might be used in the mechanization of the present system of air traffic control, without any essential changes in the philosophy of the system or in the methods of navigation and communication. The study has been made in particular reference to the Whirlwind Computer, a digital machine presently in operation at the Massachusetts Institute of Technology.

Attention has been focused chiefly upon the en-route phases of traffic control, inasmuch as it is this part of the present system which appears to be most amenable to mechanization. The general approach taken is that the most satisfactory results and most efficient system will be achieved through careful use of the capabilities of both the human operators and the computer.

The main part of the study is concerned with the standardizations in the present procedures that are necessary for efficient computer mechanization, and with the construction of flow diagrams for the fulfillment of the necessary traffic control functions. The problem of data storage within the computer is discussed in detail, and the thesis contains a brief outline of the system of communication necessary for transmitting data to and receiving data from the computer. Certain remarks of a general nature are made in the last chapter as an indication of the possible improvements which could be made in the present system through the use of a computer.

TABLE OF CONTENTS

TABLE OF CONTENTS
(continued)

TABLE OF CONTENTS
(continued)

TABLE OF CONTENTS
(continued)

CHAPTER I

Introduction

A. Background of Thesis

The past decade has seen rapid advances in the realization of automatic high-speed computation, and at the present time a number of fully-automatic digital computing machines are in operation or in the latter stages of construction.[1] The basic ability of these machines is the automatic sequential performance of elementary arithmetic and logical operations. The application of machines with these capabilities to the mechanization of the extensive computations arising in connection with certain mathematical problems is not only possible but is highly desirable, and already the progress along these lines has been such as to permit further exploration and research into previously inaccessible regions of both pure and applied science. The use of these new machines as the central or directing elements in complex physical situations is similarly possible and desirable, and in such applications these machines offer great promise in permitting humans to more fully exploit and utilize recent advances in technology and science.

The author's first interest in the use of a computing machine for air traffic control arose in 1949 as a result of his employment at the Servomechanisms Laboratory of the Massachusetts Institute of Technology. At that time the Laboratory was completing construction of the high-speed Whirlwind Computer and a project was initiated to study the possible application of computers to future air traffic control systems.[2]

This study project, sponsored by the Air Force, was concerned primarily with the use of a computer in a future system of traffic control radically different from that which is presently in use. Such a system, it was planned, would employ radar devices as well as improved navigation and communication equipment in an attempt to handle high traffic densities and permit high landing rates. Inasmuch as this work was concerned with the use of the computer in a system which itself had not been formulated, some thought was given to how the computer could be used

---

1. The difference between digital and analog machines is explained on pg. 26.

---

2. The reports of this project--Project 6673 of the Division of Industrial Cooperation of the Massachusetts Institute of Technology-- are available at the Project Whirlwind Library at M.I.T. For the most part, the literature of the project is classified as RESTRICTED.

in the existing system of control, and it was decided that such an application of the computer would be undertaken and investigated as a thesis topic.

Shortly before embarking upon the study described herein, the author prepared a seminar report on air traffic control as a part of the degree requirements at the Massachusetts Institute of Technology.[1] This seminar reviewed the past history, the present problems, and the possible future developments of air traffic control in the United States. In the course of the preparation of that report, it became evident that this thesis would represent a part of an attack on a problem of current importance as well as being an illustration of the application of a computor. As shall be mentioned later in this chapter, the results of the work indicate that the application is feasible and merits further and more detailed consideration as a solution to the problem.

B. The Air Traffic Control Problem

1. History

Improvements in the reliability of aircraft as well as new developments and improvements in communication and navigation equipment paved the way for a tremendous expansion of civil and commercial aviation in the decade prior to the second World War. The resultant increase in aircraft flights during this period necessitated the organization and control of this traffic both at the airports and while aircraft were en-route between airports. The need first arose at airports -- the focal points of air traffic -- where it was desirable to have coordinated control over the many aircraft taxiing on the ground or flying in the vicinity. During the 1930's and through 1940 this type of control was provided exclusively by means of control towers operated by private organizations and various municipalities.

By 1933 it had become evident that some form of coordinated traffic control was needed for aircraft en-route in flights between cities. As a means of satisfying this need several airlines established a system of exchanging reports on the positions, altitudes, and speeds of their aircraft. During 1935 and 1936 a number of airlines banded together to establish an experimental traffic control center at Newark, New Jersey. Late in 1936 the Federal Government assumed control of the three then existing centers and established additional centers. By 1941 a total of 12 traffic control centers were in operation with control extending over 20,000 miles of airways.

---

1. Reference 1. (Reference numbers in the footnotes refer to numbered items in the Bibliography).

During 1941 a great expansion of air traffic resulted from military preparations and large numbers of military aircraft were operating from civilian fields. As a means of establishing a unified control of air traffic, the government was authorized to maintain and operate traffic control towers at major airports. The number of control towers and control centers grew very rapidly during and after the war, until by 1950 a total of 170 Airport Traffic Control Towers and 30 Air Route Traffic Control Centers were in active operation.[1]

2. Present State of Affairs

A general description of the present-day system of traffic control is given in Chapter II, and more detailed aspects of the system are described in following chapters. It should be understood that the present system does not represent a recently-devised effort at creating a satisfactory means of control for currently existing conditions; the present system is the culmination of a number of modifications and improvements which have been made in an effort to keep pace with the progress in aircraft and air traffic. This present system is satisfactory to the extent that is provides a workable and safe system of control; however, certain limitations of the system are quite evident in the light of the experience of the past five years and the expectations for the future.

At the present time commercial airlines carry some 15,000,000 passengers per year, this figure representing 50% of the total first-class passenger travel in the United States.[2] A further increase in this percentage seems quite likely inasmuch as both the fares and safety records of the airlines are fast approaching and in some cases have already passed the corresponding figures for first-class rail and ship transportation. The experience of the past few years has clearly indicated the potentialities of low-fare air-coach service, while the field of air freight transportation, relatively undeveloped before the war except for a limited amount of air mail service, now seems capable of considerable growth.

Despite the rather optimistic picture of possible expansion, the progress of commercial aviation is being retarded by a lack of dependable and reliable service. It is obvious that air travel will not reach its true position as a means of transportation until people are reasonably certain that they can arrive and depart on time. Similar remarks apply to freight and cargo movements where the advantages of high speeds are quickly nullified by cancellations or delays. Although complete figures on delays and cancellations in all types of weather are not

---

1. Reference 2

2. Reference 3

available, it is interesting to note the figures for a representative airline operating in and out of New York City.[1] During the relatively fair-weather month of June, 1947, 89% of the arriving aircraft of this airline were late, while 40% were over one hour late. Of the departing aircraft 41% were late, with 16% being delayed over an hour.

The air traffic control problem has economic implications, and is a contributing factor in creating losses in revenue. Typical figures resulting from a study of active and potential revenue losses of airlines in 1946 showed the following items:

a) Cancellations due to weather	$ 6,200,000
b) Low load factor resulting from unreliability	12,200,000
c) Congestion at 13 stations at which studies were made	21,100,000
	$39,500,000[2]

The losses to private operations, military operations, and non-scheduled services as well as losses at airports at which studies were not made are not included in these totals. Although some improvement in reduction of delays and congestion has been made in the past few years, the situation is still far from satisfactory.

The need for an improvement in air traffic control does not result solely from the problems of civil or commercial aviation; considerations of national defense and security require that the control system be capable of meeting certain military requirements. In the event of a national emergency the United States will quite likely become an active air-supply area and both civil and military aircraft will be used to transport large quantities of men and supplies. The success of the Berlin Airlift[3] and present operations in Korea emphasizes the practicality and advantages of large-scale air supply operations. Future operations of this nature may be expected to increase to very large numbers of aircraft and it is essential that the traffic control system be geared to handle an increased level of activity.

The present traffic control system was not designed to handle the type of aircraft now in use or which will shortly be coming into use; this system was best suited for the years from 1936 to 1940, the era of the DC-3's, a non-pressurized aircraft with an airspeed of

1. Reference 4, page 107
2. Reference 5, page 5
3. Reference 6

about 150 to 180 mph. At the present time there are about 100,000 private aircraft and about 7,000 commercial aircraft (1,000 scheduled, 6,000 non-scheduled) in operation.[1] These aircraft range from an extreme of a one-passenger capacity and a cruising speed of around 100 mph to larger commercial aircraft with capacities close to 100 and speeds between 250 and 325 mph. The smaller aircraft with non-pressurized cabins are limited to altitudes below 10,000 feet, while with cabin pressurization it is possible for newer aircraft to cruise as high as 20,000 to 30,000 feet. The aircraft are all powered with propellers and conventional piston-type engines.

Present developments and future plans point to jet-propelled aircraft. Although jet aircraft are already in extensive use by the military, there has as yet been relatively little development along commercial lines in the United States. The principal work on jet aircraft for commercial use has been done by the British and Canadians, and each country has already flown models which may be in active passenger operation in the near future.[2] Considerable speculation has been advanced concerning future jet aircraft, and this coupled with what is already known about their operating principles indicates that these aircraft will fly at altitudes between 20,000 and 50,000 feet, will cruise at speeds between 300 and 600 mph, and that high fuel consumption under certain conditions will require maximum flying time at high altitudes with a minimum of delays at low altitudes.[3] The necessity for high speeds and a minimum of delays especially at low altitudes make for stringent requirements as regards air traffic control, and create conditions which the present-day system can barely cope with. Fortunately the military services presently restrict their jet operations as much as possible to fair-weather conditions. Such restrictions could not be tolerated with commercial jet aircraft which could fly above the en-route weather only to have their operations restricted due to poor weather and congestion at the airports.

The basic elements of an air traffic control system are fourfold:

a) navigational aids
b) communications facilities
c) a carefully-organized plan for supervising the traffic
d) a supervisory or controlling element for implementing c) above.

---

1. Reference 7
2. Reference 8
3. Reference 9, 10

Each of these elements is capable of satisfactorily accommodating a certain limited amount of traffic; the capacity of the composite system, however, is limited by that element with the smallest capacity. A short discussion of the limitations and capacity of these elements is given at the end of Chapter II. As noted in that chapter, studies have shown that one of the limiting factors in the operation of the current system with regard to en-route flights is the supervisory or control element;[1] the basic consideration is of the speed and reliability with which human controllers can perform certain basic, albeit simple, data-handling functions.

The capacities of the above-listed elements are not completely independent of each other, and certainly with modifications and improvements in other parts of the system it would be possible to decrease the work of the controlling element, thereby improving the system capacity. This, in essence, is the underlying philosophy governing the efforts presently being made to synthesize a new and better system of control. To this end a good deal of effort has been put into improving or developing new navigation and communication equipment as well as into organizing the traffic in such a way as to ease the burden on the human controllers.

Although the navigational aids, communications facilities, and traffic plan each have definite limitations, it is fairly clear that definite improvements in present system operation and capacity would result if a controlling element of a larger capacity were utilized. This controlling element might be totally or in part a high-speed computing machine such as Whirlwind, and the general purpose of this thesis is that of determining how and where such a computing machine might fit into the framework of the present system. In so far as is possible, this study considers the utilization of the computer in performing the necessary control functions, all other elements of the system remaining unchanged.

To the author's best knowledge, this thesis represents the first consideration of the use of automatic machinery for performing most, if not all, of the duties presently performed by the controllers. There has been one notable attempt in the past to decrease the general burden of the work of the controllers by the use of automatic machinery, this being made in 1940 at the control center in Washington, D. C. In an attempt to relieve human controllers of the routine data-handling chores and permit them to fully concentrate on the traffic situation, an electromechanical posting system was installed in the control center; data was automatically displayed and sequenced on boards similar to those used for the tabulation of stock quotations, and use was made of a teletype-like system for the internal handling and transmission of information.[2] The equipment

1. Reference 11
2. Reference 12, 13

was unreliable and was taken out of service just before the war, and no further attempts at obtaining satisfactory operation have been made. On a much smaller scale, equipment has been designed and is presently in use as an aid to human controllers in the handling of data in connection with aircraft landing at LaGuardia Airport in New York City.[1]

C. The Computer

The development and utilization of high-speed computing machines has been so rapid and of such recent data that only a limited number of people are acquainted with the principles of their use and operation. These machines will be used in very widely different fields of work; indeed, one of the major problems in effectively utilizing these machines is in bridging the gap between two groups: those who are intimately acquainted with the machines and their operation, and those who desire to use these machines for a particular purpose, but who are unfamiliar with their abilities and usage. As a means of bridging this gap, Chapter III of this thesis has been written with the express purpose of explaining the basic ideas behind the use of a computing machine. That chapter places special emphasis upon the use of a digital computing machine in a control application, and devotes several pages to a description of the Whirlwind Computer which is used as a prototype in this study. The similarity between most existing or planned computers is so great that there is little restriction in scope introduced by a specific study in relation to the Whirlwind Computer; it is also convenient and valuable to study the problem with regard to the characteristics and capabilities of a presently-existing machine. A computer designed specifically for handling the air traffic control problem would not need the flexibility which exists in Whirlwind; however, the design of a special-purpose machine for this purpose would initially require a study such as is begun here in order to determine its necessary characteristics.

Although this thesis makes use of the characteristics of an existing and operating computer,[2] it should be understood that this study is academic to the extent that no computer presently exists which could be used for this purpose, nor is it likely that the necessary machine could be built and successfully put into operation within two to five years. To a great extent, this situation exists because of the problem of obtaining continuous error-free operation of a high-speed computing machine. The reliability of electronic equipment has been greatly improved as a result of the introduction of new techniques,[3] nevertheless the reliability is obtained only at the expense of regular periods of

---

1. Reference 14
2. Note: To a large extent the results of using these characteristics are not in bold evidence; they are implied in the general manner in which the problem is handled and in the methods used to perform certain functions.
3. Reference 15

maintenance and checking. Machines presently being constructed have not been designed with the intent of continuous operation for long periods of time; the accent has been placed to a greater extent upon satisfactory error-free operation for shorter periods of time, sacrificing for this end a continuity of operation. This, however, is but a current situation which reflects the relative infancy of the computing machine, and it can be expected that improvements in electronic components and techniques will shortly permit the construction of computing machines capable of the continuous error-free operation necessary for the proposed application.

Lest it seem that the necessary improvements and technical advances make the use of a computer for air traffic control only a thing of the future, it should be noted that at the present time the work of controllers at traffic control centers and towers virtually ceases during the early morning hours. In the place of a fully-automatic system, one might compound a semi-automatic system in which the human controllers would supervise traffic during the early morning hours while the computer underwent checking and maintenance. The main body of this thesis hypothesizes the availability of a continuous error-free computer; some discussion is made in the next section concerning the coordination between a human supervisor and the computing machine.

D. Extent of the Use of the Computer

One of the first questions which must be answered in appraising the application of a computer to the present-day traffic control system is that dealing with the extent to which the computer will perform the work of the human controllers. On one hand lies the possibility of completely replacing the human controllers by a computer, on the other is the possibility of utilizing the computer only as an aid to the human controller.

In dealing with this fundamental question perhaps it is best to first enumerate several important considerations dealing with each of the two elements -- the human controller and the computer. As shall be pointed out in Chapter III, the computer is a relatively fast machine quite capable of handling and processing large amounts of data in short periods of time. The computer can easily perform simple arithmetic operations and can make certain decisions for which it has been previously instructed. The computer has a memory of a limited size, but this memory is an efficient one and information can be completely committed to memory or recalled therefrom in a uniformly short time. The human is not eminently suited for rapid and yet accurate operation upon large amounts of data, and great reductions in his operating speed are necessary to produce extremely reliable results. The outstanding characteristic of the human controller is his versatility, ability to make decisions, and ability to improvise in handling an unforseen situation. The human has a relatively large memory, yet adequate short-term retention of information usually requires the use of additional aids such as pencil and paper.

A most desirable state of affairs would be that in which every situation arising in air traffic control could be immediately handled by a specified standard procedure. Unfortunately this is not the state of affairs at the present time; as is pointed out below, the standardization of the present system is far from complete and it is often necessary for a controller to improvise or follow other than specified procedures. Nevertheless, if there exists a method by which a human controller can reach a decision as to what action is necessary in a particular situation, it is possible for the machine to reach the same conclusion. That is to say, the computer can reach the same degree of versatility as the human controller if the added costs and expense are deemed desirable. To this end, the question of using the computer for all the traffic control functions is somewhat of an economic one, and the degree of mechanization must be balanced against the cost and desirability of this mechanization. Thus the computer offers an opportunity for a completely automatic system with increased capacity, but probably with less flexibility and with certain problems of reliability.

Realizing that the computer and the human each have definite contributions to offer, there exists the possibility of a joint manual-automatic system. Such a system could utilize the computer for certain standard routine jobs, employing the human for special decision-making functions; both the computer and the human might perform certain checks on each other's work. The control of aircraft at and in the vicinity of airports has peculiarities common to the individual airports and is undoubtedly more suited under present conditions for human supervision; the decision as to how to create changes in the schedules of a number of aircraft when a future conflict must be averted is a situation which can be satisfactorily handled, in its present limited state of complexity, by human controllers.

The question of the advisability of completely automatic control by machinery is one which will plague engineers for many years in the future, and this author does not see any clear-cut decision which can be reached in the particular application studied. For this reason, after considerable thought and investigation it was decided to restrict the consideration of the use of the computer solely to the control of aircraft en-route between airports, assuming that the control of aircraft at and around the airports would remain in the hands of the human operators. This decision is justified in Chapter VII wherein a statement of the functions of the computer and human controllers in this situation is made. Within the function of en-route traffic control, this thesis formulates plans for and discusses how the computer would carry out the necessary traffic control operations. It is assumed that in certain situations, to be defined in succeeding chapters, the computer will present the situation to a human operator for guidance and instruction. It is also assumed that a human controller will be able to insert any desired information or instructions into the computor as well as being able to secure and inspect information stored and used by the machine.

One of the most difficult tasks in this study has been the assimilation and sorting out of the various rules, regulations and practices governing the operation of the traffic control system. There is extremely little comprehensive literature on the subject, and for the most part that which does exist merely enumerates certain fundamental regulations and procedures.[1]

The present system is hardly what one would call completely standardized, and to a great degree the operation of the system is based on the choice of individual controllers. Presented with a given situation, it would not be unusual for five controllers to each have a different method by which he would handle it. Even within the standardization which exists, there are certain situations which must be met and handled as the occasion necessitates. An example is the fact that controllers hesitate to use certain procedures with civil and military traffic inasmuch as the training, experience, and proficiency of these pilots may be less than that of commercial airline pilots.

The lack of rigidity in standardization is, of course, quite the antithesis of the requirements of an automatic computer. For this reason, one of the major tasks of this study has been the reaching of satisfactory compromises in the various methods now used. In so far as is known, these compromises, choices, and standardizations are sufficiently in accordance with current practice as not to render the end result unrealistic.

Within the framework of the overall regulations there exists the individual characteristics and geography of the zone under control. In planning for use of the computer, no attempt has been made to utilize any specific geometry of airports and airways; such a step might have eased several problems but would not have rendered the results general. As presented, the thesis is perfectly general in this respect, and can be applied to any particular area.

E. Discussion of Results

A complete investigation of the application of a computer to a physical control system has two essential phases: in the first phase the system must be carefully analysed and the general methods of attack formulated; in the second phase the results of the first are used in the preparation of the detailed program of action for the computer. As is discussed in Chapter III, the first phase of such a study generally results in the formulation of <u>flow diagrams</u> indicating the program of action,

1. References 16, 17, and 19

while the second phase --the more routine task of translating this plan into computer language -- results in a coded program ready for use with the computer. The first phase, by the nature of its function, not only requires a complete knowledge of the physical system and its operation, but necessitates a careful understanding and consideration of the abilities of the computer as a means of obtaining a judicious merger of it with the system.

The results of this thesis are limited to the first phase mentioned above. A study has been made of the present air traffic control system; the rules, regulations, and practices of this system have been analysed in an attempt to provide a basis for planning; and the general planning and organization has been carried out. The results of this work are contained in the discussions of Chapter II through X and in the flow diagrams presented therein.

In an attempt to obtain a clear understanding of the organization and operation of the present system of control, the author has studied all of the available literature of the Civil Aeronautics Administration, and has spent approximately 50 hours at the traffic control center in Boston talking to the personnel and observing the system in operation. In view of the extreme complexity of the present system,[1] the author does not claim to have a complete knowledge of its operation in all its attendent details. It is felt, however, that the information obtained is sufficient for the purposes at hand, i.e., a general study of the problem. Flow diagrams for all of the necessary computer functions have not been made, and those which have been made are far from being complete or totally inclusive of all details and considerations. Despite this fact, the flow diagrams appear to be sufficient to indicate the magnitude of the task and to permit certain observations to be made concerning the proposed application.

Inasmuch as the second phase mentioned above has not been carried out and the flow diagrams have not been translated into computer programs, it is impossible to state what the exact requirements for the necessary computer would be. It is possible to state, however, that the present air traffic control system is in a realistic sense susceptible for mechanization by a digital computer and that the application is feasible from that point of view. Based on only a limited amount of experience in the field, it is the opinion of the author that computers of the ultimate speed of Whirlwind (20 μsecond per operation[2]) and perhaps triple its design capacity of 2048 sixteen-binary-digit storage registers[3] would meet the requirements imposed by the application.

Although it is felt that the use of a computer in the present system of control would be feasible; it is also felt that a much better

1. The current estimate for the training of center controllers is 2 years.
2. and 3. See pages 39 and 40 of Chapter III.

utilization could be made of the abilities of a computer in a system which had been specifically designed and planned for operation under the control of a computer. The underlying reasons for this observation will be made clear in succeeding chapters where it becomes evident that modifications and changes in methods and procedures would permit a highly-efficient computer-controlled system. The complete specification of what the basic features of such a system should be is beyond the scope of this thesis; nevertheless, as a result of a study of the present system coupled with an understanding of the capabilities of the computer, it has been possible to include in Chapter X a number of observations concerning the use of the computer if certain modifications or changes were made in the present traffic control methods.

One should not underestimate the amount of non-equipmental work over and above the preparation of a general plan of attack and flow diagrams which would be necessary for the ultimate realization of a computer-controlled system. The completion, refinement, and translation of the flow diagrams into actual coded programs would be a fairly large task and would probably occupy a small group of people over the span of a year. The detailed construction of coded programs for a relatively complex problem is not easily carried out and much care must be taken to avoid errors. Few problems of this order of magnitude have as yet been carried through to completion, yet experience with shorter programs has indicated that the programming must not be only theoretical in nature but must actually involve testing on a computer as the ultimate means of discovering errors. Such testing would be purely synthetic, and parts of a complete program could easily be tested on Whirlwind. Careful consideration would also have to be given to questions of how the program could be tested synthetically for operation under all possible conditions which might arise in practice.

F. Relationship of Chapters

Chapters II and III discuss the present air traffic control system and the computer, respectively, and serve only as a means of establishing a common ground for discussion.

Chapter IV deals with the means of introducing and withdrawing the necessary traffic control information and instructions from the computer. A system of necessary external equipment is described, and the handling of input and output messages is discussed.

Chapter V is concerned with the utilization of the internal storage of the computer and treats several problems which arise in the handling and storage of necessary information and data.

Chapter VI discusses the problems arising in connection with control areas and airports. A detailed description of present system operation in these respects is given, and plans are drawn for the requirements for use with the computer.

Chapters VII, VIII and IX deal with specific programs to be utilized by the computer. Chapter VII is concerned with two programs used in regulating the general action of the computer and in initiating control over aircraft. The subject of separations between aircraft and the checking for conflicts is treated in Chapter VIII. Chapter IX discusses the computer action necessary for obtaining and maintaining clearances for aircraft.

As already noted, Chapter X contains a discussion of possible improvements which could be obtained through modification of the present-day system of control.

CHAPTER II

Present-Day Air Traffic Control

The primary objectives of a system of air traffic control are generally associated with:

1) Preventing collisions between aircraft and between aircraft and obstructions on the movement area.
2) Expediting and maintaining an orderly flow of air traffic.
3) Assisting the person in command of an aircraft by providing such service and information as may be useful for the safe and efficient conduct of a flight.
4) Notifying appropriate organizations regarding aircraft known to be or believed to be in need of search and rescue aid, and assisting such organizations as required.[1]

An attempt at fulfilling these objectives has resulted in the establishment and growth of a nationwide system for the control of aircraft both at or around airports and during the en-route sections of their flights between airports. This chapter aims at briefly describing the methods and techniques utilized in this present-day system, and is intended chiefly as background material for further and more detailed discussions of the subject in succeeding chapters. The emphasis is concentrated upon an explanation of the en-route phases of control, as it is in this part of the general framework of the present-day system that it will be shown that the use of a computer is most promising.

A. Governmental Organization

The two governmental agencies directly concerned with the present system of air traffic control are the Civil Aeronautics Board (CAB) and the Civil Aeronautics Administration (CAA). These two organizations technically constitute the Civil Aeronautics Authority of the United States Government.

The Civil Aeronautics Board is an independent, quasijudicial panel appointed by and directly responsible to the President. The Board formulates Civil Air Regulations dealing with the competency of pilots, the airworthiness of aircraft, and the conditions of flight. Other duties include the investigation of accidents and violations of the Civil Air Regulations, the establishment of air mail rates and contracts, and the certification of routes, rates, and carriers for passenger and freight travel.

1. Reference 16

The Civil Aeronautics Administration is a branch of the Department of Commerce, and operates under the direction of an Administrator of Civil Aeronautics. The maintenance and operation of communications, navigation, and air traffic control facilities was authorized in the Civil Aeronautics Act of 1938, which empowered the administrator to:

> promote the development and safety and provide for the regulation of Civil Aeronautics ..... designate and establish civil airways ..... acquire, establish, operate, and maintain along such airways all necessary air navigation facilities ..... provide necessary facilities and personnel for the regulation and protection of air traffic moving in air commerce.[1]

B. The Civil Airways System

A network of radio ranges known as the civil airways form the basic navigational aids for aircraft flights in the United States. These ranges are created by the radiation patterns of ground transmitters operated by the CAA. Four narrow spoke-like beams -- also referred to as courses or ranges -- are set up in space, extending outward from the range station. These courses, each 3° wide, are separated by about 90° in azimuth. The nature of the signal transmission in the beams or courses is such that a properly-tuned radio receiver will give an aural and/or visual indication of whether the aircraft is to the left of, to the right of, or directly in the path of beam.

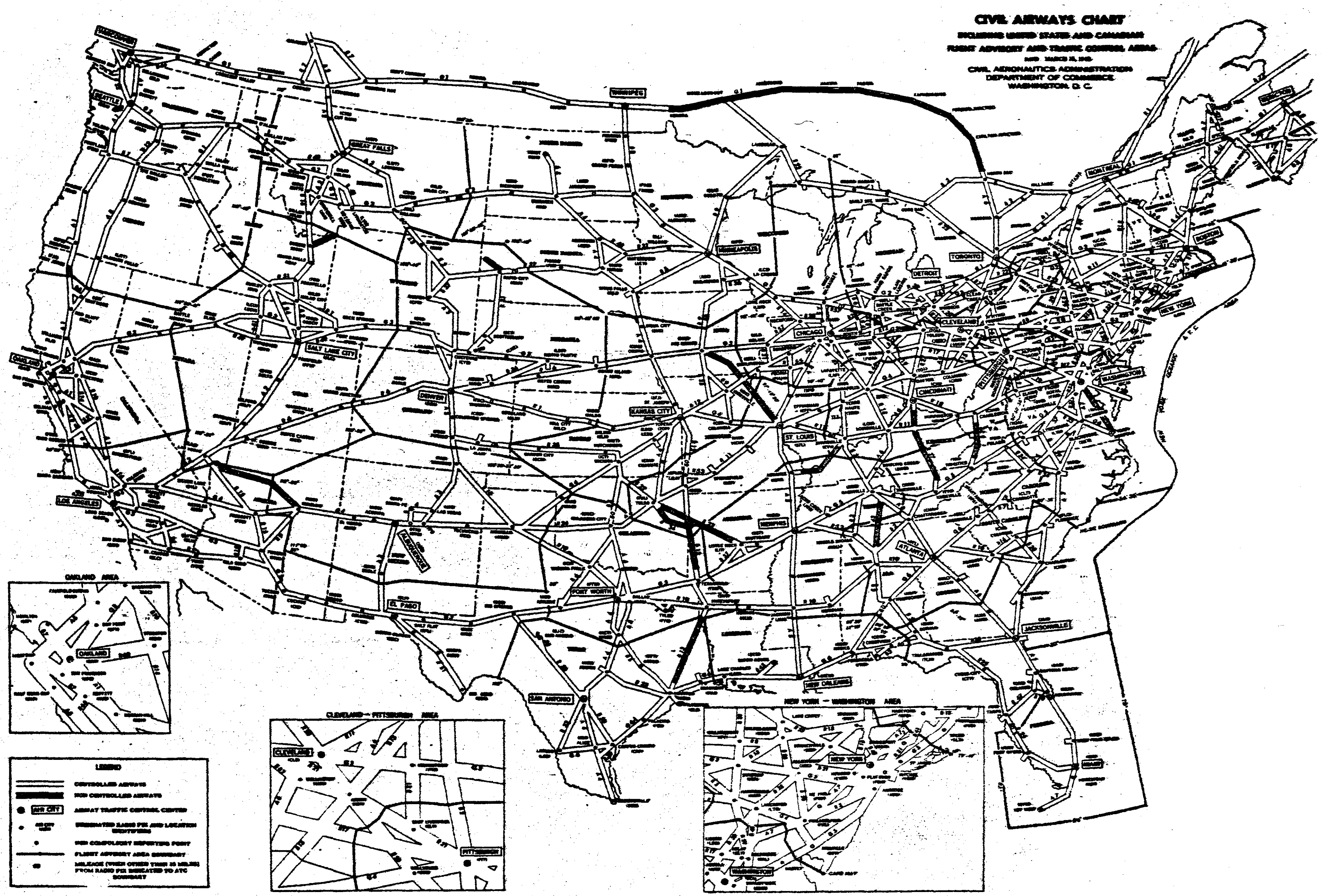
The radio range stations have generally been situated at or near major airports so as to provide direct paths, or paths consisting of straight-line segments, between most commercial or military airports. The range stations, then, provide predetermined flight paths or "roads" which pilots can "ride" by earphone or meter indications.

Radio ranges alone, however, only provide a course to be flown; navigation in poor weather and during low visibility conditions requires the definite determination of position along these courses. A radio fix or check-point is obtainable at the intersection of courses of two adjacent ranges or in the signal-free cone of silence over a range station. In order to provide additional indications of position, radio markers have been installed at specific points along the airways. These radio markers are produced by high-frequency transmitters which radiate vertically and produce a definite field pattern over a small area across the airways.

These facilities -- the radio ranges and radio markers -- provide a complete, although not perfect, en-route navigation system capable of being flown entirely by instrument. Figure 1 shows the present-day airways totalling 43,000 miles.

1. Reference 17

A-45017O


CIVIL AIRWAYS CHART
INCLUDING UNITED STATES AND CANADIAN
FLIGHT ADVISORY AND TRAFFIC CONTROL AREAS
CIVIL AERONAUTICS ADMINISTRATION
DEPARTMENT OF COMMERCE
WASHINGTON, D. C.
SEATTLE
GREAT FALLS
WINNIPEG
MINNEAPOLIS
MONTREAL
BOSTON
TORONTO
DETROIT
CHICAGO
CLEVELAND
NEW YORK
PITTSBURGH
WASHINGTON
CINCINNATI
ST. LOUIS
KANSAS CITY
DENVER
SALT LAKE CITY
OAKLAND
LOS ANGELES
ALBUQUERQUE
EL PASO
FORT WORTH
MEMPHIS
ATLANTA
NEW ORLEANS
SAN ANTONIO
JACKSONVILLE
MIAMI
OAKLAND AREA
CLEVELAND — PITTSBURGH AREA
NEW YORK — WASHINGTON AREA
LEGEND

C. Communication Facilities

The bulk of communication between aircraft and ground stations is carried out by means of two-way radio telephone. Traffic control instructions from control towers at airports are sent to neighboring aircraft over high-frequency channels assigned each airport. Control messages for en-route aircraft are sent by the traffic controllers through the facilities of airline, military, or CAA-operated communication stations.

Point-to-point ground communication among control centers, control towers, airline offices, airline radio stations, military dispatchers, military communications stations, CAA communications stations, and weather observation stations is handled over land-line wire circuits. Two facilities are in general use: an extensive teletype circuit for the transmission of weather reports or messages not requiring immediate handling, and an interphone (private telephone) circuit for the relaying of air traffic control messages.

D. Scope of Present-Day Control

The air traffic rules of the Civil Air Regulations specify two types of flight conditions, with appropriate regulations for each. The Visual Flight Rules (VFR) apply to clear-weather flights conducted under visibility conditions better than specified minimums. These visibility regulations are rather complex. Generally speaking a three-mile horizontal visibility is required and the aircraft must be at least 500 feet below or 2000 feet to the side of cloud formations. Flights which are flown under visibility conditions less than those certified for VFR are governed by the Instrument Flight Rules (IFR). Standard flight procedures and "right-of-way" rules for all flights, regardless of visibility, are stipulated in the Civil Air Regulations.

En-route flights carried out under Visual Flight Rules are not controlled by the facilities of the CAA. There are two principal reasons for this. Under the relatively low-density conditions presently encountered in en-route flight, when a pilot can see that he is about to pass, overtake, or cross the path of another aircraft he can safely alter his course to prevent collision. In full-visibility there also exists no urgent need for navigational aid. For these reasons pilots are permitted to select their flight paths independent of the civil airways, and they are personally charged with maintaining safe separation from other aircraft.

Flights conducted under IFR conditions require the en-route navigational aid and overall traffic coordination offered by the CAA facilities; these flights must be flown on the civil airways and are strictly controlled from the ground in accordance with methods described in succeeding sections.

CAA supervision also extends to the control of aircraft in and around airports, regardless of weather and visibility conditions, where high traffic densities require careful control for purposes of safety, efficiency, and expediency.

E. Types of Control

The types of control exercised in the present-day system are three-fold:

1) air route traffic control
2) airport traffic control
3) approach control

Air route traffic control, administered by control centers, is specifically responsible for the safe and orderly flow of aircraft proceeding along the civil airways in IFR flight conditions. The principal functions are:

1) To issue instructions to pilots regarding altitudes to be flown, routes to be followed, speeds to be maintained, holding procedures over specified locations, etc.
2) To advise pilots of hazardous conditions and miscellaneous information which may effect the safety of the flight, and suggest a change in flight plans.
3) To maintain a progressive check of aircraft and to initiate action for overdue aircraft.
4) To provide assistance to aircraft in difficulty and report accidents.
5) To report violations to the proper office.[1]

It should be particularly noted that air route traffic control is designed chiefly for application to en-route IFR traffic. For reasons to be mentioned in Chapter VII, this service is not used by most pilots during VFR conditions.

Airport Traffic control concerns itself with the safe and orderly supervision of aircraft which are taxiing, landing, taking-off, or flying in the immediate vicinity of an airport area. The principal functions are:

1) To issue instructions to pilots for taxiing, take-off, approach for landing, and landing of aircraft.
2) To inform pilots regarding field and weather conditions, air navigation facilities, emergency landing areas, restrictions to flight,

1. Reference 18, Page 30

and other matters which may be of assistance to the pilot.

3) To relay messages between pilots, air carrier or military operations offices, communication stations, and other appropriate agencies concerned with the operation, control, and dispatch of aircraft.
4) To inaugurate emergency procedures when an accident or emergency occurs on or in the vicinity of a landing area.[1]

Airport traffic control, it is again noted, is an all-weather service.

A third type of service -- approach control -- is presently provided as a link between air route and airport traffic control in connection with the handling and coordination of traffic in instrument weather near airports. In the words of a CAA manual:

> Approach control is a service whereby airport traffic control towers issue traffic clearances to aircraft being controlled in accordance with Instrument Flight Rule standards by communicating directly with pilots over the voice feature of the radio range, or over a very high frequency channel of the control-tower .... Coordination of traffic arriving and departing during adverse weather conditions is vested in the approach controller who is in a position to see the airport and aircraft in the vicinity and is therefore able to take advantage of every opportunity to safely expedite the flow of traffic on and around the airport.[2]

F. Air Route Traffic Control

1. General Philosophy

Air traffic obviously cannot be controlled like surface traffic; an aircraft cannot be stopped in flight but must remain in motion at sufficient speed to maintain altitude and maneuverability. (Inasmuch as the available navigational aids safely provide for only a single lane -- often called a "single wall" -- of traffic along an airway, immediate delays of en-route aircraft are possible only by flying the aircraft in race-track-like holding patterns anchored on these airways). The desire for the maximum utilization of the airways as well as the minimum amount of confusion and delay has led to a guiding principle of controlling the traffic by anticipation. In accordance with this principle, the movement of traffic is organized in advance so that no danger of collision can arise if pilots proceed according to instructions, and if the traffic control is predicted on accurate and current information of the weather and aircraft movements.

---

1. Reference 18, Page 21
2. Reference 16, Page 79

Whereas tower controllers are usually situated in a position of full visibility at the airport under their supervision, air route controllers cannot possibly view the en-route aircraft and hence must be supplied with a full knowledge of the positions and plans of these aircraft. This information is supplied both by the flight plans which must be filed prior to all IFR flights and by means of progress reports sent by the pilots to the traffic controllers when aircraft pass the particular fixes designated as reporting points. Although these flight plans and progress reports deal exclusively with times and altitudes at the discrete reporting points, these reporting points are close enough -- 15 to 20 minutes flying time apart -- so that a trained controller can extrapolate upon the given data and supply himself with a mental picture of the traffic at the present or at future times. With these pictures the controller checks for safe separation between aircrafts; when it is apparent that proper separation will not exist, the controller requests changes in the flight plans of the appropriate aircraft.

Separation between aircraft is defined in terms of distances, times, and altitudes. The separation standards -- lateral, longitudinal, and vertical -- generally require any aircraft in IFR weather to be either 1000 feet above or below any other aircraft on the same airway, or to be at least ten minutes flying time away from another aircraft at the same altitude. The stringency of these standards is primarily due to the limited nature of the navigational system and the limited reliability and accuracy of barometric altimeters and air speed indicators. Variations of speeds, altitudes, and routes, as well as the holding of aircraft over specified points, can be used to obtain proper separation between aircraft. Details of the en-route separation standards and possible variations therein permitted under particular flight conditions are discussed in Chapter VIII.

Before commencing any flight or portion of a flight which will come under the jurisdiction of Instrument Flight Rules, pilots must obtain a clearance from the appropriate air route traffic control center. The initial application for a clearance is made by the prior filing of a flight plan indicating full details of the projected flight. The flight plan must specify the flight indentification, type of aircraft, proposed airspeed, point of departure, desired altitude, proposed route, and point of destination. This initial filing of a flight plan is generally referred to as an Approval Request. Approval Requests are forwarded to the control centers some time before proposed departure time by the airlines operations offices or the military operations offices.

Clearances are issued to aircraft on a "first-come, first-served" basis with due respect to up-to-date weather information and the fullest possible knowledge of aircraft movements. The final request for a clearance, the Clearance Request, is made by the tower operator at the airport when the aircraft is actually prepared for departure. The clearance, as such, is given for the aircraft to commence the requested flight; in actuality, however, due to the fact that the weather and traffic information at any one time is known only with a limited degree of certainty, this clearance is based only on proper separations for a first section of the flight.

After receiving their clearances, pilots are required to conform to their flight plans and to inform the controllers via progress reports of the passing of the reporting points. The progress reports indicate the actual times at which the reporting points are passed, and confirm the altitudes and speeds at these points. On the basis of these progress reports, modified clearances can be given, if necessary, to provide separation for further sections of the flights.

2. Division of Control

Control of all aircraft on the civil airways of the United States from one central point is not feasible due to the high communications costs, and is unnecessary due to the localized nature of air travel. (A CAA survey of 1948 revealed that almost half of all airline passengers travel less than 300 miles and over a fourth travel less than 200 miles.[1])

For these reasons the country has been divided up into 26 domestic traffic control areas. This division has generally been made on the basis of efficiency and economy, and so that one point of major traffic congestion and the airways serving that point compose an area. The traffic within each area is controlled by a centrally-located Air Route Traffic Control Center.

The amount of traffic within any one area presents a problem of control which is too difficult for a single person to handle. For this reason each control area is subdivided into sectors. The size of these sectors varies with the amount of traffic and complexity of the routes. It has been found, however, that there exists a minimum size for a sector from a practical viewpoint, since a controlled aircraft must remain in the area long enough to permit a controller to assimilate the information, analyze the traffic flow, and issue the instructions. Generally speaking, aircraft receive clearances through one or two sectors at a time.

The subdivision of the traffic into areas and then sectors creates serious coordination problems. Coordination is needed between adjacent sectors, between areas, between centers and towers, and between successive shifts of controllers working the same sectors.

3. Processing and Handling of Flight Information

As a means of compiling and handling the information concerning the various flights within an area, the control centers are provided with a number of flight progress boards upon which can be posted current flight information in the form of flight process strips. A single flight

1. Reference 24

progress board is generally reserved for each reporting point, the name or abbreviation of that reporting point being displayed at the top of the board. Separate flight progress strips are made out and posted for all reporting points mentioned in a flight plan, each strip essentially carrying all of the information in the flight plan but prominently displaying the time and altitude at which the point shall be passed.

Adjacent reporting points are assigned, insofar as is possible, to physically adjacent flight progress boards. A group of 5 - 10 contiguous flight progress boards constitute a sector under the control of a controller. The strips on a single board are generally kept in time sequence, and hence by referring to corresponding (flight) strips on successive boards and by comparing times and altitudes, controllers are able to check for proper separation.

The CAA defines three positions of operation in a control center, these positions and their duties being:

Position A:

a) To collect flight plan data via interphone and post properly on flight progress (board) strips.
b) To maintain prepared strips in proper sequences in suspense bays.[1]
c) To prepare strips for reporting fixes within the sector assigned and prepare strips for the entry fix (reporting point) of succeeding sectors as necessary.
d) To transmit over interphone facilities assigned to the position, flight plan data and control information to other positions within the sector and adjacent sectors as necessary.
e) To transfer prepared strips to the "D" position (see below) at appropriate fixes and at proper times.
f) To monitor reports and information being transmitted and received by associated "D" position of operation, acknowledging receipt of information for which action is required by the "A" position.
g) To handle other communications via interphone facilities assigned to the position as instructed or authorized by position "D."
h) To remove and file flight progress strips from holders no longer being used for control purposes.

Position D:

a) To issue traffic clearances and other control messages either directly or through other positions of operation.
b) To revise air route traffic control estimates as necessary immediately after a flight progress report has been posted.
c) To maintain fix postings on flight progress boards in proper sequence.
d) To maintain current expected approach times as required on flight progress boards assigned to the position.

Reference 1. Suspense bays are separate flight progress boards reserved for strips of aircraft still on the ground or in adjacent areas.

e) To remove strips from the flight progress boards when the information contained on the strips is no longer required for control purposes.
f) To study all weather reports, winds aloft reports, notices to airmen, and terminal and airway forecasts, and consult with Flight Advisory Weather Service personnel as necessary.
g) to administer flight assistance to civil aircraft.

Position E:

a) To coordinate the control of air traffic between various sectors of the control area as required.
b) To check flow of traffic between sectors to insure proper separation.
c) To advise controllers as necessary to insure efficient and safe control of air traffic.
d) To regulate the flow of air traffic in an efficient and orderly manner consistent with the operational limiting factors involved.
e) To study all weather reports, winds aloft reports, notices to airmen, and terminal and airway forecasts immediately upon receipt of such reports.[1]

Position D duties are filled by <u>controllers</u>, Position A duties by <u>assistant controllers</u> or <u>calculators</u>, while the supervision and coordination of the E position is provided by a <u>senior controller</u>.

G. <u>Traffic Control at the Airports</u>

Supervision of flights at and near airports is shared by Airport Traffic Control and Approach Control. Airport Traffic Control has been established to provide adequate supervision of all traffic in the movement area and all aircraft flying in <u>visual</u> reference to the ground in the vicinity of an airport. Approach Control, a service established in 1944 and still being expanded, attempts to ease conditions at airports during instrument weather by direct and instantaneous communication between tower controllers and IFR flights arriving at, deprating from, or holding in vicinity of the airports. At the present time over 100 of the CAA-operated airport towers offer the approach control service.

During IFR conditions, when aircraft are not under control of air route traffic control centers, pilots generally contact the towers at the airport of their destination when they are from 10 - 15 minutes flying time away. The tower controllers establish landing patterns suitable for the runway in use and instruct the pilots as to how and when they should proceed with their landings. These instructions, of course, are coordinated with respect to taxiing aircraft, other arriving aircraft, and aircraft requesting permission to take off.

1. Reference 22

The situation is somewhat more complicated at the airports during poor visibility conditions. The lack of visibility and the limited nature of the navigational facilities are such that large separations between successive landing aircraft are required, and hence rather low landing rates must be expected. A sudden deterioration of the weather at a busy airport is likely to create a situation in which most arriving aircraft must suffer some delays in a holding pattern before they can proceed to a landing.

As an aid to navigation near the airports, one leg or course of the adjacent radio range is generally positioned so as to lie across the airport. Under approach control procedures the air route traffic control center clears aircraft to a radio marker situated on one leg of the radio range. Holding patterns are stacked above this marker at 1000-foot intervals, the patterns being of a race-track shape with one leg extending along the radio range from the marker. These holding patterns are under the supervision of the approach controller who informs the control centers of the free altitudes at which aircraft may be introduced into the patterns. Upon reaching the holding marker at the proper altitude, the pilot establishes contact with the approach controller who then assumes complete control of the aircraft.

H. Limitations of the Present-Day System

1. Navigation

Generally speaking, navigational aids presently in use do not give pilots or controllers continuous or sufficiently accurate positional information, nor do the facilities provide a satisfactory number of flight paths.

During poor visibility conditions, pilots know their positions along the airways only at specific points -- these points being the radio markers, cones of silence, or intersections of courses of adjacent range stations. This is a distinct disadvantage: traffic is not only restricted by the single lane of traffic and limited number of altitudes which can be flown (bounded above by considerations of cabin pressurization and below by the height of the terrain), but must be further curtailed since the limited number of reporting points requires large longitudinal separations.

The present-day airways are restricted to the fixed, widely separated courses of the radio ranges. The position of these courses usually creates flight paths of unnecessary length, since these fixed paths between range stations rather than direct straight-line routes must be followed if the navigational facilities are to be used. These paths are immobile and cannot be altered to take advantage of weather conditions. In particular, the radio ranges are less reliable in poor weather when they are most urgently needed.

2. Communication

The overloading of available communication channels and the effects of static and interference are two aspects of the air-ground communication problem. Of greated importance is a considerable time lag in handling messages as they are routed to and from the control centers. The multiple handling of messages, the necessity for frequent repetitions to avoid errors and misunderstandings, and the overloading of available circuits are problems presently encountered both in communication between ground points and between pilots and ground stations. Pilots and controllers alike spend a disproportionate amount of their time in preparing and transmitting messages: pilots must do this while busily engaged in flying; controllers must interrupt their control procedures to establish radio or telephone contact and to deliver (and possible repeat) the messages.

3. Traffic Control

The present system of control, based as it is upon the principle of anticipation, is handicapped by a lack of accurate and complete information of present and future traffic conditions along the airways. This situation arises from several causes:

a) The lack of an adequate knowledge of the winds generally results in earlier or later times of arrival at reporting points than have been previously predicted.

b) Position reports are likely to be delayed, incorrect, or inaccurate.

c) Aircraft flight plans are handled "first-come, first-serve," without regard to published schedules, inasmuch as these schedules are susceptible to rapid changes and frequent cancellation during IFR conditions. Because of this fact, because of the random nature of military and non-scheduled air-carrier traffic, and because pilots may not file an Approval Request until the time of takeoff, controllers have only a limited idea of future traffic conditions.

d) The rapid change of weather conditions may result in numerous en-route aircraft without clearances suddenly applying for IFR clearances.

It is chiefly for these reasons that aircraft can be cleared for separation through only one or two sectors at a time. Such a procedure, as noted, results in a coordination problem, with an accompanying decrease in overall efficiency and speed of operation.

An exhaustive study has been made of the conditions under which the present-day air traffic control methods and procedures might break down under the weight of an increase in traffic densities.[1] It was concluded that with high traffic densities over a prolonged period the following limitations of the controllers would become apparent:

a) an inability to properly visualize the traffic patterns beyond a certain degree of complexity.
b) an inability to resolve complexities and determine the appropriate instructions with sufficient speed.
c) failure to be able to make accurate and current tabulations of the necessary data in the time available.

The routine, mechanical task of transmitting, accumulating, sorting, classifying, recording, and distributing the information needed to perform the control functions is tremendous, and probably can only be fully appreciated when one has seen an air route traffic control center in full operation during IFR operations.

---

1. Reference 11

CHAPTER III

The Computer

This chapter is intended as a brief introduction to the general subject of automatic digital computing machines, and in particular to the Whirlwind Computer.

The first section of the chapter is devoted to a discussion of a simple computing system and to an identification therein of the basic elements of more sophisticated and completely automatic systems. The discussion is focussed on digital computers, of which Whirlwind is an example. This digital character evolves from the fact that the computer handles and stores only information which has been properly expressed in quantized or digital form -- that is to say, information which is completely expressible by a set of numerical digits. This is to be contrasted to an analog machine wherein information is not restricted to quantized levels, and in which the information is stored as a physical quantity and hence is dependent upon the capacity and sensitivity of some measuring device.

The remaining sections of the first part of the chapter are used to enlarge upon the preliminary concepts and to develop the basic notions dealing with the use of a computer in a variety of problems. Special attention is given the application of a computer to physical control systems.

The second part of this chapter discusses the specific characteristics of the Whirlwind Computer. A number of quantitative figures are introduced so as to provide the background for discussions of succeeding chapters. No effort has been made to make the description of the computer complete; additional details and descriptions of operation may be found in the literature listed in the Bibliography.

A. General Philosophy of Use of A Computer

1. Elements of a Computing System

A familiar example of a computing system is that of a human operator supplied with a desk calculating machine, a set of instructions, a pencil, and a block of paper. Despite the apparent simplicity of this example, it graphically demonstrates the basic elements of the more complex and automatic systems which are typified by the Whirlwind Computer.

One of the basic elements in this system of manual computation is the desk calculator -- this, in fact, fulfills the requirements of the arithmetic element in a generalized system. The characteristics of this particular arithmetic element are that when it is supplied with one or more numbers and when a particular mode of operation -- addition, subtraction, multiplication, or division -- is specified by activating the proper lever, button, or switch, the desired operation is automatically carried out. The computed result is generally found in the accumulator, one of the several registers used in the performance of arithmetic operations.

The numbers to be fed into the arithmetic element and the operations to be performed are usually specified in the overall instructions which must be given to the machine operator. Consider these instructions as being listed on a set of filing cards. Some cards will hold numbers to be used in the calculations, other cards will hold written orders concerning the operations to be carried out using numbers appearing on the first type of cards, and still other cards might be blank in anticipation of the storage of computed results. We shall consider these cards as being arranged in a logical sequence, with each card being numbered consecutively. The totality of these cards -- consisting of orders, numbers, and space for results -- make up the storage element.

A third component of our simple system is the human operator who effectively acts as the control element. The general function of the control element is to inspect the cards of the storage element consecutively, carrying out the orders specified thereon. By restricting the complexity and standardizing the form of these orders the intellectual requirements of the control element can be made rather small; the basic requirements are that it inspect the cards in sequence, understand the written orders thereon, and be able to carry out the simple physical operations needed to implement these orders.

If we consider the control, storage, and arithmetic elements as being physically isolated in a room, then a means of communication is required between the room and the outside world. If all of the cards of the storage element were initially blank, then an obvious need is a means of transmitting into the storage element the required contents of these cards -- the orders and numbers needed for the calculation. Furthermore, when the calculation has been completed, a means of transmitting results from the room are necessary. The apparatus necessary for the purposes of communication can be generalized into two types-- input and output. An input element and an output element constitute two additional needs of a general computing system.

A schematic representation of the comparison between the elements of manual computation and the elements of a computer such as

Whirlwind is given in Figure 2. Without loss of generality, the storage element in the human system is represented in this figure by a notebook rather than a set of cards. The analogies between the individual basic elements are given in Figures 3, 4, 5 and 6.

2. Handling a Simple Problem

As an illustration of how the five elements discussed in the previous section can be combined to afford automatic calculation, a simple example will now be considered. In the previous section the idea of restricting the number and standardizing the form of the computer instructions was mentioned; this idea will now be utilized as an attempt is made to devise a program for the formation of the expression ab + cd, where a, b, c and d have been assigned specific numerical values. For convenience assume that a is written or stored on the card numbered 9, b on card 10, c on card 11, and d on card 12, while card 13 is assumed to be available for the temporary storage of first a partial result and then the final result.

In forming the expression ab + cd, the first step might be to form ab. This is simply accomplished by the multiplication of a by b. Thus our first instruction -- the instruction on card 1 if we arbitrarily decide to start there -- would be to the effect: clear the accumulator of the arithmetic element (make it contain zero) and then add into the accumulator what is written on (the contents of) card 9. This instruction can be abbreviated as:

ca 9 (clear accumulator and add into it the contents of card 9).

As a result of this order, a is placed in the accumulator, and the next step would be to multiply it by b. Thus the instruction on card 2 would be to the effect: Multiply the contents of the accumulator by the contents of card 10, leaving the product in the accumulator. This order might be abbreviated as:

mu 10.

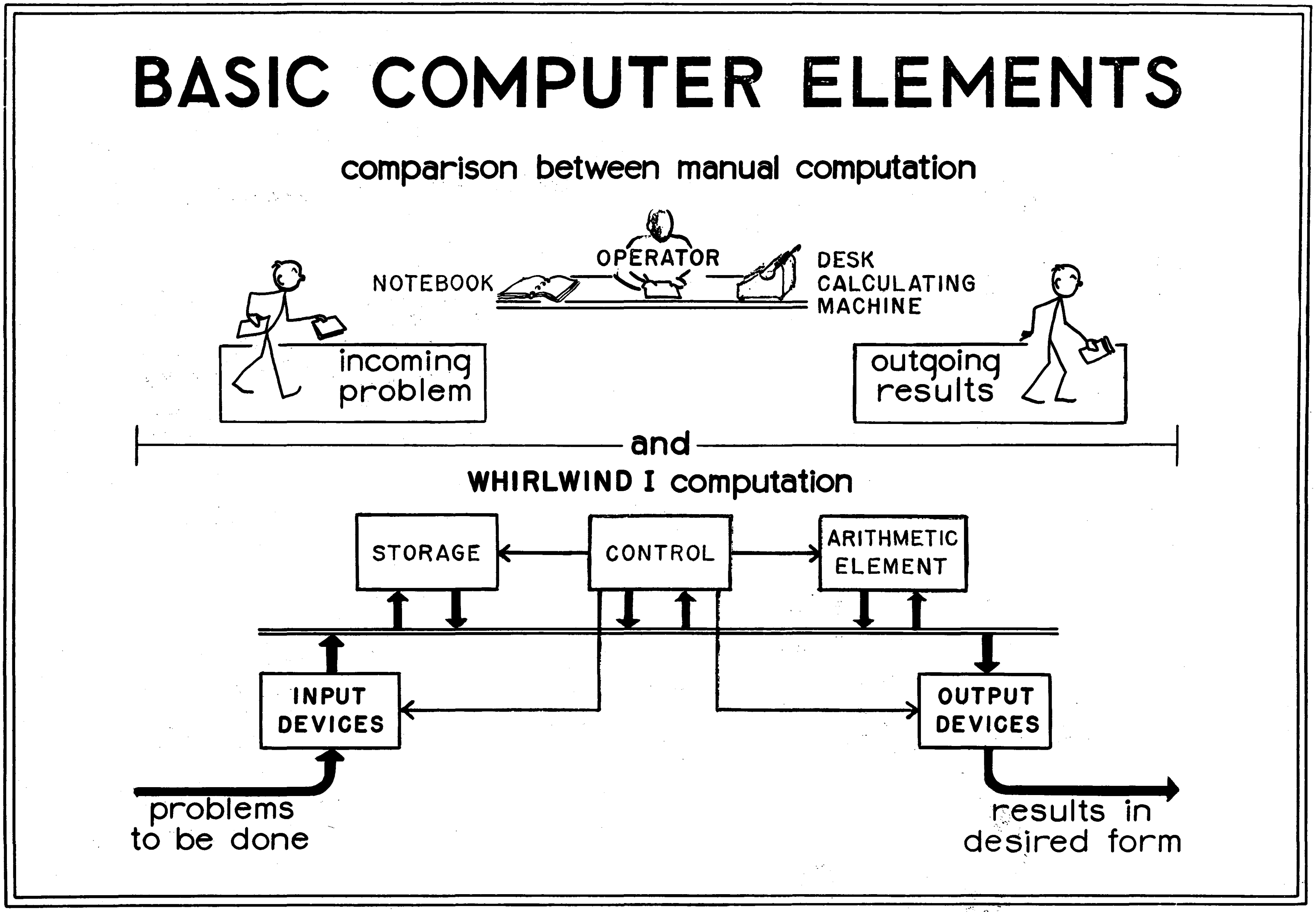
The next step in the computation would be to remove the product ab from the accumulator and store it temporarily while the product cd is formed. The temporary storage of ab can be accomplished by clearing (erasing) card 13, and then transferring the contents of the accumulator to this card of the storage element. The order for such an operation would be

ts 13.

On cards 4 and 5 would be stored the instructions for finding the product cd:

ca 11
mu 12.

A-35676
F-1028
SC-207

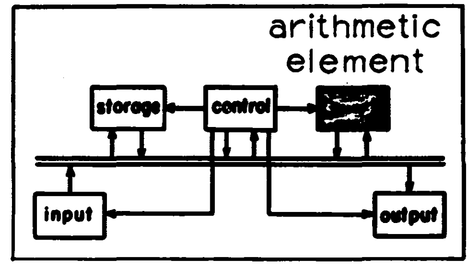


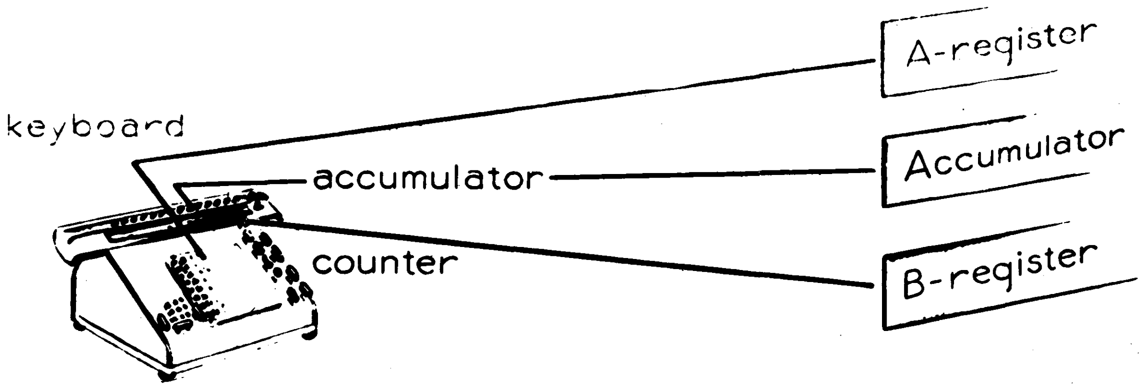
A-36233
F1034
SC-267

basic computer elements

ARITHMETIC ELEMENT

of WHIRLWIND I compared with a desk calculator





Receives number from the main bus- Holds addend, subtrahend, multiplicand or divisor

The adding unit-Holds the result of an addition, multiplication or subtraction and the dividend in division

Auxiliary register-Holds the multiplier or quotient

DESK CALCULATOR

ARITHMETIC ELEMENT

PERFORMS ACTUAL ARITHMETIC OPERATIONS SUCH AS ——

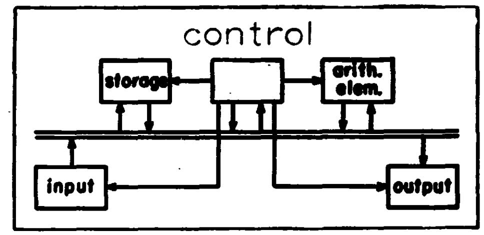
add • subtract • multiply • divide

A-36231
F1032
SC266

basic computer elements

CONTROL

Just as in manual computation the operator controls the steps to be performed • so in WHIRLWIND I computation



CONTROL

takes next instruction in sequence from storage • examines it and sends pulses at the proper times to the various parts of the computer to perform the necessary

PROCESSES

instructs STORAGE to

SELECT A STORAGE REGISTER
AND READ IN OR READ OUT
EITHER NUMBERS OR INSTRUCTIONS

instructs
ARITHMETIC ELEMENT to

CLEAR REGISTERS •
ADD • SUBTRACT • MULTIPLY
DIVIDE • COMPARE

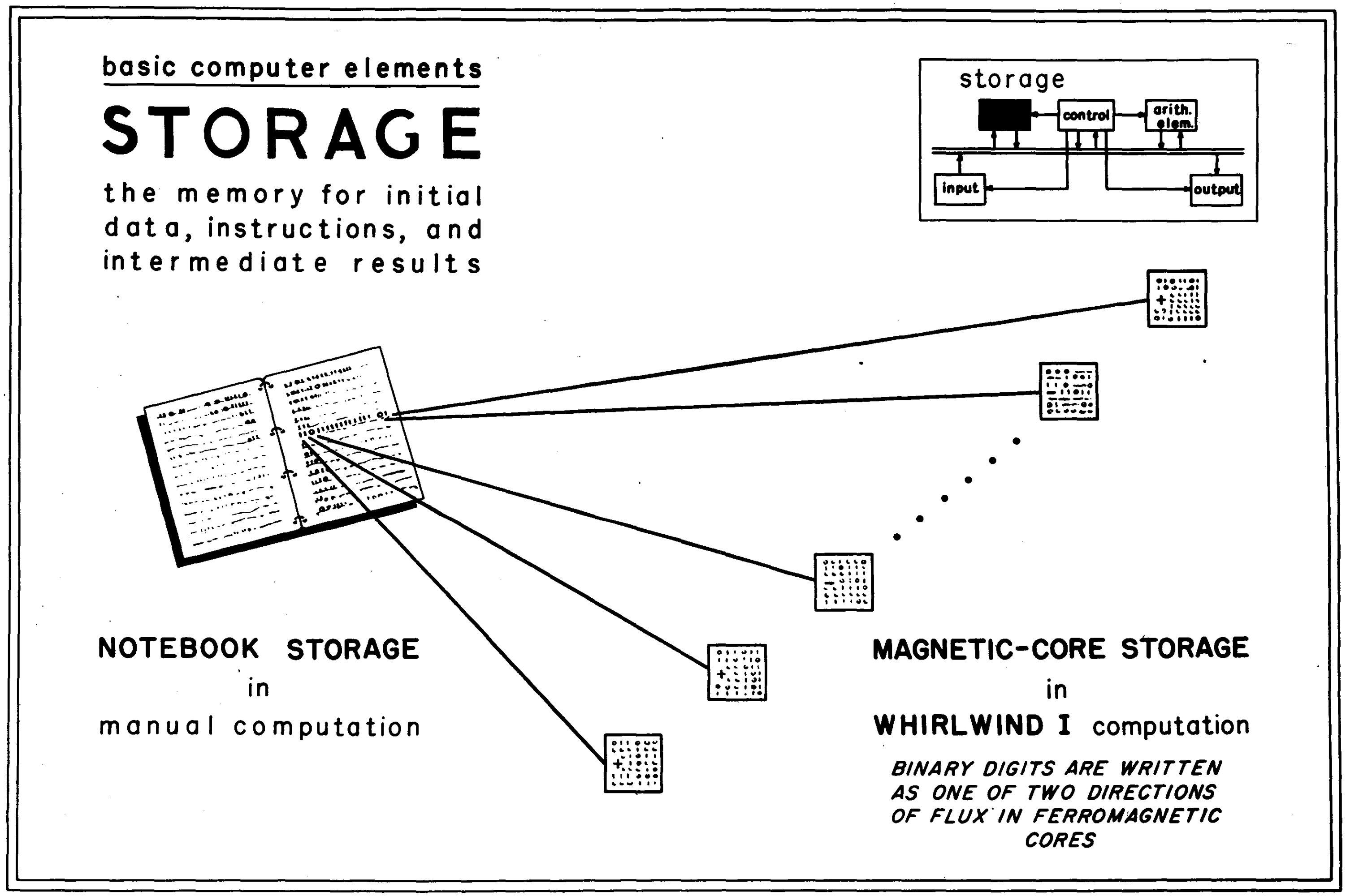
instructs INPUT to

SELECT EXTERNAL DEVICE
START — READ — STOP

instructs OUTPUT to

SELECT EXTERNAL DEVICE
START — RECORD — STOP

A-61591


basic computer elements
STORAGE
the memory for initial data, instructions, and intermediate results
storage
control
arith. elem.
input
output
NOTEBOOK STORAGE
in
manual computation
MAGNETIC-CORE STORAGE
in
WHIRLWIND I computation
BINARY DIGITS ARE WRITTEN AS ONE OF TWO DIRECTIONS OF FLUX IN FERROMAGNETIC CORES

To the product cd, must now be added the previously obtained product ab stored on card 13. This addition is obtained with the order

ad 13.

With the computation complete, the result can be stored on card 13 by another application of the ts order, this time as

ts 13

Having completed the evaluation of the expression ab + cd, one might then wish to proceed to another computation, as for example one whose first order was to be found on card 50. Inasmuch as the control element has been automatically proceeding from order to order (card to card) in sequence, the control element must now be instructed to stop and then recommence its action at card 50. This can be done by a special order for this purpose, which shall be abbreviated as

sp 50

The cards and their required contents for the program of calculation outlined on the previous pages are:

Card	Contents	Action
1	ca 9	a in accumulator
2	mu 10	ab in accumulator
3	ts 13	ab on card 13
4	ca 11	c in accumulator
5	mu 12	cd in accumulator
6	ad 13	ab + cd in accumulator
7	ts 13	ab + cd on card 13
8	sp 50	control element reverts to card 50
9	a	
10	b	
11	c	
12	d	
13	Initial contents immaterial	
.		
.		
.		
.		
50	start of next program of calculation	

The orders in the above program when carried out in the card sequence 1, 2, 3, ...8 enable the evaluation of the expression ab + cd, provided that the proper numerical values of a, b, c and d are initially stored on cards 9 through 12. By the use of input and output equipment one might supply various values of a, b, c and d for cards 9, 10, 11 and 12 prior to the calculation from a teletype tape or some other type of input medium; furthermore, after the calculation one might take the result stored on card 13 and transmit it out onto a teletype system. An order such as

rd 9

might be used to read in a value of a from teletype tape and store it on card 9, while the order

rc 13

might be used to record from card 13 onto teletype. Inasmuch as there might be several types of input and output equipment available, prior to the use of either an rd or rc order one would use an additional order to specify the particular equipment to be used. As an example, the order

eu 29

might be used to prepare for the subsequent use of an external unit numbered 29.

3. Comments on Computer Orders

The orders described in the previous section are not of a particularly complex nature, but merely require of the control element that ability to perform several simple tasks. In fact these orders are of such a simple nature that a dull or unimaginative person would suffice as the control element. As might be expected, because of the standardization and simplicity of the orders it is possible to synthesize a satisfactory control element purely from electrical or mechanical components. It is this fact, coupled with the electronic and mechanical realization of the other basic elements -- storage, arithmetic, input, and output -- that makes possible the construction of an automatic computer. For convenience in this and the succeeding section the existence of a satisfactorily automatic system of the five basic elements shall be postulated without specification of construction details. In accordance with current terminology, we shall refer to storage positions or registers rather than cards, with each storage position or register being assigned an address corresponding to the previously-described card numbers.

Two-lettered abbreviations have been introduced for denoting orders, the two letters selected so as to be suggestive of the meaning of the orders. The choice of the two-letter notation was completely arbitrary, and other notations or representations -- numbers, symbols, Greek letters, etc., -- could have been employed without any change in the basic reasoning. The orders used in the previous section also represented extreme simplification, and if so desired each card could have contained a good deal more information and thereby have ordered the performance of a more complicated arithmetic manipulation. For example, the order

mu 21/35/53

could have been used to indicate that the contents of storage position (card) 21 was to be multiplied by the contents of storage position 35, the product being stored in storage position 53. The discussion here, however, will be limited to the single-address type of order such as:

ca 9

which is the system used in the Whirlwind Computer.

The orders already introduced are but a small sample of a wide range of possibilities. Additional orders such as subtraction and division would find wide use. Beyond the initial stage of a few simple arithmetic orders such as addition, subtraction, and multiplication, the idea of convenience enters heavily into the choice and complexity of the computer orders. Although an arithmetic element capable of extracting the square root of a number can be built, this is possible only at the expense of additional equipment; on the other hand, however, one can find the square root without a special order or special equipment by means of a small program of computation using the more elementary arithmetic orders. In particular, the square root can be found either by evaluation of a power series or by application of Newton's Method.

Arithmetic orders represent but one type of action which a computer can execute. As an example of the non-arithmetic type, we can consider the <u>sp</u> order used at the end of the example presented on page 29 This order, indicating to the control element that it should recommence its sequential examination and performance of instructions at a specified storage position, constitutes what might be termed an <u>absolute</u> change of control, and is one exception to the stated convention that the control element always inspect the storage positions in sequence. There is another form that the change of control might take; this would be a <u>conditional</u> change of control. An example would be an order with which the sequential examination is interrupted and a change of control effected only when the contents of the accumulator of the arithmetic element are negative at the time when this order is used. This order, designated as <u>cp</u>, would act in the same fashion as the <u>sp</u> order whenever the contents of the accululator are negative, but would have no effect upon the sequential examination when the contents of the accumulator are positive.

As an example of the application of a <u>cp</u> order, consider the small program given below:

```
 9  ca  25     a in accumulator
10  mu  26     ab in accumulator
11  cp  35     If ab is positive, go to order 12.
               If ab is negative, go to order 35.
12  ca  25
 .
 .
 .
 .
25   a
26   b
 .
 .
 .
35  ca  26
```

In this case if the product ab is positive, the computer proceeds with a calculation beginning at order 12; when the product ab is negative, the computor takes its next order at register 35.

The logical action of the cp order provides a most powerful tool and greatly enhances the versatility of a computing system. As noted, depending upon the presence of a positive or negative result at a certain point in a program, different orders or sequences of orders can be brought into play. This, in effect, means that it is possible to program for alternative courses of action, and it also makes it possible to make the remainder of any computation depend upon the nature of one or more intermediate results.

In conjunction with the use of the cp and sp orders, note should be made of the possibility of changing the addresses of some of the orders in a program. As an example, the program given on page 29 could be used to evaluate ab+cd for another set of values of the parameters stored in registers (storage positions) 17, 18, 19 and 20 if the addresses of the corresponding orders in the program were changed. If proper changes in the addresses of the orders were made, the computer could be instructed to first evaluate the expression ab+cd for values of the parameters stored in registers 9, 10, 11, 12, then for values in registers 17, 18, 19, 20 and then for values in registers 22, 23, 24, 25, etc.

In many cases, such as that above, one has a group of orders which are used over and over in a cyclic fashion, sometimes with the address sections unchanged, sometimes with the addresses changed. In any case, a sequence of consecutive orders can be used in a cycle if the loop is closed by a cp or sp order. When a cp order is used for this purpose, one can arrange to go through the cycle any number of times, using the discriminatory feature of the cp order to end the process. Such cyclic programs are invaluable for iterative processes in mathematical calculations.

4. A More Generalized Attitude

In developing a broader view of the capabilities of a computer, closer attention must be given to the function of the input and output equipment. Rather than being considered merely as devices employed by individuals to insert or extract information from the computing system, one should regard such equipment as the sensory faculties of the system-- the eyes, ears, nose, tongue, and fingers -- these faculties being under the direct supervision of the control element -- the brain of the system.

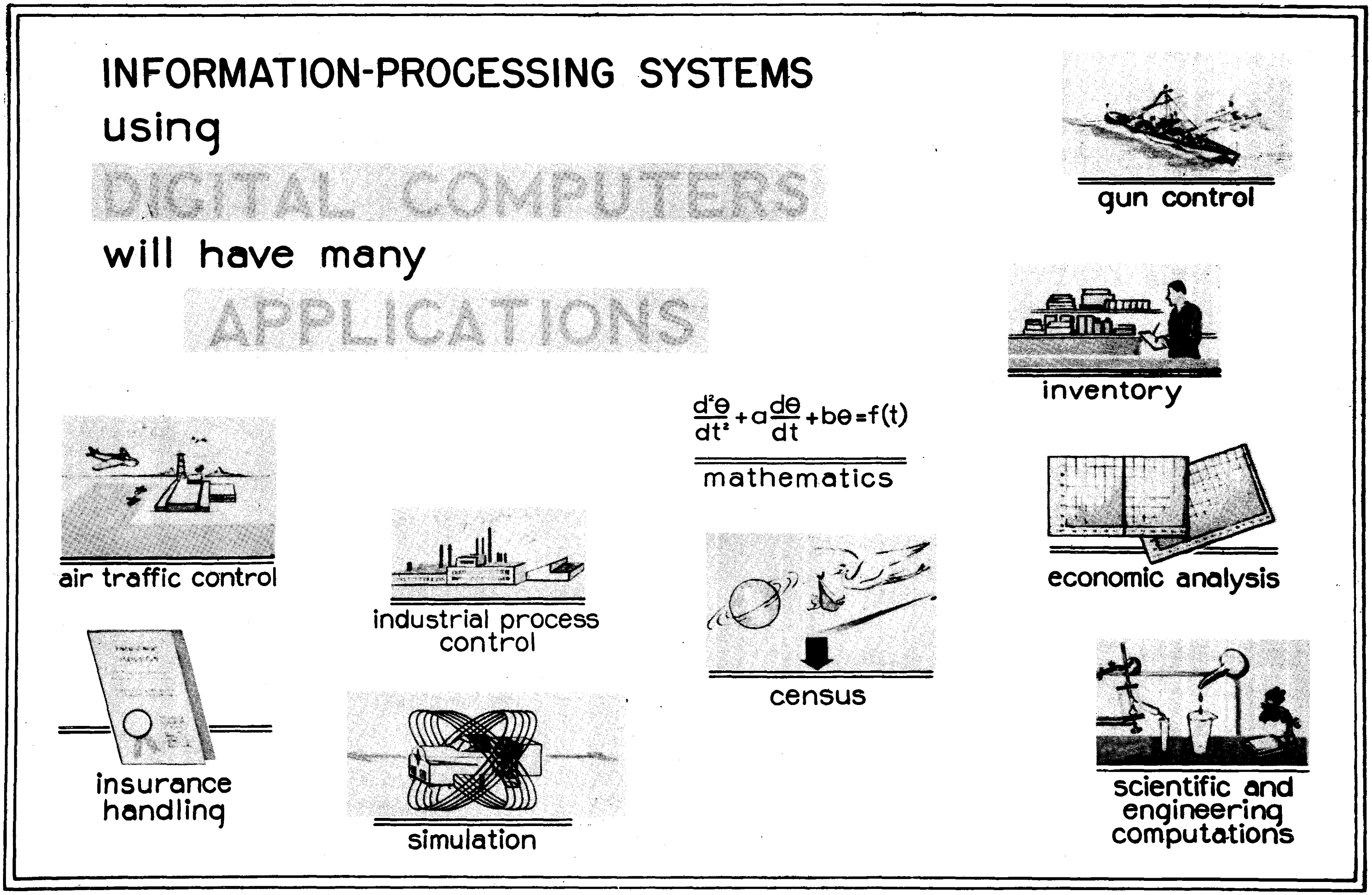
As an example of this use of external equipment, we might note that information in the form of appropriate electrical signals can come to the computer from a photoelectric cell, a mechanical counter, or as a measurement of a shaft position or a phase difference; on the other hand, the computer can feed out information in the form of electrical signals to a teletype system, to a servomechanism, to a relay, to a bell, or to any piece of equipment whose operation can be controlled by electrical signals.

This more generalized concept of the function of input-output equipment is in agreement with the more generalized attitude which can be adopted towards a computing system. This concept holds that a computer is actually a processor of information in a general information handling or processing system. With such a viewpoint, the capabilities and possible applications of a computer are impressive. Figure 7 indicates but a small number of these applications.

The requirements which a computer must meet are obviously dependent upon the type of application considered. In one example, such as a mathematics problem, the input information may be a relatively small amount of numerical data, the output being but a single calculated result. In such a case the storage element of the computer would predominately contain arithmetic orders for carrying out the computation. In a second example the input to the system might consist of a large amount of uncorrelated data assembled in a random or haphazard order. This would be true of data collected in a census. The output in this case might be the same amount of data -- the data, however, being carefully processed and compiled in an ordered and usable form. For this job the arithmetic ability of the computer would not be heavily taxed, although the discriminatory feature of the computer -- as evidenced by the cp order -- would be of great importance. The storage of the computer would essentially contain programs for the sorting and ordering of information, while sophisticated input and output equipment would be needed for the tremendous data-handling problem.

In another example the input to the computer might be information relative to the state of affairs of a physical system or situation. The storage of the computer would contain the necessary instructions so that the existence of various conditions could be discerned, following which the computer would determine the necessary steps or actions which should be taken in accordance with these conditions. In this case the output of the computer would consist of instructions or information for various members or elements of the physical system, the information destined to effect a change in the external conditions.

One outstanding feature of this last example is that the output instructions from the computer may be required almost immediately after the input information has been received. That is to say, time and speed of response may be of vital interest because of the fact that one of the dimensions of the problem is time. A high speed of computer response might also be needed in the first two examples given above; however, this is generally so only because of the fact that if high computing speeds were not possible the results would not be available in practical lengths of time. If this condition does not exist, though, the question of whether the problem is carried out today or tomorrow or whether the time for the solution is one or two hours is of relatively little


INFORMATION-PROCESSING SYSTEMS
using
DIGITAL COMPUTERS
will have many
APPLICATIONS
gun control
inventory
$\frac{d^2\theta}{dt^2}+a\frac{d\theta}{dt}+b\theta=f(t)$
mathematics
economic analysis
air traffic control
industrial process control
census
insurance handling
simulation
scientific and engineering computations

consequence; in <u>real-time</u> problems, such as control applications, high machine speeds are necessary and in some cases it is only the high speeds of automatic computing systems which make the solution to the problem possible at all.

Two types of real-time problems should be mentioned: one is the <u>control</u> of the elements in a physical system according to a predetermined plan, the other is the <u>simulation</u> of the performance of some type of physical system through the solution of the equations describing the system and the appropriate interpretation of the calculated results. The use of a computer for the supervision of the present-day air traffic system belongs to the first category.

5. <u>The Problems of Programming.</u>

At the present state of the art, automatic computers are not yet able to exercise any imaginative thinking. Their whole course of action or commutation must be explicitly outlined to them beforehand in terms of orders and instructions. A computer can recognize a situation only if it has been programmed to recognize it, and hence it is vitally important that all possible alternatives and situations be planned for in setting up the calculation.

The first step in the planning for the use of a computer in a large-scale control problem consists of a careful and exacting study of the physical system itself. This study must enable one to determine all the possible situations that might arise and the appropriate action which would be taken in these cases. In effect, this requires that a detailed handbook of instructions, carefully indexed and cross-referenced, be compiled.

As noted previously, the logical effect of the <u>cp</u> order is to give a <u>yes</u> or a <u>no</u> answer to the question of whether a particular number is negative or not. Surprisingly enough, almost all physical situations can be resolved into a series of such questions. In this sense the general action of the computer could be described as the repeated process of sensing whether a condition exists (a <u>yes</u> or <u>no</u> answer) and then performing certain actions.

The analysis of a problem generally permits one to state the required computer program as a series of statements, each of the form: "If condition A exists, and if condition B exists, and if condition C exists. ...., and if condition N exists, then action W is to be taken." If there are separate conditions, each of which can take either a favorable or an unfavorable state, then there would be 2^N statements and 2^N different actions. In many cases, a good deal of these conditions and actions will overlap or coincide, but in any event it is obvious that the problem and its solution stated in terms of all possible conditional statements and actions would be cumbersome. A neater and more concise phrasing is usually possible with a flow diagram.

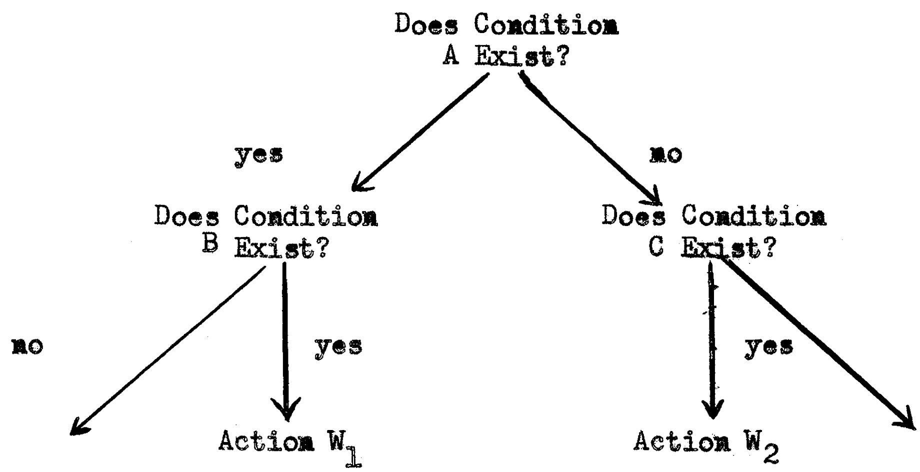
A simple example of a flow diagram is given in Figure 8, where action W_1 is taken if conditions A and B exist, while action W_2 is taken if A does not exist and C does exist. As noted, the flow diagram is incomplete in that it does not indicate what occurs if B or C do not exist, or what happens after actions W_1 and W_2. It is seen that a flow diagram is more convenient than words in describing the action to be taken under stated conditions.

Generally speaking there are a number of different ways in which a problem can be handled, and the statement of a flow diagram must be based on the assumption of a particular method. The assumption of a method of solution and the construction of a flow diagram must in turn be based on a knowledge of how the computer would proceed to separate and distinguish separate conditions and how it would carry out the desired actions by means of the available orders.

The next step in preparing a program for the computer is the process of coding or translating the problem into the actual machine language -- the specific orders and numbers. The end result of the coding process is a coded program for the computer. From this coded program the storage space and operating time requirements for the program can be determined. If it is found that the solution requires more storage space or operating time than can be allocated to the problem, a new method of approach, a new flow diagram, and a new coded program must be made.

Although the process of coding can be done in all degrees of complexity, less sophisticated programs are likely to be quite uneconomical in storage space. It has been found that an experienced programmer can usually effect a 20% saving in programs coded by newcomers, these savings being made possible by the knowledge of special methods and techniques. An experienced programmer is usually able to discern parts of programs which have some amount of similarity, and in such cases he does not use separate orders for each of these similar portions, but rather he uses a subprogram or group of orders which can be put to joint use by various sections of the main program.

In summary, the general requirements for using a computer in a problem are two-fold: first, the problem must be analyzed and a proper formulation of the solution must be made in terms of conditional statements or a flow diagram -- that is, the problem must be reduced to a logical formulation; secondly, the flow diagram must be mechanized in the language of the computer with due regard to the capabilities of the computer and its associated input-output equipment. The two phases of the planning for the use of a computer entail considerable analysis and study: the first to ensure that all possible conditions are met and treated; the second to obtain favorable storage and time requirements and to ensure proper functioning of the program in terms of the computer orders.



Illustrative Flow Diagram

Figure 8

B. The Whirlwind Computer

1. Representation of Information

In accordance with the discussion in the first part of this chapter, the information stored in the Whirlwind Computer relates to the operations to be performed, the addresses of particular storage positions used in these operations, and to data retained in certain storage positions. Direct digital representations are used for the addresses and for the numerical data, whereas a coded numerical representation is used for the various operations which are otherwise specified by two-letter abbreviations. The computer, can, in effect, store and handle non-numerical quantities -- for example, alphabetic information -- if an appropriate coded numerical representation is used.

The number system chosen for the digital representation in Whirlwind is that with the base (or radix) 2. As contrasted with the more familiar decimal system which uses numbers whose digits may be 0, 1, 2, 3, ... 8, and 9, the binary system employs only the digits 0 and 1. In either system the magnitude and position of a digit specifies a particular multiple of a power of the base. For example, the decimal number 203.9 is interpreted as

$$2.10^2+0.10^1+3.10^0+9.10^{-1}$$

The binary number 1011.01 is interpreted in a similar fashion as

$$1.2^3+0.2^2+1.2^1+1.2^0+0.2^{-1}+1.2^{-2}$$

For purposes of convenience in reference, each piece of information retained in a storage position is termed a <u>word</u>. As noted in previous sections there are two types of words -- one is an <u>order</u> or <u>instruction</u> which consists of a specified <u>operation</u> and an associated <u>address</u>, the second is a <u>number</u> or piece of data. Words in Whirlwind are 16 binary digits in length; the assignment of these 16 digits for orders and numbers is shown in Figure 9.

In representing a number the first digit position is reserved for the sign digit, while the other 15 digits are considered as numerical digits with the binary point at the left. The following conventions are employed: if the number is positive, the sign digit is <u>0</u> and all other digits correspond to the binary digits of the number; if the number is negative, the sign digit is a <u>1</u> and the digits of the word are the complements (<u>0</u> for <u>1</u>, <u>1</u> for <u>0</u>) of the positive magnitude of the number. This particular representation of negative numbers is known as the "nine's-complement" and is used for convenience in arithmetic operation. It should be noted that there are two representations of zero:

$$+\ 0 = 0\ 000\ 000\ 000\ 000\ 000$$
$$-\ 0 = 1\ 111\ 111\ 111\ 111\ 111$$

A-36237
F1039

WHIRLWIND I

WORDS are held in storage registers and represent either *NUMBERS* or *INSTRUCTIONS*

number

0	1	0	0	0	1	1	0	1	0	0	0	1	0	1	1

SIGN: +

NUMBER: .55112

instruction

0	1	0	0	0	1	1	0	1	0	0	0	1	0	1	1

OPERATION CODE: TRANSFER TO STORAGE

STORAGE ADDRESS: REGISTER NO. 1675

CONTROL DETERMINES WHETHER A GIVEN WORD REPRESENTS A NUMBER OR INSTRUCTION

With the representation used and the position of the binary point at the left, the numbers which can be stored are $+0$, -0, and all integral multiples of $+2^{-15}$ between $-1+2^{-15}$ and $1-2^{-15}$. The choice of the position of the binary point at the left means that multiplicative constants or scale factors must be associated with the storage of quantities outside of the range $-1+2^{-15}$ to $1-2^{-15}$. For example if a number of angles ranging between $0°$ and $360°$ were to be stored they could be stored as $\theta/720°$ by the use of the scale factor $1/720$.

The representation of orders or instructions is shown in the lower part of Figure 9. The first five or left-hand digits of an order are used in the binary-coded representation of an operation. These five digits suffice for the definition of 2^5 or 32 operations. The remaining 11 digits at the right-hand end of the word permit the specification of 2^{11} or 2048 addresses of storage positions.

Reference to Figure 9 shows that orders have the same appearance as numbers or data, each being a 16-digit binary word. Given a word from the internal storage of the computer, one could not identify it uniquely as an order or a number; a word obtains significance as an order or number depending upon its position and use in a computing program. An important result of this fact is that arithmetic operations can be carried out upon orders as well as numbers making it possible to change the address sections of orders and hence obtain greater versatility in the use of these orders.

2. Electronic Aspects and the Storage Element

The fundamental reason for the use of the binary system of notation is its great convenience in electronic manifestation. The fact that any digit in the binary system can only be a 0 or a 1 enables one to represent a digit by a device or means capable of two distinct and distinguishable modes of operation. The static representation or storage of a digit is possible with a flip-flop, a bi-stable circuit of the Eccles-Jordan type. Storage of a digit is also possible by the presence or absence of a charge on dielectric surface. The dynamic representation or transfer of a digit is possible by one of two conditions on a transmission line -- either the presence or absence of a pulse, or the presence of one of two different voltage conditions. Through the use of electronic elements in essentially either an on or an off state, large signal-to-noise ratios are obtained with a corresponding increase in reliability.

The internal operation of the computer is organized and carried out by the transfer, routing, and storage of pulses or binary digits. In performing the majority of the computer operations, a number of associated pulses must be dealt with -- arithmetic operations requiring manipulation with 16 digits. One of the factors behind the high speeds obtainable in Whirlwind (see page 11) is the simultaneous transmission and operation upon digits by parallel identical channels. This is to be contrasted to a possible serial manipulation using but a single channel.

The arithmetic and control elements of Whirlwind are compounded from flip-flops and other standard pulse-technique circuits. Storage registers built of flip-flops are used in both of these elements; however, the cost of such registers precludes their use on any other than a small scale. The large-scale internal storage medium in Whirlwind is composed of specially-designed electrostatic storage tubes. Binary digit information is stored in these tubes as charges on a dielectric surface.[1]

The design specifications of the storage tubes call for a tube capacity of 1024 (2^{10}) binary digits. A parallel storage system is used whereby each digit of a word is stored in a similar position in each of 16 tubes. In this fashion, the deflection plates of all 16 tubes are operated in parallel and a complete word can be read into or out of storage in the same time that is required for the storage or recovery of a single digit. By using two blanks of 16 storage tubes each, a total capacity of 2×2^{10} or 2048 words can be achieved. This corresponds to the existence of 2048 sixteen-digit registers.

In their final form it is expected that the storage tubes will permit the storage or extraction of a word in 6 μseconds. At the present time neither this projected storage access time nor the planned storage capacity has been achieved, although progress is being made towards these goals. The storage tubes now permit access times of about 20 - 30 μseconds, while the operating capacities of the tubes are 256 digits each. With only one bank of tubes installed, the existing capacity of the storage element is 256 words. The computer has been operating quite satisfactorily for a period of six months at this capacity, and present plans are to double this capacity within a year.

3. <u>The Control Element</u>

The general functioning of the computer is best described as a continued repetition of two basic steps:

a) obtaining the next order (operation and address) to be performed

and

b) carrying out the operation specified in that order.

The control element of the computer supplies the necessary pulses for both of these steps, and carries out step a) itself. Step a) is always the same, and relates to finding out where the next order is stored, obtaining this order from electrostatic storage, and preparing the machine to carry out that order. The second step, that of carrying

---

1. Reference 28

out the operation, varies according to the nature of the operation and is usually carried out by the control element in conjuction with the arithmetic, storage, input, or output elements.

Step a) above is performed in 8 useconds plus the time for one storage access. Step b) usually involves at least one storage access plus anywhere up to about 24 useconds for the longer arithmetic operations. At the present time the average computer order is performed in between 50 and 100 useconds; in the future this time should be reduced to between 20 and 30 useconds

4. <u>The Arithmetic Element</u>

The chief components of the arithmetic element are three 16-dgit flip-flop registers. These registers — The A register (AR), B Register (BR), and Accumulator (AC) — have a striking correspondence to the keyboard and counters of a desk calculator. The AR is buffer register by which information is fed into the arithmetic element, while the AC performs the bulk of the arithmetic work. The BR acts as a part of the AC and is used chiefly for multiplication and division.

The basic arithmetic abilities of the arithmetic element are addition, subtraction, mutiplication, division, shifting (multiplication by powers of 2), and point-off (finding the characteristic of $\log_2 X$. The arithmetic orders of the machine — and it has already been noted that the choice of the orders is based chiefly on convenience and flexibility — also have certain added features dealing with round-off, magnitudes, etc.

There is a considerable amount of fine detail regarding the effects of the arithmetic orders and other orders used in the machine, these effects relating to matter of electronics, logical necessity, and convenience; for reference these orders are summarized in Appendix 1. Literature dealing with the use of these orders is listed in the Biblie-graphy I.

5. <u>Input-Output</u>

Information is introduced to and extracted from whirlwind primarily as electrical signals. At the present time the input and output equipments are fed and receive their signals from several flip-flop registers, this arrangement is only tempory and in its final for the link between the computer and the outside world will be a general-purpose <u>input-output register</u>, together with and <u>in-out switch</u> for selecting various pieces of terminal equipment.

A large variety of input and output equipment has been considered for use with Whirlwind (see Figure 6), Up to quite recently the efforts have been directed towards the use of photographic film and punched paper tape. Extensive use has also been made of cathode ray

1. References 25, 27

tube displays and a typewriter-printer as output means. The paper tape equipment used is similar to that employed in standard teletype applications, and the procedures and conventions employed are such that direct input from or output to teletype equipment could be easily obtained. The flexibility of the computer makes it readily adaptable for use with other types of equipment, the choice of external equipment depending chiefly on the applications for which the computer is to be used. For use of the machine in general non-real time applications, magnetic tape units are now being prepared for use with the computer; the use of the machine for real-time applications will probably utilize a magnetic drum either for additional external storage or as a buffer storage for information from asynchronous sources.

The punched paper tapes are used both for the supplying of the initial contents of storage -- orders and data -- as well as for data needed later in calculations. The slow, mechanical paper tape units permit special techniques in the reading-in and reading-out of date, and also allow rather thorough checking of the input data. Further comments on this subject are made in the succeeding chapter where the input-output problem is discussed in relationship to the air traffic control application.

CHAPTER IV

Input-Output Considerations for the Computer-Controlled System

Although the general purpose of this study is to consider the mechanization of the present-day system without any essential changes in the techniques and methods currently employed, one obvious change which must be considered is the means of introducing the information concerning aircraft movements and weather conditions into the new controlling element of the system--the computer. The problem is essentially one of handling and processing large quantities of information. A large amount of information and data must be supplied to the computer in a never-ceasing flow, and the computer in turn must provide information in the form of instructions for the control air traffic. The information-handling problem must be satisfactorily resolved, or it stands as a possible barrier to the success of the computer application: if information cannot be supplied to and withdrawn from the computer in the proper manner--with due respect to speed and accuracy--a computer-controlled system is not feasible.

This chapter first discusses the data-handling presently involved in the en-route phases of air traffic control. A second section outlines in fairly general terms a system which will meet the existing requirements, while a third section discusses certain aspects of the use of the proposed input-output system.

A. Information-Handling in the Present-Day System

The controlling element in any scheme of air traffic control must have (a) ready access to current information regarding both the flights in progress and those being planned, (b) as extensive a knowledge as possible of existing and expected weather conditions, and (c) complete information regarding conditions at and about the airports. Under the present-day system this information comes to the controller from a variety of sources, and in a number of different ways.

Information regarding commercial and military flights is obtained by the controllers over an interphone system from operations offices established by the commercial carriers and the military services. These operations offices are in direct radio contact with their aircraft; they file the initial requests for a clearance (Approval Requests), and relay flight progress reports from aircraft in the air. Private, civil, and non-scheduled flights -- this class of traffic being termed "itinerant" by the controllers--either subscribe to privately-operated communications stations or use the Flight Advisory Service[1] rendered itinerant traffic by the Civil Aeronautics Administration and the Weather Bureau. Reports concerning certain aircraft are also received by the center controllers via interphone from centers in the neighboring control areas.

---

1. The Flight Advisory Service performs for the itinerant traffic the general functions of an operations office.

The last-minute requests for takeoff clearance for aircraft (Clearance Requests) are received via interphone from the tower operators when the aircraft are ready to depart. The center controllers are supplied with up-to-the-minute information regarding acceptance rates and stack heights at the airports by approach controllers in the airport towers. Quite recently the use of VHF radio has permitted the center controllers at Boston to establish limited but direct contact with pilots as an aid in sequencing for landing. This innovation has not yet been made a national practice.

Weather reports are normally received at the control-centers by members of the Weather Bureau who collect reports from regular observation points via teletype, analyze these reports, and then distribute the information to the controllers. Further information regarding weather conditions is obtained directly by the controllers via interphone, both from airport towers and from operations offices which relay observations from the pilots.

The flow of information also proceeds in the opposite direction. Instructions, confirmations, and information destined for the control of en-route traffic leave the control centers over interphone on the way to operations offices, airports, or centers in adjacent areas.

The amount of information handled by controllers can be quite large, depending of course upon the weather conditions and the density of traffic. During a "busy session" at the Boston Center it is not unusual to see ten controllers and their assistants continuously accepting and dispatching messages over the interphones. The situation is further complicated because the information arrives from a large number of independent sources. Each controller has access to 10 - 20 circuits, each circuit having up to five parties. There is no switchboard to give any orderly flow to calls, and at peak loads a controller usually has a backlog of unanswered calls awaiting his attention.

B. <u>An Outline of an Input-Output System</u>

The computer can only utilize information in a binary form, and can generally only initially accept this information as binary-type electrical signals. One of the first problems in the input-output arrangements, then, is to convert the information which originally exists in written or oral form to the required binary signals. Of similar importance is the necessity to convert the binary-type electrical information produced by the computer to a form recognizable and usable by humans.

The conversion of information to binary electrical signals and the transmission of this information to the computer site can probably be best accomplished with a minimum of expense through the use of existing teletype facilities and techniques.[1]

1. Reference 29

The introduction of information to the system would be by means of teletype typewriter units situated at the locations presently connected by interphone to the control centers--that is, at the airport towers, operations offices, weather observation stations, etc.; the present system of radio communication between the aircraft and ground installations would be retained. Messages introduced into these input typewriter units would probably not be directly transmitted over the teletype system, but would be temporarily stored on punched paper tapes (see page 47). The information on these paper tapes could then be read to the teletype system by means of mechanical or photoelectric tape readers.

Considering first an individual input unit (typewriter) linked directly to the computer, the factor of speed evidently is of major importance. At one end of the link is a human operator capable of typing only a limited speed--the limitation either being of the human or of the input unit itself--and at the other end is a high-speed computer which operates most efficiently when accepting data at a rapid rate. Some speed-up of the input can be obtained through the use of paper tapes and photoelectric readers, but the speeds of these readers as well as bandwidth considerations in a low-cost communication link will not permit the improvement necessary for efficient utilization of the information with high computer speeds, and it would appear that a buffer storage device must be used. Similarly, in satisfying the requirements of handling information flowing away from the computer, a storage medium is needed as a buffer between the output of the computer and the relatively slow output typewriter units.

The buffer storage medium which is to provide the necessary flexibility in speed should also be capable of providing a means of channeling and sequencing the flow of information arriving from a large number of independent input units. Although on the input end there is no question of the destination of the messages--all messages going only to the computer--it does become necessary to provide a means of routing the outgoing messages from the computer to the individual destination; this function could be handled by the buffer storage unit.

The most suitable buffer storage device, from the viewpoint of availability, reliability, flexibility, and cost, would seem to be a magnetic drum on which information is stored by magnetizing small portions of the drum surface. A drum presently being marketed by Engineering Research Associates has the following characteristics:

a) speed of rotation of 3600 rpm
b) 2048 angular storage positions around the drum
c) 80 channels along the length of the drum, each channel being provided with a reading writing head.[1]

---

1. Reference 30.

These 80 channels permit a capacity of some 160,000 binary digits; increased capacities are easily obtained by using longer drums. The drum can also be efficiently broken down into smaller units by the appropriate grouping of individual channels into fields.

Information can be stored on the drum in a number of ways; information can be introduced in a parallel manner with the digits of each piece of information each being stored in a different channel but all at the same angular positions, or information can be stored in a serial manner with each digit using a successive angular position in the same channel. Techniques such as these would be employed to handle the messages arriving from the individual input units; in particular it might be desirable to assign a field on the drum to each input unit.

With the speed of 3600 rpm, information can be introduced to or read out from successive registers or angular positions on the drum every 8 μseconds, a speed even faster than that at which the information can presently be inserted or withdrawn from Whirlwind. However, by making use of non-consecutive registers and by utilizing some of the drum channels for control information, almost any desired reading and writing speeds can be obtained. For example, pieces of information could be introduced into consecutive registers once each drum rotation (16 milliseconds) and could then be read out during one rotation of the drum at 8 μseconds intervals. It is this type of operation which could be used to permit the desired speed increase in information coming from the input units.

A schematic representation of the major components of the projected input system is shown in Figure 10. Information introduced into the system would be processed onto paper tape and would then be read to the teletype system and transmitted to the computer site. The Drum Control would supervise the reading of the information to the appropriate fields and registers of the drum, and indications would be given to the computer by the Drum Control of the times at which the computer may proceed to withdraw information from a selected portion of the drum. The automatic and direct insertion of the information to the computer through an input-output register would be under the joint control of the computer and the Drum Control.

The read-in of information to the computer would be done periodically at about one-minute intervals. This periodic read-in would provide that no message would suffer too long a delay on the drum. On the other hand, in order to handle expected variations in message traffic the computer would also be programmed to execute a read-in whenever a sufficient amount of information--usually a sufficiently large block--had been accumulated. Signals indicating the presence of such a condition would be provided to the computer by the Drum Control.

As noted in Figure 10 there will be a number of remote locations each supplied with input units. As mentioned in Chapter I, it will probably be necessary for a local operator to insert control instructions and

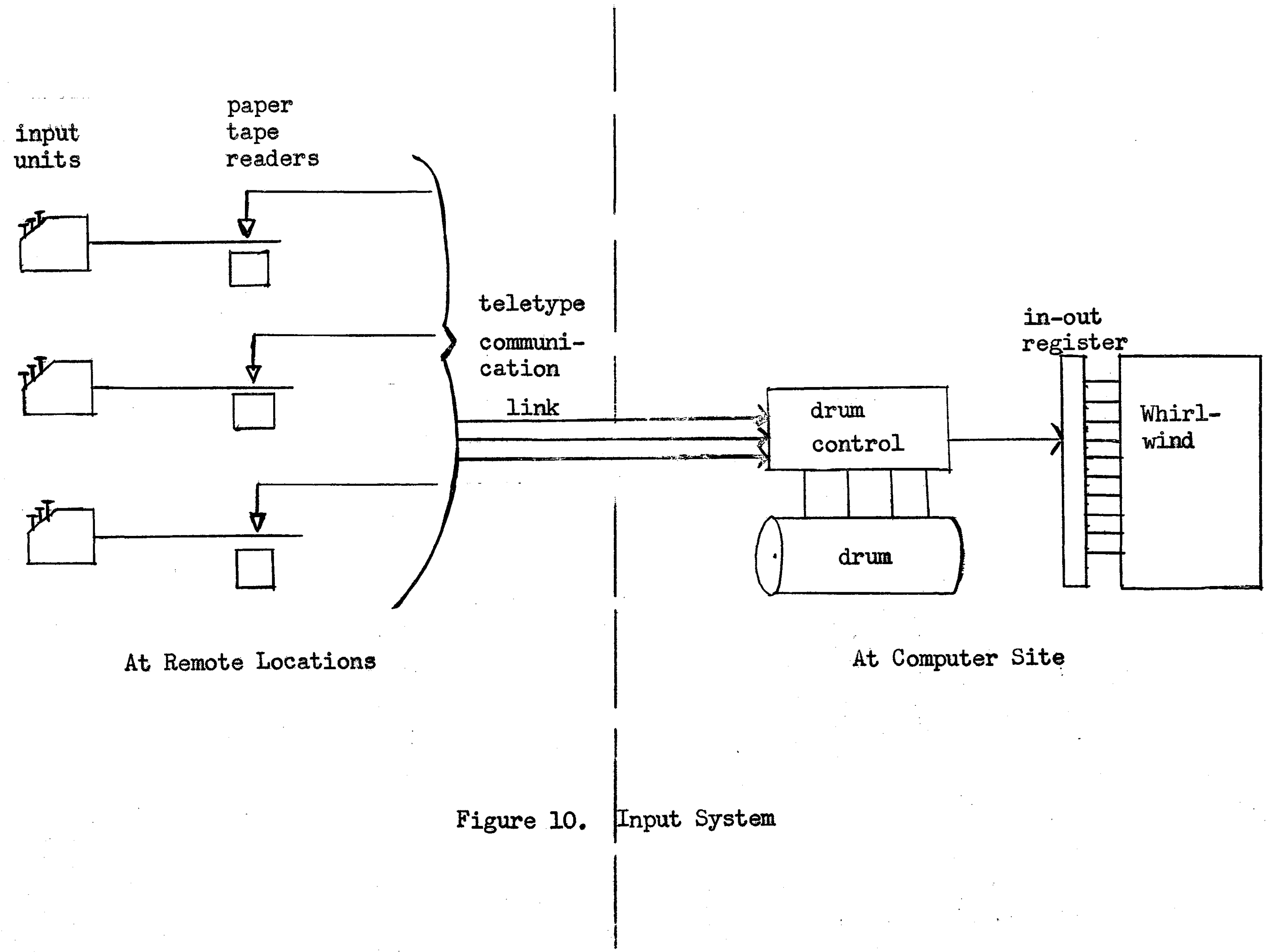


Figure 10. Input System

information into the computer. This would probably be done by a special input unit at the computer site. It will probably also be necessary for there to be a special channel or means of communicating with the computer for high-priority emergency messages.

The arrangements for the output of information from the computer would be quite similar to those indicated for the input, and the same equipments would be used. The computer would accumulate a certain amount of information, and then would perform a high-speed read-out to the drum. Provisions would be made to read out information whenever a certain quantity of output information had been accumulated; however, in order to guard against long delays during slack periods there would be a periodic read-out from the computer regardless of the amount of information which had to be collected. The Drum Control would share with the computer the direction of the read-out of the information to the drum where it would be stored prior to transmission to the remote sites.

C. Further Considerations of the Use of the Terminal Equipment

1. Reliability and Checking

As noted in Chapter I, in order that the use of a computer as the central element of an air traffic system reach any degree of feasibility, the reliability of the computer must be extremely high. It is similarly imperative that the input-output system possess a high degree of reliability, and further that it be operated in an error-free manner with great care being taken to avoid those errors due to human operation as well as errors arising from deterioration or failure of mechanical or electrical components.

A large number of methods have been developed to improve the reliability of communications. These include the retransmission of the information over the same or duplicate facilities and the transmission of the information in coded forms which are highly susceptible to checking. The problems which are encountered are quite similar to those which arise in connection with the internal reliability of computers, and similar steps and techniques will have to be employed to obtain satisfactory operation.

Certain precautions must also be taken with regard to the human element associated with the terminal equipment. Extreme care must be taken that the messages be correct in content, and that they be properly introduced into the system. Such precautions would probably take the form of repeated handling of the messages during their preparation and typing. This handling would probably entail duplicate or check typing of the messages; a first typing would be used to prepare a tape against which a second or duplicate typing could be compared. This increased message handling should in itself greatly reduce the number of message errors and prevent improper preparation or encoding of the messages.

It is always possible, however, that compensating errors in the transmission of the message will permit an error to enter the computer undetected, and it is similarly possible that the original message upon which the first and second typing were based might have an undetected error. In either case, the resulting errors in the messages may be of an obvious kind or may be rather subtle and difficult to detect. An example of an obvious error would be an air speed of 800 mph rather than 300 mph; an example of a more subtle error is the filing of a requested altitude of 7000 feet instead of 9000 feet.

The obvious type of error can be detected by an alert human operator if it arises in the initial message; similarly, the computer may be programmed to spot such errors which arise mechanically or electrically and which escape the measures used to check the transmission. The subtle types of errors provide a great deal more difficulty in their detection. Such errors are kept to a minimum in the present-day system by a large amount of repetition in successive messages pertaining to a single flight. That is to say, each message not only contains the pertinent information, but is also likely to include a certain amount of information which is redundant. A particular example of this is the repeat-back by the controller of all the details of a flight plan even when the flight plan has been approved without change. If this type of operation proves to be necessary in the computer-controlled system it can easily be incorporated.

2. Conversion

The input units mentioned earlier in this chapter permit a direct translation from oral or written information to electrical signals of a binary nature. It is necessary, however, to specify the relationship between the oral or written information, the binary information produced by these units, and the 16-digit binary words stored by the computer.

Most of the information in air traffic control communication can be rather easily abbreviated into groups of three characters, each character being either a letter or a decimal digit. Upon this basis, input messages would be made up of sequences of three-character groups of words. Each of the characters used would be translated by the input unit into a combination of binary digits; if the direct binary representation were used for each decimal digit, then an airspeed of 185 mph would be typed into the unit as 185 and would result in the flowing sequence of binary information:

0001 (=1)
1000 (=8)
0101 (=5)

Unfortunately there are 26 English letters and 10 decimal digits, and this total of 36 characters would necessitate the use of six binary digits in the representation of these characters; a group of three characters, then, would require 3x6=18 binary digits and hence could not be conveniently stored in a Whirlwind register. The most convenient arrangement for the internal storage of the three-character words in Whirlwind would be to have but five binary digits per character. This, of course, would create 15-digit words, although at the expense of there being only 32 different characters which could be used. Fortunately, it appears that a limitation to 32 characters would not be particularly restrictive inasmuch as all of the alphabetic characters are not used in traffic control messages.

Since the restriction to five-digit binary-coded pentads is made necessary only because of the existing register length of Whirlwind, the problem is probably not of sufficient generality to merit detailed consideration. It might also be necessary that the transmission of the messages in the teletype system include the transmission of extra digits with each pentad for checking purposes. For these reasons, it will merely be assumed that the binary-coded pentads can be formed and transmitted to the computer. This does not necessarily place any particular restrictions on the input units or other elements of the input-output system; if desirable, the input-output system may operate with ordinary teletype techniques and the necessary conversion to the proper pented form can be carried out just prior to the storage of information on the drum.

It should be realized that the three-character words made up of binary-coded pentads represent meaningful information, as do pure binary numbers--the chief difference being that the computer operations of addition, subtraction, multiplication, etc., are meaningful only with pure binary numbers. One major reason for a further internal conversion from binary-coded pentad to pure binary form, then, is to permit ease in arithmetic manipulation.

There are several other important reasons, however. One of these is the saving in storage space. For example, the binary-coded pentad representation for the altitude 18,500 feet, abbreviated to three characters as 185, would appear as

$$\begin{array}{cccc} 0 & 00001 & 01000 & 00101 \\ + & 1 & 8 & 5 \end{array}$$

and in this form it fills a register. In the direct binary form this could be represented as 185×2^{-15} or

0000000010111001.

In air traffic control work it is not necessary to specify altitudes closer than 500 feet, and in general there would be no need to go above a maximum altitude of 63,500 feet. With these provisions, then, a least significant binary digit can be thought of as representing a 500-foot increment. There are but 128 ($= \frac{63500}{500} + 1$) possible altitude levels and these can be represented by seven binary digits. If these seven digits are considered at the right hand end of the register, then altitudes are are represented as follows:

Feet	Unused Digits	Used Digits
0	000000000	0000000
500	"	0000001
1000	"	0000010
4000	"	0001000
32000	"	1000000
63500	"	1111111

Thus an altitude A measured in feet is stored in the computer as the binary form of $\frac{A}{500} \times 2^{-15}$. With such a representation there are nine unused digits in a register which can be used for the storage of other quantities. Further comments on the mechanization of the storage of two or more quantities in a single register are reserved until the next chapter.

The problem of conversion is rather closely associated with matters of checking and storage allocation. This fact can be better appreciated if two aspects of a conversion or translation process are mentioned. The first is the decision as to the end result of the conversion --that is, to what pure binary form the binary-coded pentads should be converted. In the case of numerical information the conversion will be directly to pure binary form, suitably scale factored. For facility in the utilization of the available storage of the computer, however, it becomes desirable to establish a rather arbitrary converted form for certain numerical and alphabetical quantities. For example, the three-character abbreviated form for the Boston reporting point might be BOS, and for convenience in determining the sequence of registers containing data pertaining to the Boston reporting point it will be necessary to establish a particular pure binary equivalent for the three-character group BOS. (The details of this scheme are mentioned in the following chapter). For reasons such as these, the conversion from the binary-coded pentads to the pure binary form is not so much an additional piece of work as an aid in the programming for the computer.

The second aspect of the conversion or translation is the means by which it is carried out. If there is a definite arithmetic relationship or correspondence between the original and the converted form, then it is possible to perform the conversion by arithmetic operations. In other cases where the correspondence is not direct but may actually be rather arbitrary, a stored table of values must be used for the conversion process. With the table-type conversion, inasmuch as all the unconverted forms must be stored in order to obtain one-to-one correspondence between the two forms, it is an easy matter to discover if a particular unconverted form does not exist among the stored values. If such is the case, then it is reasonable to expect that the unconverted form was in error. Similarly, with the arithmetic type of conversion the computer can be programmed to investigate if a converted number falls within a reasonable range of values. Examples of the use of such checking are given in the following chapter.

3. Message Form and Standardization

In order to be able to properly convert, check, and then act upon the contents of any message, the computer must be able to determine what each word (three-character group) of the message represents--whether it is an altitude, speed, reporting point, etc. Human controllers are able to identify various quantities because of their size, units, or position in messages. Although similar techniques could be made to apply to the use of the computer, it is far more practical to use a method by which information is identified as to its type only by its relative position in a particular message.

At the present time the CAA has no rigid regulations covering the contents and forms of air traffic control messages. CAA manuals do specify the necessary minimum contents of messages; however, the flexibility of voice communication and the ingenuity of the human controllers have combined in such a way that the contents and sequence of information in most messages is varied from controller to controller, as well as being varied to meet existing conditions. This is especially true of the addition of further information or comments at the end of messages.

An example of the lack of standardization of message forms is the specification of the flight path of an aircraft. The various reporting points across the country have been given three-letter abbreviations: Boston=BOS, Chicago=CHI, etc. In addition, a large number of interconnecting airways throughout the country have been given route designations, examples being A5, B3, R12. At the present time the path of an aircraft along the civil airways is indicated by one of the following methods:

a) specifying the point of departure, the airways to be followed, and the point of landing. Example:

    STL A5 B6 R12 CHI

b) specifying the point of departure, all intervening reporting points, and the point of landing Example:

    STL SPI PIA BDF CHI

c) by a combination of a) and b). Example:

    STL A5 B6 R12 CHI NBU WDF

The specification of a path by one of the above methods permits the traffic controllers to determine--either from memory, by reference to tables or maps, or directly in the case of b) above-- all of the reporting points over which the aircraft will pass en-route. This is a condition which must also be met by the computer. Inasmuch as a route designation such as A5 implies a number of reporting points along that route, it would be possible to program the computer to convert a path designated in form a) or c) above to the series of desired reporting points as given in b). The storage requirements for such a conversion, however, are likely to be excessive, and it does not appear to be too restrictive to assume that a path will be specified to the computer only as a list of successive reporting points. Similarly, the form of all messages incoming or outgoing, must be standardized -- each piece of information having a designated position in each type of message, with particular type of any message being designated by a key word early in the message.

4. Computer Operation As Regards Input-Output

The present facilities and computer orders for the input and output of information from Whirlwind were designed chiefly for specific application with photographic film units, and as such are not applicable to the input-output problem under consideration.

The input and output of information from paper tape uses rather makeshift arrangements as a temporary expedient until general purpose input-output equipment can be designed and installed. The handling of this problem has been such as to put the burden on computer programs, with the computer executing a number of orders between successive read-ins or read-outs; these programs process and store the words during a read-in, prepare and transmit the words during a read-out. Such a technique is feasible only under the rather special conditions and slow speeds which exist with the paper tape equipment; since the reading and writing is done at such a slow rate, there is not much of a decrease in the input or output rate due to operation of the computer between the handling of successive lines on tape.

With the use of a drum as a buffer storage, information can be made available at a rate which is commensurate with the speed of the computer itself. In order to meet such a challenge, it is felt that there must be no intermediate action by a program, with its resulting delays, in the following respects:

a) taking the pentads from the drums

b) performing any necessary checking operations on the transmission

c) assembling three pentads to give a complete word

d) storing the assembled words in the registers of Whirlwind.

Special orders would probably be necessary to perform these functions most efficiently. Similar orders would be needed to perform similar functions in the output of information from the computer.

The general scheme of operation would be to have a 16-digit input-output register connected directly to the 16 digit columns of Whirlwind. The binary-coded pentads would be introduced in sequence into this register which would then perform the necessary shifting and checking operations to assemble three pentads into a computer word. While the components of one word were being read in from the drum and assembled in the input-output register, the previously-formed word would be stored in the internal storage of the machine. As an aid in handling the messages, special key words would probably be used to indicate the end of a message. Normally, an acknowledgment of receipt of the message would, in time, be sent to the message originator. If an error were detected in the input message the computer would take steps to send a message to the originator of the message to perform a retransmission; an indication would also be given to a human operator that an error had occurred so that appropriate maintenance action might be initiated.

There are two special cases of errors in the input which should be mentioned. In one case the error might happen to be in the word which designated the originator of the message. To guard against this eventuality it would probably be necessary to transmit the word designating the originator both at the beginning and end of a message. Equally serious might be an error which lost part of a word or which caused a change such that in reassembling the message in the computer a staggered version of the original message was obtained. Such a condition might not be noticed immediately, and even worse, the key word indicating the end of the message might not act properly. Here again, the repetition of certain words and a special form and means of distinguishing the key word would be necessary.

Somewhat similar considerations to those mentioned above apply to the read-out of information. The words of the message, three pentads per register, would be prepared by the computer. A special order would read the words from storage into the output register where the shifting and transmission to the drum would be performed. From the drum the messages would be transmitted to their destinations. Messages on the drum would not be obliterated until an acknowledgement had been received indicating that the message had arrived safely at its destination.

CHAPTER V

Storage

The operation of the computer requires the storage of both the necessary machine orders and the information and data upon which these orders are to operate. Inasmuch as the information-handling aspect of the air traffic control problem is of the utmost importance, it is necessary to consider the means and methods of storing the large quantity of information and data to be used by the computer.

This chapter first considers the nature and characterization of the stored data, and then discusses techniques to be used in its storage and utilization, especially in light of a general need to economize on storage space. Several flow diagrams are included as a means of illustrating particular storage programs. A final section of the chapter mentions several possibilities offered by the availability of an external storage medium.

A. Data Storage in the Present-Day System

The operation of the present system of traffic control requires the storage and utilization of a large amount of information and data. To a large extent this consists of data which is made available to the controllers in the form of messages. This includes information concerning current and projected flights, traffic conditions near airports and in adjacent areas, and information regarding weather conditions. This general type of information is of the transient type; it describes the present conditions of the variables in the system, it has but a limited time of application, and it must be renewed or replaced at frequent intervals.

Except for weather reports, the bulk of this transient information relates to altitudes, speeds, and times of arrival of aircraft at the different reporting points. As has been previously mentioned, each reporting point is alloted a space on the flight progress boards under which the flight progress strips concerning traffic at that point can be placed. These flight progress strips are made out from the flight plans, each flight progress strip essentially carrying the full information concerning the flight. In a position of prominence on each strip is placed the time and altitude at which the aircraft will pass the reporting point. The flight progress strips are made out in pencil, permitting easy alteration or correction. These strips are usually sequenced in position under each reporting point so as to give the proper time sequence of arrivals over that point.

Other types of variable data -- weather information, traffic conditions at the airports, etc., -- are distributed on paper to the controllers, or else are displayed on blockboards where the information is visible to all concerned.

In addition to the data describing the variables in the system, there must be available for continuous use a large amount of information describing the system constants. Examples are the geographical locations of the reporting points, the separation between reporting points, the minimum altitudes which can be flown along a certain route, types of radio aids, etc. The controllers must also be familiar with the performance characteristics of all types of aircraft: cruising speeds, maximum operating altitude, rates of ascent, rates of descent, etc. Although the amount of this "constant" information is tremendous, in order to ensure rapid and efficient operation of the system it is all committed to memory by the controllers. Even more startling is the fact that each controller is required to be able to control traffic in any of the several sectors in the control area, requiring that the controllers memorize these system and aircraft parameters for the complete area. The magnitude of the task of memorizing the information as well as knowing the general procedures for the control of air traffic is evidenced by the two-year period necessary for the training of a controller.

B. A General Relationship Between Storage Capacity and Operating Time

It has been the common experience of people who have considered the solution of a number of varied problems on a digital computer that there usually exist a wide selection of methods which can be successfully employed for any single problem. Usually these methods vary between those which on one hand require a large amount of internal storage (orders and data) but permit rapid times of solution, and those methods at the opposite extreme which require a small amount of storage, yet involve a long solution time. Between these two extremes there are methods which permit compromises in storage space or operating time at the expense of the other variable.

As an example of the variation in storage and time requirements between different methods, one might consider the problem of evaluating a trigonometric function such as the sine for a particular value of the argument. One approach is to store a large table of values of the sine for various values of the argument. The sine of any particular value of the argument can then be quickly found by inspection of the table and by the use of an interpolation formula. This method is quick, but does require the storage of a table of values. On the other extreme one can use a series approximation to find the sine. Here the storage requirements are likely to be small, yet a large number of computer operations are necessary to find the desired results. Another commonly occurring example is that of the longer problems where the results of calculations at an intermediate stage are again used at a later stage of the problem. In such a case it is a question of whether these intermediate results should be stored for later use, or whether they should be recalculated at the later time when they are again needed.

There is, of course, no direct relationship between the storage and operating time required for the solution of a problem by various methods of attack. To a first approximation, however, such a relationship might be of the form

$$c \sim s \cdot T \qquad (1)$$

where $\underline{c}$ is a measure of the complexity of the problem, $\underline{s}$ is the storage space needed, and $\underline{T}$ is the total operating time. Since $\underline{T}$ results from a number of single computer operations, this could also be written as

$$c \sim s \cdot n \cdot t \qquad (2)$$

where $\underline{n}$ is the number of operations and $\underline{t}$ is the average time per single operation. Equation (2) is used only to demonstrate the generally observed fact that with a fixed time per unit operation, there remains some latitude as to the choice of $\underline{s}$ and $\underline{n}$ which will give a satisfactory solution.

Of course it should be noted that there are certain limitations which must usually be placed on $\underline{s}$ and $\underline{n}$. In non-real time applications the restriction is generally on $\underline{s}$, this being limited by the storage space of the computer. In real-time applications there also exists a limit on $\underline{n}$, since $\underline{nt}$ or $\underline{T}$ must be equal or less than the permissible time per solution permitted by the physical system.

1. Storage-Time Considerations in the Present-Day System

As previously pointed out, the present method of storing flight data involves a duplication of the information on all of the flight progress strips corresponding to that flight. Since the flight progress strips are stored together by reporting points, this technique might be termed "duplicate storage by reporting points."

The cost of additional data storage space is very small in the present-day system, and this method of "duplicate storage by reporting points" produces no limitations from that point of view. Despite its seeming uselessness, in general agreement with the relationship of Equation (2) this duplication of storage does permit a decrease in the amount of work or number of operations. This is primarily due to the fact that instead of having to refer to a number of flight plans in order to determine what time relationships exist between several aircraft at a certain reporting point, the information is already available, sorted out by reporting points. Further, when by reference to a particular flight progress strip one has become interested in a particular flight, there is no need to refer to a master flight plan to determine other characteristics of the future or past of that flight inasmuch as all of the pertinent information is reproduced on that flight progress strip.

Any other scheme than that presently used would be prohibitive from considerations of operating time. The large amount of cross-referencing and comparisons of data which would be necessary in some other method would too severely tax the human controllers. It is only by capitalizing on the large redundancy in stored data that satisfactory operating times are achieved with the present methods and human operators.

2. <u>Storage-Times Considerations in a Computer-Controlled System</u>

It has been pointed out that in real-time application both the <u>s</u> and the <u>T</u> of Equation (1) assume major importance. In the present example <u>T</u> is limited by the rate at which information arrives at the computor and the rate at which it must be processed and instructions determined for the control of aircraft. The storage limit, of course, is the physical capacity of the computer.

At the outset, and before any programming has been done on a problem, it is impossible to determine the true complexity of the problem. In terms of Equation (1), the <u>c</u> is not known, and hence it is difficult to say whether any chosen method of approach will produce values of <u>s</u> or <u>T</u> which lie outside of the acceptable limits. In view of the discussion above, if either of the limits is exceeded it is likely that an adjustment of the other variable will permit both limits to be met. This fact can only be confirmed in a particular case, however, by the actual attempt at solution with a new approach.

As a starting point in the consideration of the air traffic control problem as applied to the Whirlwind Computer, one is inclined to believe that in view of the limited amount of storage space the emphasis should be made at conservation of storage at the expense of computer operations, particularly in view of the relatively low times per unit operation with this machine. This is the attitude which is adopted in this chapter and in those that follow. This attitude, however, is not blindly applied to all problems which arise, especially those in which it is rather evident that the duplication of a small amount of data will save both in orders and operating time.

The foremost application of the principle of stressing storage economy is found in the method which will be adopted for the storage of flight plan data. Rather than storing this data by reporting points as is done at present, thereby requiring a large amount of duplicate storage, the method to be used is that of storing all data concerning one flight in a separate group of registers corresponding to that aircraft--that is, the flight data will be "stored by aircraft." This means that in comparing two flights, the data will not be pre-sorted as to reporting points and the computer will have to search and hunt for the data among the stored flight plans.

It is possible to employ storage schemes which involve compromises between the storage of flight plan data purely by aircraft or by reporting point, however the storage requirements as well as the ease in utilizing the data seem to point towards the method selected. Further reasons which consolidate this attitude shall be made evident in sections which follow.

C. General Problems Associated with Storage

1. Characteristics of the Stored Information

For convenience in considering a number of problems which are encountered in the utilization of the computer's storage space, it is desirable to mention some of the general characteristics of the various types of information which must be stored. There are two characteristics which are of particular interest: the first is the permanency with which the data can be assigned to a register or group of registers, the second is the amount or length of the storage space which must be allocated to various associated quantities.

A large amount of the general data which the computer must operate upon can be assigned to permanent positions in the storage. This is true of quantities which must always be available for use by the computer, regardless of whether the values of these quantities are changed or not to correspond to existing external conditions. The important point is that this information will be continuously needed for program operation, and the permanent allocation will aid the utilization of this information by the programs.

A large part of the stored data fits into the "permanently-stored" classification. Examples are the geographical information regarding areas, airport, and airways; conversion tables; aircraft performance characteristics; and weather information at various points and altitudes in the control area. This last example is one in which the stored quantities must be varied to meet existing conditions.

The "permanently-stored" characteristic does not apply to the flight plan data. Here the data is needed for a limited time only, this time being equal to the period that the flight is under control of the computer. If all aircraft flew according to schedule, it might be advisable to permanently allocate a set of registers to each flight; however, such a scheduled flow of traffic is not achieved at the present time, nor even approached under any conditions. Even under highly optimized conditions involving only prescheduled traffic, the efficient use of the storage space would require a large amount of double or triple tenancy of this space under some form of time-sharing. In order to achieve an economy of storage under the non-prescheduled conditions it will be necessary to consider only a temporary allocation of a set of registers to an individual flight. As shall be described in the next section, this allocation would be made from a common pool of registers reserved for that purpose.

For the most part there will be very little need of storing a single, unassociated piece of data. Most quantities can be associated with larger classifications such as flight plan data, aircraft performance characteristics, airways data, reporting point data, etc. Under the major division by classification, there is a further logical division into the individual flights, individual types of aircraft, individual airways, etc. These may be referred to as the members of the various classifications. Each of these members of a classification will generally require a small block of registers for the storage of the associated data. As mentioned, for each member of the aircraft performance characteristics classification, the cruising speed, rate of ascent, rate of descent, etc., must be stored.

In considering the member blocks of a single classification, there are two general cases; either these blocks are of a uniform length, or the block length varies from member to member. Constant-length blocks are the usual occurrence, a common example being the aircraft performance characteristics wherein the same number of quantities must be stored for each aircraft. An example of non-constant-length blocks is found in the storage of the flight plan data. In this case each member block corresponds to an individual flight, and since the length of a flight is fixed by the number of reporting points over which it will pass, the blocks of flight data will generally vary considerably from flight to flight.

2. Finding Stored Data

As a general example, consider that at some stage in a program the computer desires to deal with a certain member of a classification. Assume that each member in this classification has associated with it a constant-length block of n registers and that the addresses of the consecutive storage registers in the block used for the i^{th} member are given as $a_{i,1}, a_{i,2}, \ldots\ldots a_{i,n}$. In particular the address of the first register of the first block will be $a_{1,1}$.

The need for referring to a particular member of this classification may arise because this member was referred to or specified in an input message; for example, a flight plan might specify that the aircraft under consideration is a DC-3. The three-character binary-pentad designation of any such member will be designated as $\overline{M}_i$. (Lines above letters will be used throughout this chapter when referring to a binary-coded pentad representation). $\overline{M}_i$ would be the appropriate pentad designation of the i^{th} member.

A first problem which arises is that of finding the address $a_{i,1}$ of the first register of the block corresponding to $\overline{M}$. One method of attack would be to arrange that addresses $a_{i,1}$ be derivable by simple arithmetic operations upon the quantities $\overline{M}_i$. Since the $\overline{M}_i$'s will be somewhat arbitrary, it becomes convenient to consider a pure binary number M_i associated with $\overline{M}_i$. If the M's are appropriately chosen as a sequence of consecutive numbers, then in particular it could be set up so that

$$a_{i,1} = a_{1,1} + n \cdot M_i - n.$$

In this way the members occupy consecutive blocks of n registers each. For example, if $M_1 = 1$, $M_2 = 2$, $M_3 = 3$, etc., $a_{1,1} = 100$, and $n = 10$, then the first addresses of the member blocks are given as:

Member	First Address in Block
1	100
2	110
3	120
.	.
.	.
.	.
.	.

The scheme is easily extended to other consecutive values of M, and can be modified to utilize other arithmetic relationships.

As noted, this scheme requires that the M's be assigned in an orderly fashion. This function is easily performed by an input conversion table. A neat method of saving space is to let the M's be arithmetically related to the addresses of the consecutive registers in which the $\bar{M}$'s are stored. Thus, given any $\bar{M}_i$ a search would be made through the table to find the address of the register containing the quantity $\bar{M}_i$. The address is then operated upon arithmetically to give M_i and hence the address $a_{i,1}$. This scheme shall be termed the coded-address method.

In some cases it is not convenient to have a conversion table of the type described above. A particular example illustrated later in the chapter concerns the storage of data regarding the various airways. In such a case a different approach can be applied to the problem of finding the position of a block of storage registers corresponding to a particular member. In this method the member designator D_i (this may either be a 3-character binary-coded word or any arbitrary binary number) is stored in the register whose address is $a_{i,1}$. Hence to find the appropriate block of registers used for member D_i, the computer would investigate the registers $a_{1,1}$, $a_{2,1}$, $a_{3,1}$, etc. until the quantity D_i were found. (In this connection it is convenient to have constant block lengths, where $a_{2,1} = a_{1,1} + n$, $a_{3,1} = a_{2,1} + n$, etc. This method shall be termed the search method.

A comparison of the above two methods will indicate a certain fundamental similarity; in each there is an extra allotment of one register for each member. In the coded-address method this manifests itself as an input conversion table; in the search method this takes the form of an extra register per member block. There is a difference in application of the two methods. The search technique is useful when no conversion table is otherwise needed, and is better applied to constant-length consecutive blocks. The coded-address technique is useful when combined with an input conversion table, and is also better designed for use when the pure binary designation of the member M must be stored in other registers, as is the case in handling flight plan data where the designations of reporting points must be stored with each flight plan. In this case, whereas the $\bar{M}$'s will each be a full register in length, the M's can be shorter binary numbers and as is mentioned in Section C4 of this chapter, they can be stored in a register together with another quantity. A further advantage of the coded-address method is pointed out below in connection with the handling of non-permanently-stored data.

In using a block of data it is generally necessary to extract and use subdivisions of that block. As mentioned, under the classification of aircraft performance characteristics there will be stored the cruising speed, the rate of descent, the rate of ascent and the maximum operational altitude for each member aircraft. In such cases where a similar storage pattern is repeated for each member block and the blocks are consecutive and of the same length, the computer can be programmed to look for, say, the cruising speeds in registers $q_{i,p}$, $i = 1, 2 \ldots$.

In the above case, the computer is programmed to know where to find the various quantities. Such programming is not possible when each block does not contain a similar storage pattern. This is the situation encountered with the storage of flight plan data, where each flight will have a different number of reporting points. In order to properly locate the subdivisions of the data the number of reporting points in each flight plan can be counted and stored as an aid, or else key words can be stored to indicate the end of a variable-length section. The latter technique is probably best suited to the case of the handling of flight data, inasmuch as the flight progresses some of the stored data can be eliminated.

3. Handling of Variable-Length Data

In considering the problem of handling data which has a permanent location but which is on non-constant length, a block size equal to the maximum expected length can be allocated, and the coded-address or search schemes are applicable. Extra registers resulting from any member using shorter blocks than the maximum can be used for the storage of general constants needed by the computer program.

When dealing with flight plan data which is non-permanently-stored and is of variable length, serious questions arise as to the means of obtaining maximum utilization of storage. As an example of the problem consider that a group of registers beginning at address m have been alloted to flight data as follows:

Flight	Addresses	Number of Registers
I	m to m + 19	20
II	m + 20 to m + 29	10
III	m + 30 to m + 59	30

A typical situation which might arise is that in which flight II terminates and its storage space is made free, and shortly afterwards flights IV and V, requiring 25 and 15 registers respectively, wish to join the system. The questions which such a situation creates are two-fold:

1) How do we determine where free registers are available?

2) How do we best decide which flights to assign to free space which is available?

The first question can be resolved by either storing key words in each register when it is made free -- such a key word possible being a negative number -- or by separately storing the pairs of addresses indicating the first and last registers of available groups. In the above example the space made available by flight II cannot be used for flight IV because of its short length, while if it were used for flight V five registers would be wasted, especially since this leftover space would be too short for any other flight. The problem becomes even more difficult when it is realized that as time passes and the flights progress, each flight needs less and less space. Unless this space is made available for use, the efficiency of the use of the storage space of the computer becomes rather low.

One scheme which permits a satisfactory solution and which permits economies in storage would be to shift all data upwards filling any free register which might occur, thus always moving the available storage space to the end. Such a scheme is likely to involve considerable time and somewhat complicated programming. It is felt that an alternative scheme presented below is simpler and faster.

The suggested method is one which uses blocks of a fixed length. This block length would be considerably shorter than the average number of registers needed for storing the complete data for a single flight, and would probably be of a length sufficient to store the flight data corresponding to about two reporting points. A sufficient number of these blocks would be assigned to each flight so that all of the data could be accomodated. The address of the first register of each of the blocks would be related to another address in an assignment table, in a manner similar to the coded-address scheme. The registers of the assignment table would initially be negative, indicating free blocks. The storage of the three-character binary-coded designation of a flight in any register or registers of the assignment table would indicate the allocation of a block or blocks to that flight. The reporting points in the flight plan might actually be stored backwards (although in the input message they would be in the correct order) so that as the flight progressed, blocks used to store the reporting points could be made free from the end. Fuller details of the scheme are given in Section E of this chapter.

4. <u>Half-Length Storage</u>

As noted in the previous chapter, with suitable scale-factors and by utilizing the fact that only certain discrete values of variables are of interest, it is possible to represent most of the data stored in the computer by only seven or eight binary digits. It can also be noted that most of major classifications of storage have less than 128 members and hence seven digits suffice for the member designations after the conversion of the input. This being the case, it appears that advantage can be taken of the economies afforded by storing two pieces of information in a single register. No complication arises due to the algebraic signs inasmuch as most of the quantities to be dealt with are positive.

The present Whirlwind orders are not very well suited for this half-length storage -- either in the assembling or separation of a compound word. Although a special order would be useful, there would not be a considerable saving in storage inasmuch as the assembly, separation, or change of a component part of the compound word could be done by a few special subprograms which would be usable by all parts of the main program. The special order would save considerably in operating time, however.

5. Applications of Programs to Various Blocks of Storage

Although each of the component parts of the overall computer programs will necessarily apply at some time or another to various members of a classification, the programs as written and stored in the computer must have definite addresses supplied with the orders. A problem which arises, then, is the adaptability of the programs to the various member blocks of storage.

Of course, once it has been determined what the member is and where it is stored, the address sections of the program in question can be appropriately modified. This technique is rather lengthy and wasteful of storage, especially when it is considered that almost all of the programs must be modified. A more acceptable technique is that in which all such programs would be written with the critical addresses referring to a fixed set of otherwise unused registers; then for proper program operation the pertinent member's block of storage would be bodily transferred to the fixed set of registers. This transfer might be best implemented by one or more special computer orders, particularly of the self-indexing type; however, as in the case of half-length storage the end result could also be accomplished by a small subprogram which would be in common use. This subprogram would either have to be supplied with the number of the registers to be transferred, or else a key word could be employed to stop the transfer in a manner similar to that in which a key word designated the end of an input message.

D. Point and Path Data

1. Information to be Stored

For purposes of computation and control the computer must have available certain operational and geographical information regarding both the various reporting points and the airway or paths joining these points. This information is most easily considered as being separated into two distinct classifications: point data and path data. As noted earlier in this chapter, all information regarding flights shall be separately stored by flight plan, and hence the point and path data represent permanent allocations of storage space.

The following listing indicates the types of information which must be stored for each of the reporting points in the control area:

a) indication of whether the point in question is internal to the area or whether it is near the boundary.

b) information regarding the approach control facilities. This will include the position of the stacks, the highest stack altitude in use, the time intervals for successive approaches, etc.

c) information regarding altitude restrictions or time limitations on traffic over the point. An indication must be stored as to whether the point is suitable for holding aircraft en-route, this being determined by the position and general traffic density at this point.

d) information regarding visibility and ceiling conditions if there is an airport at that reporting point.

The following listing is typical of the information which must be stored for each of the paths joining the reporting points:

a) the length of the path.

b) the minimum flight altitude which is permissible along this path.

c) weather conditions, to include visibility conditions, cloud tops, and wind magnitudes and directions at various altitudes.

d) any radio beacons or markers (non-reporting points) which can be used by the computer as an aid in the traffic control.

2. Point-Path Relationship

The various paths and points in a control area are not totally unrelated quantities inasmuch as the area possesses a certain geometry as defined by the geographical location of the points and their connecting paths. To be able to properly direct traffic in an area, the computer must be able to reconstruct and utilize this geometry. It is necessary to determine which paths meet at a point and which points lie at the ends of a particular path. In the present-day system the controllers have maps available for reference, although they are usually able to remember and mentally reconstruct the necessary geometry. A computer, lacking an inherent sense of spatial relationship, must perform the task by means of stored information.

The storage and utilization of the path and point data will require the assignment of designations to the individual members of these two classifications. Consider that these designations are P and Q, for point and path respectively. One means of retaining the necessary geometrical information would be to store with each member P of the point data the designations of all the paths Q which meet at that point, and similarly to store with each member Q of the path data the two P's at the end points of that path. Such a method is quite wasteful of storage inasmuch as a good deal of the stored information is redundant.

An alternate scheme might employ the assignment of particular numerical values to P's and Q's in such a way that the relationships between adjacent points and paths would be determinable from these numerical values. This scheme was rather thoroughly investigated by the author, and it was determined that such a numbering system was rather difficult to implement due to difficulties encountered when three or four paths[1] joined at a particular point. Although a feasible numbering scheme might easily be synthesized for a particular area, the method turned out to be extremely difficult and lengthy of storage space when applied to an area with a general geometry.

As a point of introduction to the scheme which it is thought presents the best solution to the problem at hand, it is recalled that all reporting points are to be designated in messages by three-letter abbreviations as in the present practice. These unconverted designations shall be denoted by $\bar{P}$. In a normal size control area today there are between 25 and 75 reporting points. It is convenient to consider a maximum of 128, inasmuch as pure binary designations requiring only seven binary digits are then required. These pure binary member designations are denoted by P, and could be assigned by means of a coded-address conversion table.

Each path in the area is completely defined by the points at its two ends. If these two points are P_j and P_k, then the compound 14-digit word produced by joining P_j and P_k can serve as a designation for the path. This compound path designation can be denoted as Q_{jk}, and if P_j and P_k are thought of as numbers between 0×2^{-15} and 128×2^{-15}, $Q_k = P_j \times 2^7 + P_k$. The word Q_{jk} would be composed such that the first seven digits came from the P with the smallest magnitude. The storage of the path data can then be done in blocks according to ascending order of the Q's using the storage technique given on page 60.

---

1. Since the present radio range stations only provide four courses, this determines the maximum number of intersecting paths. The installation and imminent use of new radio ranges which provide a good deal more than four usable courses or paths would complicate the numbering plan considerably.

The methods by which the essential facts of the area geometry can be reproduced using the above-described method of storage are given in the following sections.

3. Illustration of Point Data Storage

As an illustration of the coded-address technique applied to point data storage, the following situation can be assumed. A group of consecutive registers are used for a combined coded-address and conversion table. The contents of these registers are $\overline{P}_1$, $\overline{P}_2$,.....$\overline{P}_n$, the unconverted member designations; while the addresses of these registers are related in some (simple) fashion to P_1, P_2,......P_n, the corresponding binary member designations. For simplicity these addresses are given as f (P_1), f(P_2),.....f (P_n). Thus the stored table is as follows:

Address of Register	Contents of Register
f(P_1)	$\overline{P}_1$
f(P_2)	$\overline{P}_2$
.	.
.	.
.	.
f(P_n)	$\overline{P}_n$

The addresses of the first registers of the blocks assigned to the members P_1, P_2,....P_n are given as g(P_1), g(P_2), ...g(P_n), where g(P) represents a simple arithmetic manipulation upon P.

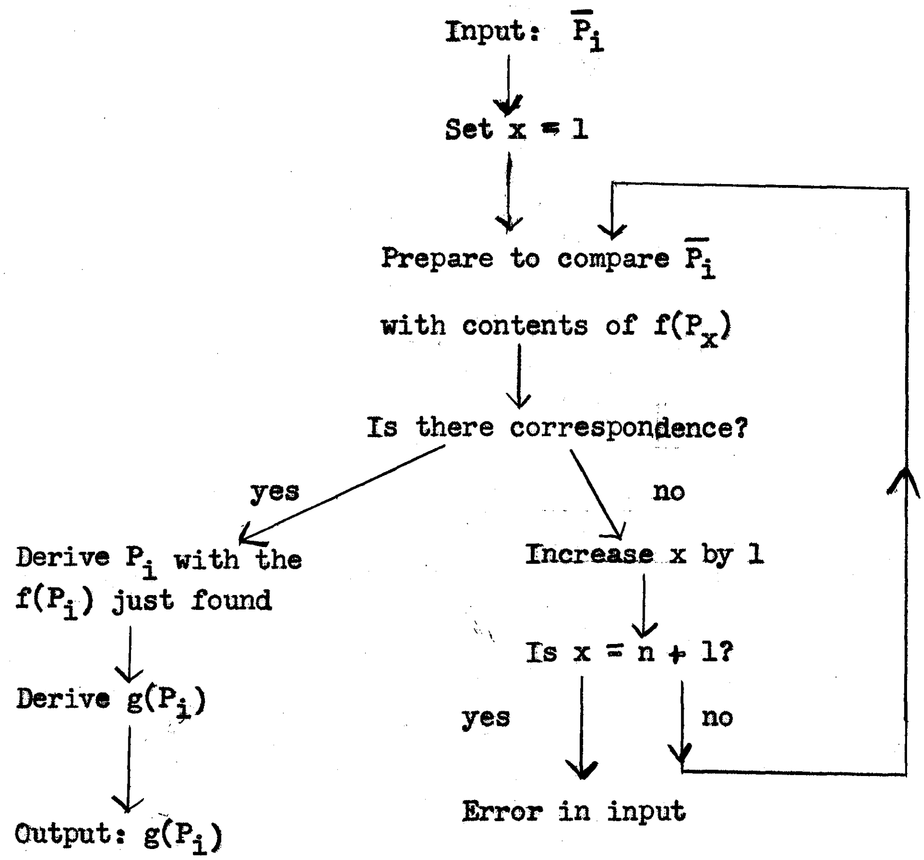
With such a set-up, a flow diagram for a program which finds g(P_i) for any input $\overline{P}_i$ is given in Figure 11. As indicated in this flow diagram, a check is made to see if all the registers f(P_1), ... f (P_n) have been inspected. This feature permits a check on the $\overline{P}_i$: if this value is not found, then the computer knows that an error has been made and can take appropriate action.

Another interesting aspect of the flow diagram is the way by which the computer determines if there is a correspondence between $\overline{P}_i$ and $\overline{P}_x$. It should be remembered that the conditional order cp is only able to determine whether a number is negative or not. If two quantities are subtracted, the result may be positive or negative; if they are equal it will be a negative zero. Hence several additional orders are needed to definitely determine if two quantities are equal. A special-purpose order which directly determined the equality of two numbers and based its conditional character on that criterion would be very useful in this situation and would find wide application in related programs.

4. Flow Diagram for Path Data

As mentioned on page 65, the member designation for the path between points P_j and P_k shall be given as $Q_{jk} = P_j \times 2^7 + P_k$, where it

Let x be a running variable



Flow Diagram for Finding Block of Storage Corresponding to Point $\overline{P}_i$

Figure 11

is assumed that $P_j < P_k$. Each path will be allocated a block of **m** consecutive registers, and as a means of recognizing any member block, the designation Q will be stored in the first register of that block. The blocks themselves will be stored in sequence according to the magnitude of the Q's, and in the first register following the last block will be stored a negative number.[1] If the address of the first register of the first path data block is q_o, then the addresses of the first registers of succeeding blocks are given as $q_o + m$, $q_o + 2m$, ...

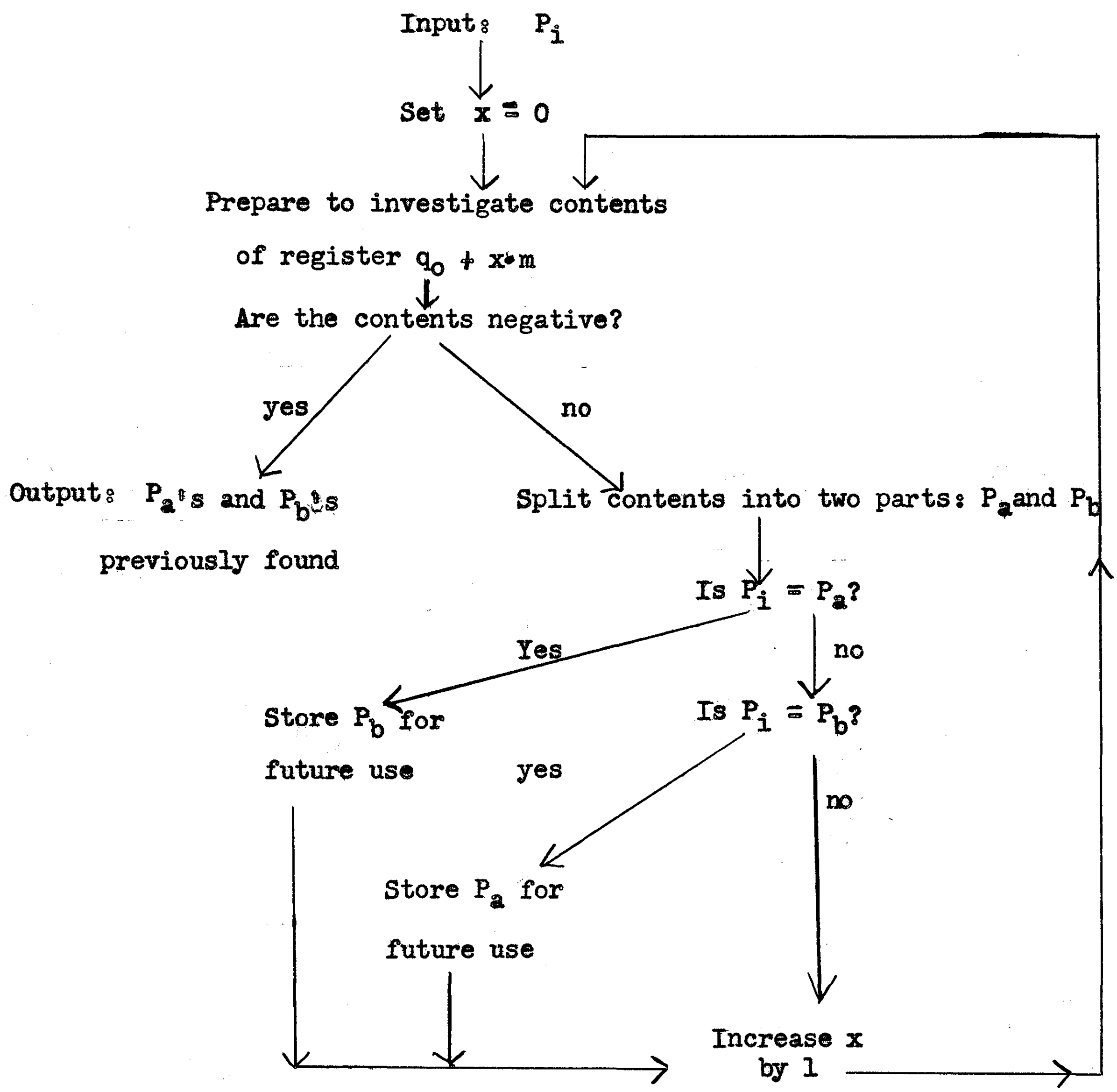
A program which will be frequently used in connection with path data is one which determines which paths join at a certain reporting point P_i. This program would have wide applications in checking upon the validity or correctness of a sequence of reporting points as given in a flight plan. With the storage technique used, the knowledge of paths joining at a point is equivalent to knowing the identities of all of the adjacent reporting points. A flow diagram for determining these adjacent points is given in Figure 12, and a flow diagram for finding the block of registers which is associated with the path between any two reporting points is given in Figure 13.

There are several interesting points concerning the flow diagram of Figure 13. Inasmuch as the P_h and P_i inputs will have been determined internally by the computer in another program, possibly from the program of Figure 11, there does not appear to be any need for inserting an error-detecting check as was done in Figure 11. It can also be noted that there is enough of a similarity between Figures 12 and 13 so that careful programming should be carried out in order to determine whether or not a joint or composite program might not be preferable. A further point to note is that the searching procedure of Figure 13 does not utilize the fact that the blocks are stored in sequence of the values of Q. If there are **s** of these blocks, then on the average the program of Figure 13 will have to search through $\frac{s}{2}$ registers before it finds the desired Q. If the program were written so that it first looked at the contents of register $q_o + \frac{s}{2}m$, one half of the possible blocks could be immediately eliminated due to the sequenced feature of the Q's. The program would then investigate the contents of register $q_o + \frac{s}{4}m$ or $q_o + \frac{3s}{4}m$, depending upon the results of the first try. In this way the program would at most have to do $\log_2 s$ searches, and on the average only $\frac{1}{2}\log_2 s$ searches. The programming for this type of search requires more orders and storage than that of Figure 13 and hence it represents a situation where storage space could be sacrificed for speed.

---

1. This storage register is not wasted since the negative number would be a constant or the negative of a constant used by other programs.

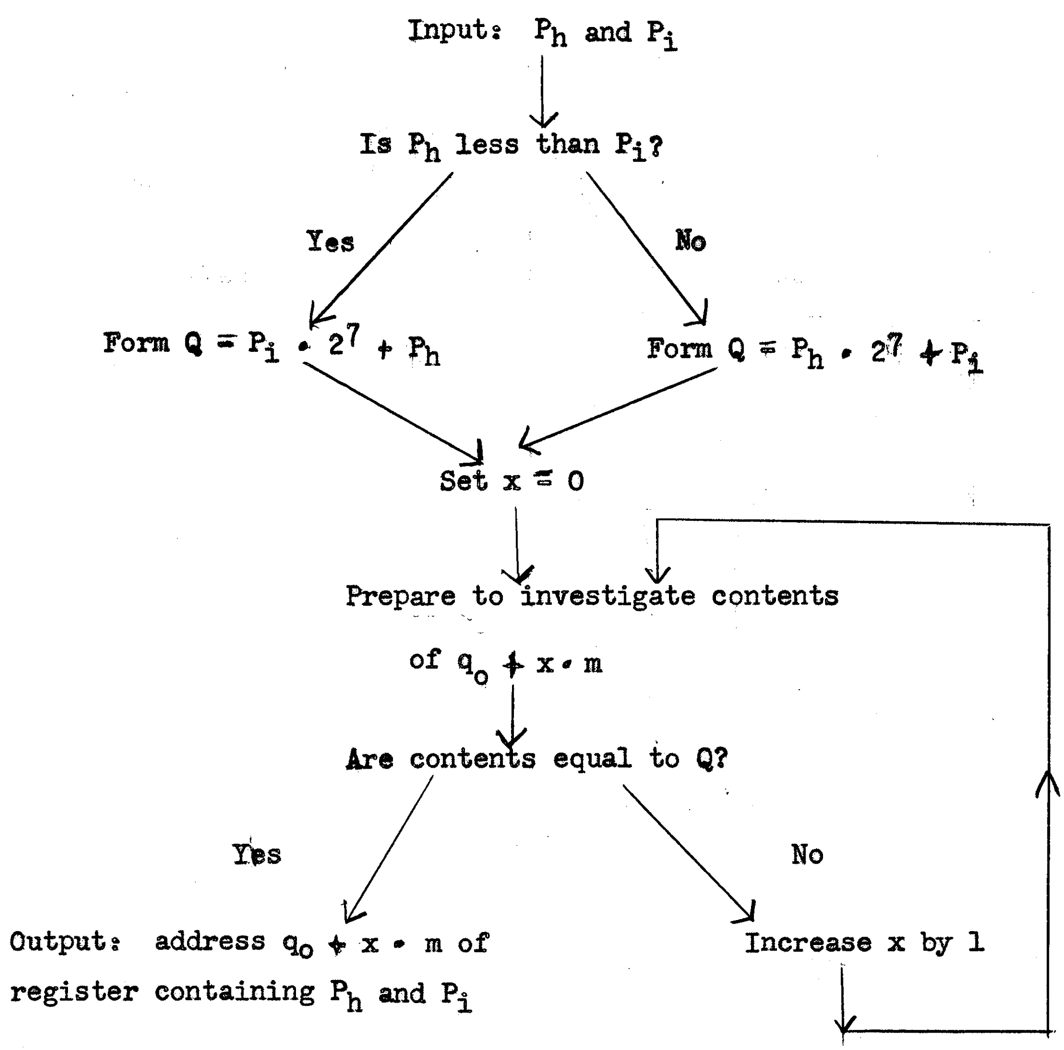
Let x be a running variable



Flow Diagram for Finding Reporting Points Adjacent to P_i

Figure 12

Let x be the running variable



Flow Diagram for Finding Path Data for Points P_h and P_i

Figure 13

E. Handling of Flight Plan Data

The most important part of the flight plan concerns the various reporting points over which the flight is to pass. For each of these points the computer should store the following data:

a) designation of the reporting point
b) time at which this point shall be passed
c) altitude at which this point shall be passed
d) general condition of flight at this point. This will include information regarding whether the aircraft will be IFR, VFR or "500 on top"[1], and whether the aircraft is cruising, ascending, descending, or holding.

As shall be described in succeeding chapters, the information for items b), c), and d) will be supplied both during the initial processing of the flight data and later during the flight as a result of the messages received from the aircraft. For convenience in future reference, item d) will be termed the point condition information.

As has already been established, the designation of the reporting point and the specification of altitude will each require only seven binary digits. The method for specification of time is discussed in Chapter VII where it is established that only 11 binary digits will be required. Thus, if the method of storing two quantities in a single register is used, both the designation of the reporting point and the specification of the altitude can be stored together in a single register, while the time and the point-condition-information can also be stored together, permitting the specification of a 2^5 or 32 conditions. It might appear that there is no need to store the times over each reporting point inasmuch as this information can be determined from an initial time and the speed of the aircraft; however, in view of the effect of winds and delays it appears that an economy of storage would result from the explicit storage of each time.

In addition to the information regarding the reporting points, it will be necessary to store for each flight the following general information:

a) type of aircraft.
b) communication routing for messages to the aircraft or to associated operations offices.
c) information indicating what action has been taken in regard to the coordination of the aircraft when entering a neighboring area or being turned over to approach control for landing.
d) present status of aircraft.

---

1. See page 106

As regards item d), it should be noted that by virtue of the method described for the storage of flight information, in order to determine clearances for aircraft or in order to check upon separations at certain points the computer must search through all the stored flight plan data. In order to simplify and shorten this job, a certain amount of information can be stored in a particular register regarding the present status of each flight. This would include indications as to whether the flight plan had been processed and approved, whether the flight was still on the ground, whether the flight was in another area, when the next progress report from the aircraft should be expected, and whether the flight is receiving special handling during ascent or descent, etc. A fuller explanation of the need and use of these pieces of information will be given in succeeding chapters. Items c) and d) shall be termed coordination information and present status information, respectively.

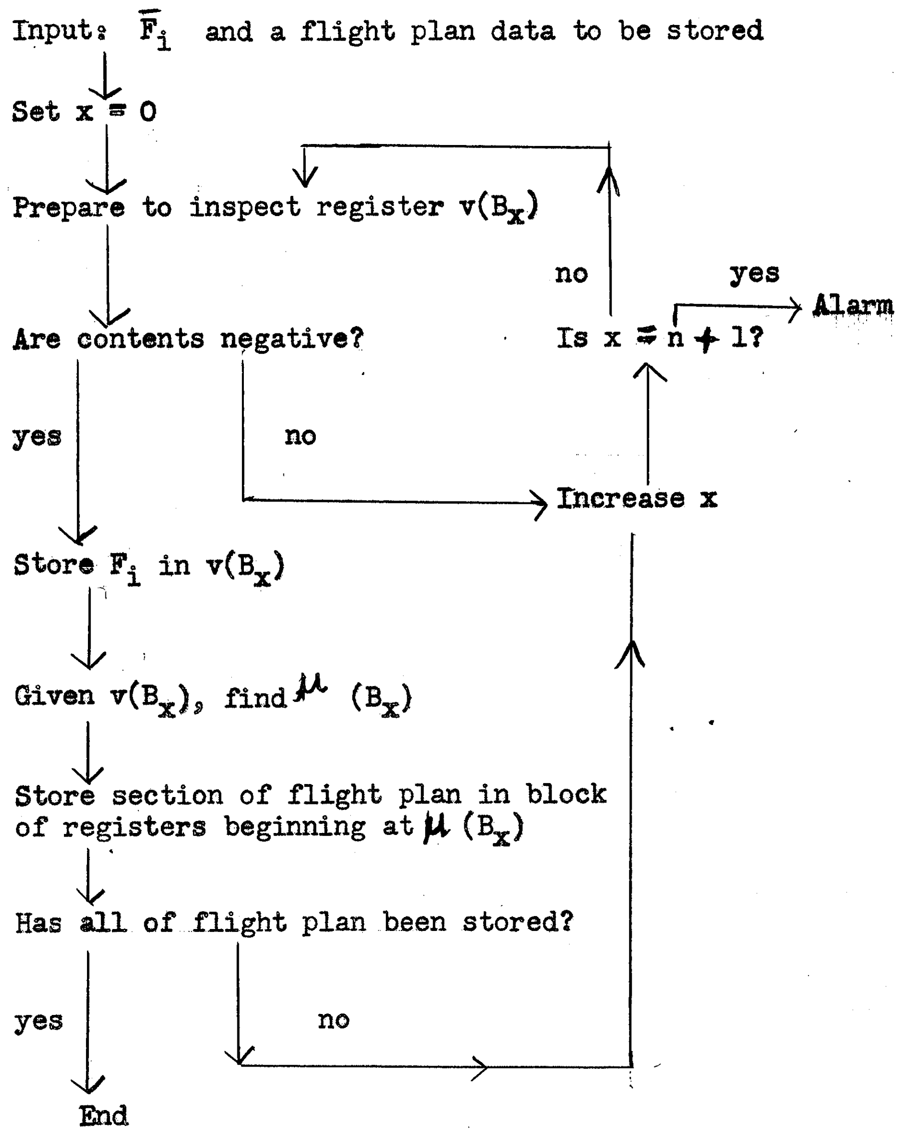
In accordance with the discussion of the earlier part of this chapter, the variable-length flight data will be stored in a number of relatively short blocks. The short length of the blocks will aid not only in economizing on the initial storage of the information, but will permit savings to be made as a flight progresses and its storage requirements decrease. The blocks shall be assigned from a coded-address or assignment table; the registers of this table will be negative when its associated block is free, and will contain the binary-pentad flight identification $\bar{F}$ when the block has been allocated for the storage of part of a flight plan.

As an illustration of the assignment of flight data to storage space, consider the flow diagram of Figure 14. The various blocks of registers used for storing the flight data are designated by $B_1, B_2, \ldots, B_n$. The addresses of the first registers in these blocks are given as $\mu(B_1), \mu(B_2), \ldots, \mu(B_n)$, and the associated addresses in the assignment table are $v(B_1), v(B_2), \ldots, v(B_n)$, where μ and v represent simple arithmetic operations upon $B_1, B_2, \ldots B_n$.

In order to guard against an unexpectedly large amount of flight data, the flow diagram has provisions for indicating when all the available flight data blocks are filled. It should be noted that although in general a flight will not be assigned successive blocks of storage, the order of the flight plan is preserved by sequence of the registers $v(B)$; in particular, if the reporting points are stored in reverse order of sequence at the end of the flight plan data, then the blocks corresponding to the largest $v(B)$ are made free first as the flight progresses.

In recapitulation it should be noted that the method chosen for the storage of the flight data not only economizes on storage, but essentially separates this variable-length, non-permanently assigned type of storage from the fixed-length, permanently-assigned point data storage. This latter fact permits better utilization of the storage space and eases the programming problems. Another feature of storing the flight data by sequence of reporting points is that it implicitly reveals the direction

Let x be a running variable



Flow Diagram for Finding Storage Space for Flight $\overline{F}_i$

Figure 14

of progress of the flight. Storing the flight data by reporting points alone would require the additional storage at each reporting point of the names or designation of the preceeding and succeeding points of the flight.

F. Use of Additional External Storage Space

As a contrast to the previous sections of this chapter which have concentrated upon the necessity of economizing storage space, it is interesting to introduce several comments concerning the possible use of an external storage medium with the computer. The remarks which are made below are purely of an illustrative nature, however, and the remainder of this thésis is based upon the techniques and methods already mentioned.

The use of an external storage medium implies that information to be used must be transferred to and from the external medium, this transfer being either of a single word or of a block of registers. Both the reading to and from the external medium and the subsequent use of the information requires a certain amount of time over and above the time required if it were initially stored internally. In spite of this consideration there are two factors which make the use of such devices quite feasible. In the first place, although a large amount of data must be stored, only a small amount of data -- usually of block size -- is actually needed at a particular time; in addition, the need for a particular block or section of the data will generally be known somewhat in advance of the time that it can actually be used. Similar considerations apply to various programs and subprograms used by the computer; only a small number of them are needed for any particular task being done by the computer, and the need for these programs is usually known in advance. This forewarning of the use of data and programs will become more evident in succeeding chapters when the large amount of bookkeeping or manipulative operations necessary for the execution of the various computer programs or subprograms is discussed. In view of this fact, it would be possible to arrange the programs and the various sequences of calculations and operations in such a way that inherent initial delays in the use of an external storage device would offer but a small drawback. If one had a magnetic tape unit which could be started and stopped rapidly, then in the period between the time when it becomes known that something is wanted and the time when it is needed, the tape could be moved forward to the desired information in preparation for a read-in. A second factor to be recognized is that if the external storage device is used predominately for permanently stored data or programs, there is no need for any time used in reading information back to the storage device. This might make the use of paper tape and a photoelectric reader feasible.

The availability of the external storage would introduce large changes into the provisions already enumerated for the allocation and use of the internal storage space of the computer. A change to the storing of flight information solely by reporting points, as in the present-day system, might be made or some compromise between the two radically different storage schemes adopted; storage schemes which economize on time rather than storage could be adopted. The necessity for conversion might be eliminated if the computer were programmed to compute in terms of the binary-coded three-character groups. Whereas this chapter has considered that times and altitudes be explicitly stored as numerical quantities, if a large amount of additional storage space were available it would be feasible to allocate particular registers to particular times and particular altitudes. The occupancy of that time or altitude would be indicated by storing the appropriate flight designation in the corresponding register. Such a scheme would save greatly on the amount of time which would be required to detect situations in which there is insufficient separations between aircraft. As shall be mentioned in Chapter X, the availability of additional storage space would make it possible in a modified system to handle and give priorities to scheduled aircraft.

CHAPTER VI

Areas and Airports

Before a study can be made of the computer program, it is necessary to discuss in fuller detail some of the problems which arise in the control of aircraft flying between areas or approaching and leaving airports. This chapter discusses these subjects from two points of view: the necessity of a more formal standardization of control procedures for efficient computer mechanization, and the means of coordinating between the computers controlling adjacent areas or between a computer and the approach controllers in the airport towers.

A. Areas

1. Elimination of Sector Control

In Chapter II mention was made of the general division of authority in the control of nationwide en-route traffic: first into areas and then into sectors. As noted, the division into areas, each supervised by a single control center, was made for reasons of economy, while the division into sectors was necessitated in view of the limited speed and data-handling capacities of human controllers. In both cases, however, the division of authority requires that careful attention be given to the means of coordinating the individual efforts and actions of the sector and areas.

The speed and capacity of a computer is such that one can reasonably expect it not only to replace a single controller, but all the controllers in an area. For reasons somewhat similar to those which justify the present organization of the control system into areas, it does not seem either necessary or advantageous to postulate the use of a single computer for nationwide control, even if a super-computer such as would be needed were available. In fact, a division of control into a number of area computers would offer certain advantages as regards maintenance and overall system reliability.

The use of a computer as the controlling element in a single area obviates the need for sector control and sector coordination; nevertheless, provisions must be made for the successful coordination of the individual areas into a single unified system of control.

2. Area Coordination in the Present-Day System.

Under present methods, centers in adjacent areas coordinate and share the control over aircraft flying along airways or over reporting points which lie near or along the boundaries between these areas.

Both control centers store the flight data regarding those paths and points, and the two centers agree upon a common clearance for the aircraft involved. In these cases one of the centers normally has explicit and final control over an aircraft until it reaches a certain point in its flight. The point where the transfer of control is made may either be a reporting point or may be a point defined as being a certain amount of flying time away from a particular fix or marker. The point of transfer of control is fixed by agreement between the two adjacent areas, but the agreement is usually of such flexibility that variations are permitted to handle dense traffic conditions, especially in the case of aircraft landing near the boundary. To quote from the CAA regulations:

> If weather and/or traffic conditions require, the center controlling the point of intended landing may request an adjacent area to clear aircraft to a specific point during a specific period.[1]

The sharing of flight information is made possible by the provision that appropriate flight plan data and control information pertinent to an inter-area flight be forwarded from area to area as the flight progresses. This data normally includes:

a) Flight identification and type of aircraft.
b) Estimate (time) and altitude over the last fix within the control area and the altitude of entry into the adjacent center's area if different from the altitude over the last fix.
c) Actual ground speed, if determined; or estimated ground speed.
d) Point of departure; the remaining portion of the route of the flight, specified in the original or amended clearance; and the point of first intended landing.
e) The estimated time of arrival as specified in the flight plan (time of departure plus elapsed time) based on the time zone of the departure point.
f) Clearance information:
    1) Clearance limit, if other than the airport of destination.
    2) Special information, if issued.[2]

The above information, with the exception of item c) which need not be included in the case of scheduled air carrier or military aircraft, is transmitted by the center which has initial control of the aircraft so as to permit reception of the data by the adjacent center at least 30 minutes prior to the time that the flight is estimated to enter that area. If the point of departure is not at a sufficient distance to permit the transmission within the specified time, the coordination is made prior to the takeoff of the aircraft.

---

1. Reference 16, page 20.
2. Reference 16, page 15.

Because of the fact that an overall picture of the traffic cannot be projected very far into the future, it is impossible for the coordination between areas to effect very much more than a check between centers regarding traffic at or near the boundaries. The acceptance or denial of a clearance by an adjacent center is usually based on immediate conflicts affecting aircraft arriving at or departing from boundary airports, and in very few cases is the acceptance or denial of a clearance based on expected traffic conditions at points in the interior of areas.

The only other form of coordination between adjacent areas is the nature of restrictions: restrictions as to usable altitudes over certain points or to the number of aircraft which may be dispatched to an airport in another area over a period of time. Such restrictions are usually caused by abnormally bad landing conditions which have resulted in congestion, high stack altitudes, and long delays in landing. The two examples which are familiar in the Boston Control Center are time restrictions on flights into the metropolitan New York area, and altitude restrictions over Hartford, Connecticut, a crossing point for North-South and East-West traffic in New England.

Although the controllers check all proposed flights for conformity to existing time and altitude restrictions, for the most part they find little need to enforce such restrictions. This situation arises because the operations offices (military and commercial) are informed of the restrictions and hence plan their flights accordingly. Nevertheless, in order to guide itinerant traffic and check upon the military and commercial operations, the pertinent information must be stored in the control center.

Outside of the time and altitude restrictions, which are sparingly used, there are no attempts made at the present time to control or regulate the overall flow of traffic between areas. As will be mentioned in Chapter X, such flow control offers a possible chance for improvement in the present system.

3. Criteria for Area Coordination in the Computer-Controlled System.

Coordination not only involves a sharing of information between adjacent centers, but requires a procedure for reaching an agreement between adjacent centers as to the control of flights near the boundary. For human operators communicating by means of interphone, the compromise and agreement upon a satisfactory clearance and the decision as to who shall control the flight until a particular point can easily be made.

The computer, on the other hand, cannot be easily programmed to compromise or bargain satisfactorily, and it is much more desirable to have a rather standardized procedure for the coordination. The procedure which shall be adopted for this study is that of having one of the two involved (area) computers propose a clearance, and then assume the responsibility for making changes or corrections upon the suggestion and advice of the second computer. That is to say, the coordination is to be effected by a procedure of proposal and confirmation. For such a procedure to be mechanized, a distinct method is needed for deciding which of the two computers will assume the task of making the proposal and carrying out the control.

It does not appear very desirable to have the question of which area is to control a flight near the boundary of two areas be completely dependent, as it is at the present-time, upon the actual area in which the aircraft happens to be, particularly in the case of aircraft ascending from or descending to airports at or near the boundary. As will be noted in Chapter IX, it is these sections of a flight which offer the most difficult problems in control, and it appears to be much wiser and more practical to have the supervision of a flight be dependent upon both the position and present plans of the aircraft; that is, the complete supervision of departing and ascending or arriving and descending aircraft will be allocated to a single computer, regardless of the actual position of the aircraft with respect to the boundaries. This procedure makes it much simpler to check and clear for separations on ascents and descents.

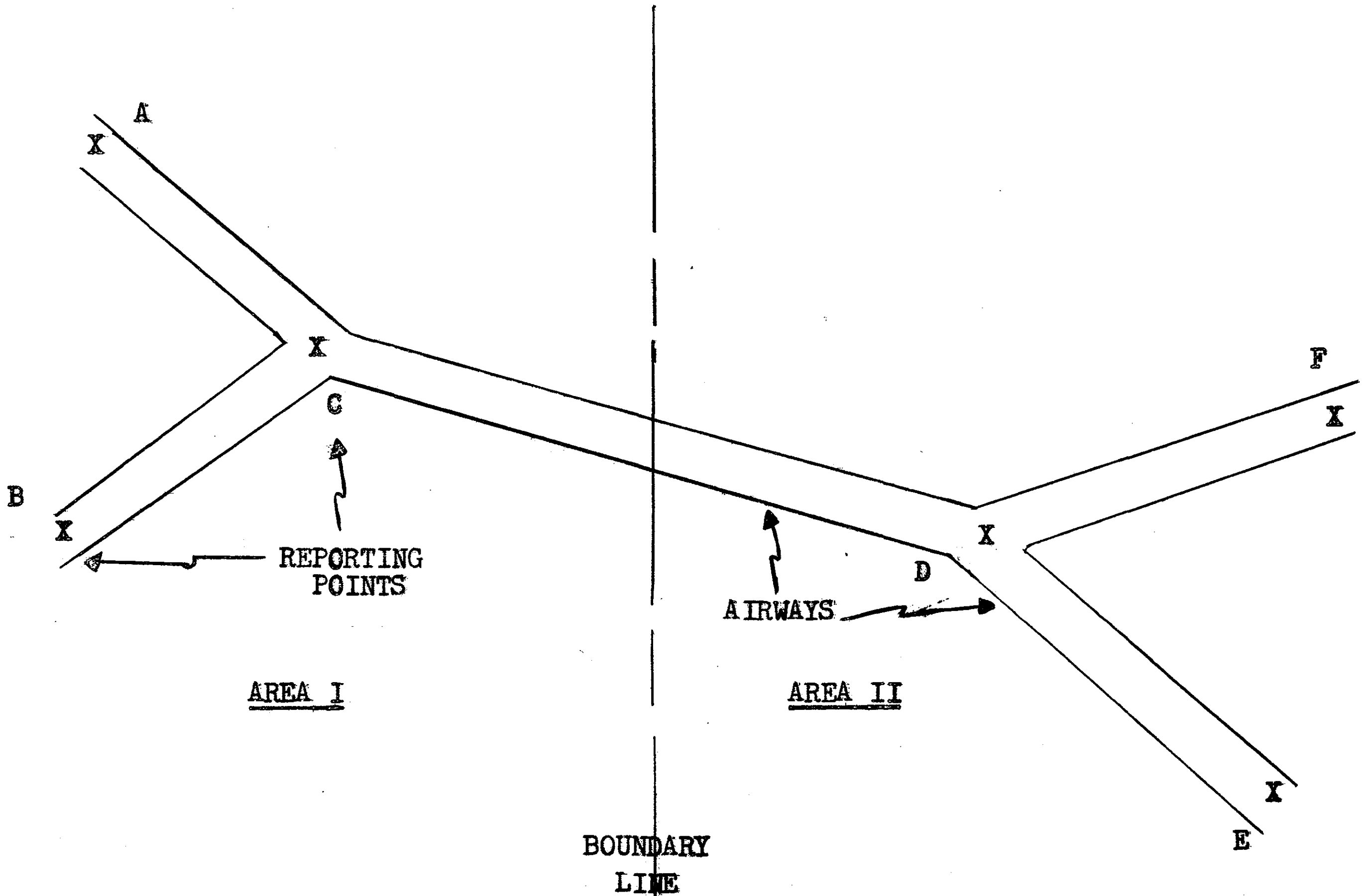
In order to appreciate what this plan of unique control for ascents and descents entails, it is interesting to note the performance figures of typical aircraft. The rates of ascent and descent vary according to the type of aircraft. Generally, the faster aircraft fly higher, and because of cabin supercharging are able to descend or ascend more rapidly. Typical speeds for faster commercial aircraft are in excess of 250 mph, with altitudes of between 10,000 and 30,000 feet and rates of climb or descent between 750 and 1500 feet per minute. The older, slower and smaller aircraft generally do not have cabin pressurization and hence are limited to a maximum altitude of 10,000 feet, with rates of climb and descent up to 500 feet per minute; representative air speeds are between 150 and 250 mph.

From the above figures it can be seen that the rate of climb or descent expressed in terms of <u>vertical distance per horizontal distance travelled</u> is essentially constant, regardless of aircraft type. The figures also indicate that the maximum distance required for a full on-course[1] ascent to a cruising altitude or a complete on-course descent from cruising altitude is about twice the average distance between reporting points. For purposes of standardizing the coordination procedures it shall then be assumed that any full ascent or descent will at most cover two reporting points. As is noted in the next section, in the special case of short flights from one area to the next it will be assumed that a single point ascent or descent is sufficient.

4. Area Coordination for Computer Control

A representative plan view of two adjacent areas and an interconnecting airway is shown in Figure 15. As shown, it is assumed that the boundary will be placed so as to intersect the airways about midway between reporting points. A, B, E, and F are <u>internal reporting points</u>,

1. This is to be distinguished from an ascent made while circling.



PLAN VIEW OF BOUNDARY BETWEEN AREAS

Figure 15

C and D are boundary points. Each area computer will store the data for and have unique control of flights over or between its internal boundary points; both computers will store the relevant data concerning the boundary points C and D, and control of flights over and between those points shall be according to situation as enumerated below. (The individual situations are described for traffic flowing from left to right in Figure 15; by an obvious interchange of letters they apply to traffic in the other direction).

1) Flights originating at or to the left of A or B and terminating at C are to be under the control of Area I. In this case, the computer of Area II need not store flight plan data corresponding to point C.

2) Flights originating at or to the left of A and B and terminating at D are to be controlled by Area I and will receive clearances coordinated with Area II. Area II should receive and store the flight plan data for points C and D of these flights at least 30 minutes before the aircraft arrives over C.

3) Flights originating to the left of A or B and terminating at E, F, or beyond are to be initially controlled by Area I, control reverting to Area II over point C. In such cases Area II must receive a 30-minute notification of the arrival time at C, and if necessary that area may request the aircraft to be at a specified altitude at that point.

4) Flights originating at A or B and landing at E, F, or beyond should be initially cleared and controlled by Area I upon proper coordination with Area II. Assumption of control by Area II should be made when the aircraft passes over point D.

5) Flights originating at C and entering Area II should receive their clearances from Area II upon proper coordination with Area I. Area I should receive a 30-minute notification and should store the data for points C and D.

6) Flights originating at D and proceeding to the right are solely under the control of Area II.

7) It will be assumed for convenience that no flights proceed from A to B via C, or that C is crossed in any other than an inter-area flight. The boundaries between areas will be chosen with this fact in mind.

The situation of 4) above does not permit a complete coverage by a single computer of a two-point ascent or descent when an aircraft originates at A or B and terminates at E or F. For these relatively short flights, however, an aircraft would not reach or fly at a high cruising altitude and satisfactory control should be possible by a single-point descent.

5. Transmission of Flight Plans from Area to Area

Under the present air traffic control regulations, pilots file but a single flight plan, regardless of the length of the flight or whether it enters one or more other areas. This flight plan specifies the complete route of the flight, and it is passed from center to center at least 30 minutes in advance of the expected time of entry of the aircraft into the next area. The only exception to this rule is in the case of aircraft departing from airports at or near the boundaries of areas; in this case the flight plan is filed with both traffic control centers.

For long flights, the specification of the route completely in terms of reporting points would be quite lengthy. This does not create any difficulties in the present-day system due to the relative cheapness of storage space; in addition, the problems are lessened by the relatively small number of long flights and because the route of the flight, especially that part outside of the originating area, is usually specified by airways designation.

There are two approaches which may be taken towards this problem in using the computer. The first would entail the storing of all the necessary flight plan data and the forwarding of same. Such a scheme would be rather expensive in storage space and appears to be less favorable than a procedure under which only the relevant part of a long flight plan would have to be filed and stored by any single computer. The scheme would mean that each computer must notify the next area of the need to secure a part of the flight plan from an operations office. The mechanization of the plan is as follows:

> The original filing of an extended, inter-area flight plan would include only the points of the original area, except in the situation where the flight covers only a few points in that area. In the latter case the filing would contain all the points of the first two areas. If only the points for the original area are filed, then the computer in that area has the responsibility for notifying the computer in the succeeding area 30 minutes in advance of the arrival of that flight to secure its portion of the flight plan. If the original filing contained both areas completely, then the flight plan should be forwarded by the first area to the second within an appropriate time. (The previously described procedures for area coordination permit a 30-minute advance warning to be made).

The same procedure is to be extended for longer flights, each area either receiving its part of the flight plan from a previous area or as a result of a request to an operations office. In the latter case, the requesting computer would receive either the reporting points for its area alone, or if the flight is of short duration in that area, the reporting points for it and the succeeding area.

The differences in the methods of forwarding the flight plan data are necessitated by timing difficulties, in particular the necessity of having the computer in an adjacent area receive the flight plan before it receives a notification of the arrival of the flight from the preceeding area.

B. The Problem at Airports

1. Present-Day Coordination at the Airports

As has been mentioned in Chapter II, in order to handle the increased traffic at airports in recent years, especially during poor weather, it has been becessary to supplement the normal airport tower control with special approach control procedures and facilities. Inasmuch as all airports are not supplied with these facilities at the present time, it is necessary for the centers to be able to properly coordinate and handle the arrival and departure of aircraft from airports which may or may not have approach control service.

At the airports where only the normal tower control is exercised, the bulk of the task of handling arrivals and departures is carried out by the center controllers. The center has control over all departures as well as over separations between successive departures and between departures and arrivals. This responsibility requires that in congested conditions the center must specify characteristics of the takeoffs -- direction of takeoff, turn after leaving ground, climbing instructions, etc. As regards arrivals, the center has complete control over the aircraft until they have been specifically released to the airport tower. In low density conditions, the aircraft are usually released to the tower at a distance of about 30 miles where they can establish radio contact; under more dense conditions the center exercises a more rigid control over the traffic and approach patterns, and aircraft are not released to the tower until visual contact between the aircraft and the tower has been established. In situations where holding or stacking becomes necessary, the holding patterns are under the control of the center and only one aircraft at a time is released for an approach and landing, the aircraft being under center control until it has made visual contact with the tower. If no visual contact is made at a specified minimum altitude on an approach, the center controller has the responsibility for handling the missed approach.

Under normal conditions at the non- approach control airports, the small density of traffic both at the airports and on surrounding airways permits a great deal of flexibility in the control procedures; nevertheless, in order to handle any conditions which might arise, it is necessary that the center controllers be completely informed of the physical characteristics of these airports and of the special procedures which must be used.

The purpose of approach control is to expedite traffic at busier airports by relieving center controllers, insofar as possible, of specialized procedures used in connection with departures and arrivals. Under approach control procedures, the center clears all arriving aircraft to a holding point established either by prior agreement or specified in the air route clearance upon confirmation with the approach controller in the airport tower. This holding point is usually a special approach control radio marker. The approach controllers in the towers supply the centers with the altitudes at which aircraft should be cleared to these points when holding patterns and stacks become necessary. The aircraft contact the approach controllers after arrival at these points, and from then until they land the aircraft are under the supervision of approach control. Under these procedures, approach control handles missed approaches.

Approach control is charged with providing separation between:

a) all arriving aircraft under approach control jurisdiction,

b) (the initial separations between) successive departing aircraft,

c) departing aircraft and all other aircraft under approach control jurisdiction.

Under these conditions, approach controllers, because of their close familiarity with the traffic and airport conditions, are able to use techniques in which several aircraft can be on an approach for landing at the same time and in which smaller separation standards can be used.

In regard to departures, aircraft must receive a clearance from the approach controller as well as from the air route traffic control center. The center clearance to the departing aircraft includes specific information regarding altitudes and flight procedures as well as departure restrictions necessary to provide separation from traffic not under approach control jurisdiction. The time of takeoff, direction of turn, altitude restrictions immediately after takeoff, and other instructions necessary to provide proper separation from traffic under its jurisdiction are specified by approach control. The center may request a certain takeoff time or may establish a <u>clearance void time</u> - a time after which the clearance is not valid - if such measures are necessary to avoid conflicts with aircraft not under approach control jurisdiction.

When centers clear an aircraft to a point prior to the assumption of responsibility by approach control, the aircraft is given specific holding instructions, including altitude and the expected time at which the approach and landing will be made. This function, as well as the general coordination of the two traffic control services, requires the following exchange of information:

Approach Control to Centers

a) Highest altitude in use by Approach Control at the holding point.
b) Average time interval between successive approaches as determined by the tower.
c) Revision of the expected approach time issued by the center when the tower calculation indicates a variation of 10 minutes or more.
d) Arrival times over holding point or statement that aircraft is under tower control, if released prior to arrival over holding point.
e) Departure times of departing aircraft.
f) Available information relating to overdue or unreported aircraft.
g) Missed approaches.[1]

Centers to Approach control

a) Identification, type, and point of departure of arriving aircraft.
b) Estimated time and proposed altitude of arriving aircraft over holding point or actual time if aircraft is released to Approach Control after arrival over the holding point.
c) Expected approach time issued.
d) Statement that aircraft has been released to Approach Control, including the point or time at which released if other than the clearance limit.
e) Anticipated delay to departing IFR traffic.
f) Identification and destination of proposed IFR departure.[2]

Approach control, it is noted, handles a good deal of the duties regarding arriving and departing aircraft. Despite the great usefulness of the approach control facilities in the present-day system, the problem of controlling traffic in and around approach control airports still presents a good deal of complication for center controllers. The problem manifests itself chiefly in the handling of departing aircraft and in the avoidance of conflicts between departing aircraft and other traffic along the airways.

It should be noted that there is no strict standardization of the location of the airports with respect to the range stations and airways. In many cases one leg of the range station falls across the airport, but this is not always true and the airport may lie a short distance from the airways and the range station. This fact, coupled with the necessity of using different runways in different wind conditions and the existence of various obstacles near the airports, requires that various flight paths be used in joining the airways after a takeoff.

1. Reference 16, Page 17
2. Reference 16, Page 18

In particular, these paths must be such as to permit the aircraft to join the airways at positions or altitudes at which they will not conflict with holding traffic. The problem is complicated by the existence of adjacent and conflicting airports in metropolitan areas. A further complication is that of getting aircraft to altitudes above those established minima which can be safely flown along the airways. In some cases, this latter problem requires that the aircraft climb above the minimum altitude while shuttling back and forth between two points, usually the airport and the adjacent range station. At Burlington, Vermont, aircraft climb while flying out and back along an otherwise unused leg of the range station extending over Lake Champlain.

2. Requirements for Computer Controlled System

The preceeding section pointed out the specialized problems which exist at the airports. The problems are seen to be greatly eased and simplified from the point of view of the air route controller by the establishment of approach control services. The specialized nature and the individuality of the approach control procedures at each airport are such that it is somewhat doubtful if a high-speed digital computer could be economically and practically useful in this phase of the overall traffic problem. At the present time, special purpose equipment[1] as well as radar devices[2] are being used to great advantage in the operation and improvement of the approach control service, and it would seem that the particular nature of the approach control service is best served by developments along these lines.

From the point of view of using a digital computer for en-route traffic control, there is little doubt that it is very important to separate the specialized problems of airport traffic control from the general control of airways traffic. That is to say, it is desirable to restrict the use of the computer to purely airways control, leaving the off-airways control to approach controllers at the individual airports. For this reason, it shall be assumed that all airports in the computer-controlled system will be provided with trained personnel and the necessary radio equipment such that the approach control service can be implemented. The standardized coordination procedures that shall then be assumed are not in strict accordance with current practice, but are sufficiently similar to make them realistic:

1) If an aircraft approaches and desires to land at an airport equipped with an approach control marker or specific holding point, the pilot will receive center clearance to this marker where he is to contact approach control for further instructions. When there is no holding traffic, the pilot will have been instructed by the computer to approach the marker at an altitude commensurate with an immediate landing; if there is holding, the computer clearance will instruct the pilot to hold over the marker at a specified altitude while contacting approach control.

1. Reference 32.
2. Reference 14.

2) If an aircraft approaches an airport not equipped with a special approach control marker, the pilot will be instructed to contact approach control at a specified flying time away. When there is no holding traffic, the computer will have brought him down to an approach altitude by that time; if there is holding -- and the holding pattern in the absence of a special marker will be anchored on the range station -- he will have been cleared to hold over the range station at a specified altitude while awaiting his turn to land.

In performing and coordinating these control functions, the flow of information between the computer and the approach controllers in the towers would be the same as is listed on page 85.

As noted, present-day approach control procedures do not eliminate the necessity of center controllers handling certain situations with regard to departing aircraft, especially in regard to getting aircraft on the airways at proper altitudes. In accordance with the decision to restrict computer control solely to the airways, the following assumptions are made:

> Each airport will have specialized departure procedures and traffic patterns which aircraft must use in reaching the airways from the airports.[1] The control and separation of all departing aircraft from the point of takeoff to the point at which they reach the airways will be the responsibility of approach control. The computer will be informed by means of the Approval Request of the point, position, and altitude and time at which the aircraft will join the airways.

In this way the computer need be concerned only with separations after the aircraft are on the airways. It is assumed that the flight paths used in reaching the airways and the points at which the aircraft join the airways will be selected so that aircraft will be in favorable positions as regards minimum altitudes and existing holding stacks.

For convenience in inter-area coordination, it will further be assumed that if an aircraft departs from an airport at a boundary point P and will next pass boundary point Q in an adjacent area, the aircraft will join the airways somewhere beyond P on the way to Q. Reference to Figure 15 will show that such a provision eases the inter-area coordination problem for aircraft departing from points C or D inasmuch as path data for paths AC and BC or DE and DF need not be stored by the other areas.

---

1. This was done in the Berlin Airlift with great success. See Reference 33.

CHAPTER VII

Direction and Approval Request Program

In addition to the necessary constants and data, the storage element of the computer must contain the programs to be used in implementing and carrying out the various traffic control activities and functions. Taken together, these programs do not represent a single coordinated unit: rather they are individual entities, each designed to handle special problems and situations. In a fashion similar to that in which orders or instructions guide the course of action of the computer and tell it what operations to perform, the computer will use a Direction Program to guide its action and to indicate to it the general traffic control activities and programs which are to be undertaken. The first part of this chapter is devoted to a discussion of the Direction Program and its chief elements.

The second part of this chapter discusses a program to be employed preparatory to dealing with clearances for aircarft. This preparatory program will be used in initially storing and checking the items of a flight plan, in preparing for the necessary coordination measures, in arranging details of the initiation and termination of control, and in preparing for the issuing of the clearance itself. The action of this program parallels to some extent the operations set into action in the present-day system as a result of the Approval Requests; for this reason, the program is named the Approval Request Program.

A. Direction Program

1. Message and Time - Ordered Programs

A large number of the activities of the computer will be initiated as a result of input messages: these are termed the message-ordered programs. Examples are a program for storing and checking flight plans; a program for checking upon and issuing clearances; a program for coordinating with approach control towers or adjacent areas; and a program for rechecking clearances as a result of progress reports.

On the other hand, a certain number of the computer activities or programs are not undertaken directly or immediately as a result of an input message, but will be delayed and will be put into operation at some later time. These are the time-ordered programs, comprising the following activities:

a) A frequent check must be made to determine if all aircraft have filed progress reports within a reasonable time after passing over reporting points. If no report is received within a certain time after an aircraft was estimated to pass a reporting point, the computer must undertake emergency action.

b) As was noted in Chapter IV, a periodic read-in and read-out feature must be interlocked with the normal read-in and read-out which are performed only when a sufficient quantity of input or output information has accumulated.

c) In handling ascending and descending aircraft under congested conditions, it will frequently be advisable to have pilots report when they leave or reach certain altitudes. As in a) above, a frequent check should be made to see if the required reports are received.

d) Under certain traffic conditions it is only possible to obtain proper separations between aircraft by holding an aircraft which is already en-route. The aircraft will usually be held until a certain time, at which time a check will be made to see if it can safely proceed.

e) Delayed action will be used in the case of an aircraft departing on a VFR flight plan but desiring an IFR clearance at a specified point within the control area. In this case the computer will have available an estimate of the time at which the aircraft is estimated to reach this point and will attempt to have the clearance ready at that time.

f) In accordance with statements made later in this chapter, Approval Requests should be followed in less than 15 minutes by a Clearance Request from the airport tower. In the event that the Approval Request is not followed by either the Clearance Request or a cancellation of the Approval Request, a time-ordered program should effect the cancellation.

A number of other functions such as coordinating with adjacent centers and towers or preparing and planning for descents could be carried out as true time-ordered programs: however, it is easier to have these activities be message-ordered, using for this purpose the frequent progress report messages from the aircraft.

As a means of keeping track of what actions must be undertaken at future times, use can be made of the present-status-information register associated with each aircraft (see page 72). In this register would be stored a coded indication of the necessary action required, together with the time at which it should be undertaken.

2. Timing

Most of the input passages to the computer will have to specify certain times: times of departure, times at which reporting points are passed, times at which messages are sent, etc. In order to implement its time-ordered activities, the computer must also have a direct means of access to an external time-keeping device. In accordance with the current practice, a 24-hour clock, rather than the more conventional 12-hour system, will be used; precision requirements will be satisfied if the smallest time increments are in minutes.

In the input messages, the representation of time is most conveniently (as regards the human elements of the system) made in terms of hours and minutes. Specification of time in hours and minutes necessitates the use of at least four characters in the message; this, in fact, appears to be the only situation in which the previously-described three-character words are not capable of conveniently representing a single piece of information. For this reason, time will be given in the input and output messages by two 3-character groups; a zero and two numbers (00 - 23) for the hours, with two numbers for the minutes (00 - 59) and a third character to indicate the time zone (Eastern Standard, Central, etc.).

Internally, the computer would best utilize a time system based entirely upon minutes, probably using 0000×2^{-15} as midnight, 720×2^{-15} as noon, etc. The times given in the input messages could be easily converted to this system. The clock used for the direct input of time to the computer could be made to indicate in this binary system, counting by minutes, thus obviating the need for conversion.

It should be noted that the use of time expressed only in minutes eliminates the discontinuities associated with the end of each hour. However, at the end of each day there still remains a discontinuity since the minutes must change from a high value (1439) to zero. This fact will require special programming in cases where comparisons of times are made. (Inasmuch as 24 hours is sufficiently long compared to the duration of a flight, there should be no questions of whether any time corresponds to the past, present, or succeeding day.)

3. Read-In and Read-Out Programs

In accordance with the discussion of Chapter IV, the computer will receive input messages from the drum via an input register and will store these words sequentially in a selected block of registers of the internal storage. A read-in order will read-in, assemble, and check the words of the input message, stopping the process after the read-in of a complete message. A check will then be made by the Read-In Program to see if errors were discovered in the message; no follow-up action need be taken at this time if errors are discovered, and if the first message has not used too much of the available storage space, additional messages can be taken in and stored. Following the read-in, the computer will take such action as is necessary to reset the read-in order and to take account of any errors discovered in the read-in. In the event that no errors are found, the computer would then proceed to those programs that are required by the input message. The choice of a direction to the proper programs would be aided by special code words in the input messages.

The Read-In Program can be entered in several different ways. The program will be undertaken when the Drum Control indicates it has accumulated a sufficient number of messages for transfer or when the Drum Control indicates that it has a special emergency message; the program will also be used as a result of time-ordered activities.

The Read-Out Program will take words stored in a special block of registers and read them out to the drum. The words will have been previously placed in these registers as a result of message or time-ordered programs. These programs would jointly employ a conversion program to prepare the output messages in proper form.

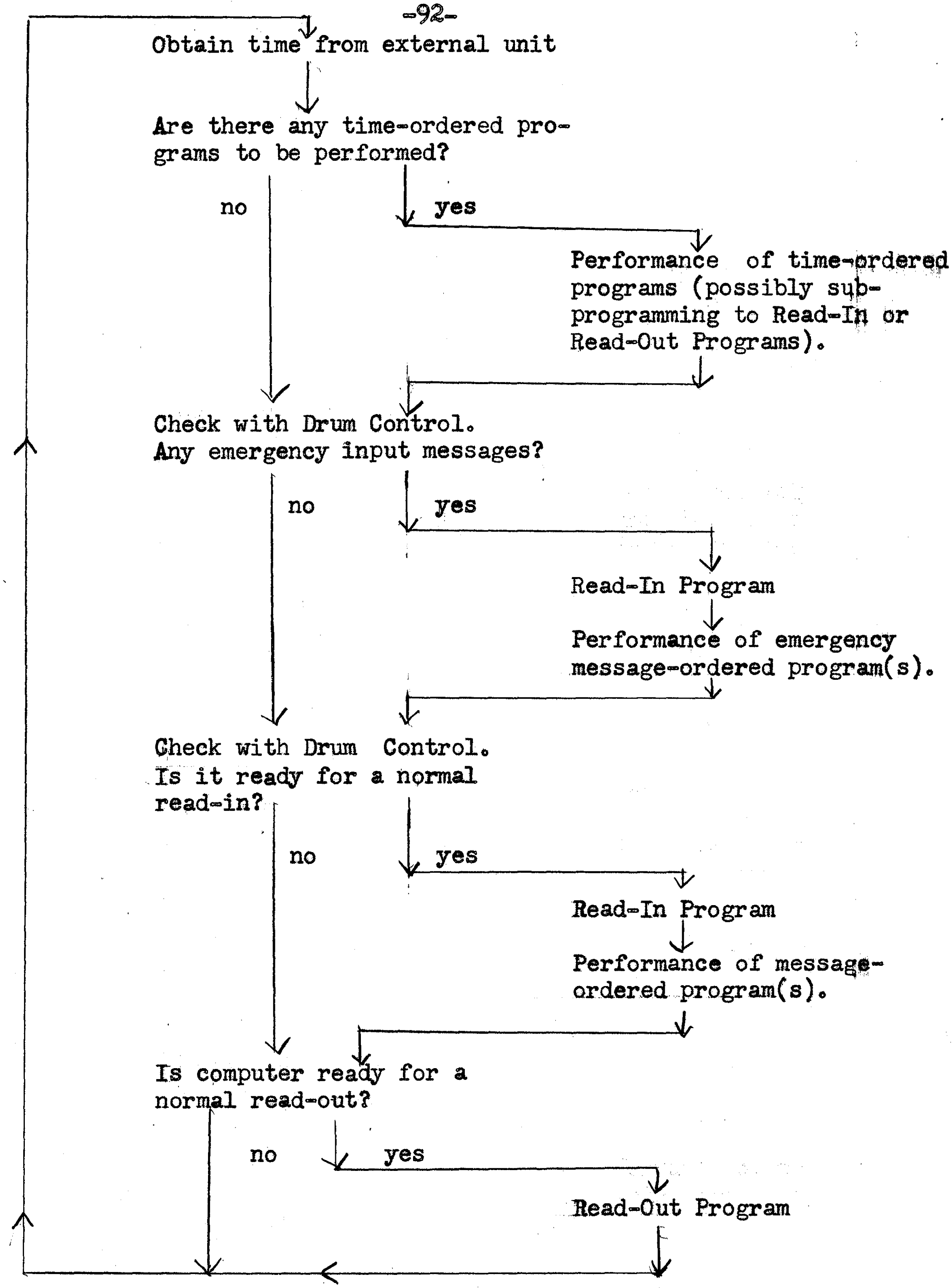
Flow Diagram

The flow diagram for the Direction Program is given in Figure 16. As noted, the sequence of the program is such that a check is first made for time-ordered programs, following which checks are made for emergency input messages, a normal read-in, and then a normal read-out. In the form shown, these four checks are made in a cyclic fashion, and hence no particular priority is given to any single function. Studies of the statistics of the expected input message traffic as well as the length of time required by the computer to complete the various time-ordered or message-ordered programs should enable one to determine whether or not this cyclic (serial) order of events is satisfactory. If not, a readjustment can be easily made so as to give more priority to the checks for emergency input or for time-ordered programs.

B. Approval Request Program

1. Purpose and Present Use

The first step in obtaining a clearance for an IFR flight is the filing of an Approval Request with the appropriate traffic control center. The term Approval Request is somewhat of a misnomer since it is not an actual request for a clearance but rather a means of notifying the center of the intention to conduct an IFR operation, the notification being performed through the filing of a flight plan.



Direction Program

Figure 16

As was briefly outlined in Chapter II, upon receipt of an Approval Request the assistant controllers prepare the necessary flight progress strips, retaining these strips in suspense bays in anticipation of the receipt of a Clearance Request and then an actual time of departure from the airport tower. The controller receives a flight progress strip for the departure point at least 30 minutes in advance of the proposed departure time as an aid in determining the expected traffic conditions. After the flight has received its clearance and the airport has reported the actual departure time, the estimated times are placed on the remaining progress strips and these strips are posted on the flight progress boards. Thus, although the receipt of the Approval Request does not in itself lead directly to the issuance of a clearance, the request leads to a good deal of preparatory work by the controllers and assistant controllers.

The actions presently carried out upon receipt of an Approval Request will form the basis of the Approval Request Program. The program will perform certain checking operations upon the information contained in the Approval Request and will store this data in chosen blocks of flight data registers. The program will perform the necessary operations concerning coordination details, as well as those of handling the initiation and termination of control. As an aid in planning clearances for other aircraft, the Approval Request Program will, in so far as is possible, calculate and store the estimated times at which the aircraft will pass over the reporting points. These times will not be checked during the Approval Request Program for possible conflicts with other aircraft: such checking will be made at later times with up-to-date weather information. The times supplied by the Approval Request Program will be marked as being only preliminary and very rough estimates by an appropriate storage in each point-condition-information register.

2. Initiation and Termination of Control

Several considerations should be noted in regard to the initiation and termination of control of IFR flights. Probably the most important of these is the fact that in so far as is possible pilots do not like to fly under an IFR flight plan. The chief reason for this is the existence of regulations and restrictions which do not otherwise exist when aircraft are flown in VFR conditions. In clear weather, pilots can navigate visually and may select a direct route between the point of departure and point of destination rather than fly a route marked by radio ranges. Under these VFR conditions the pilot need only carry out a minimum amount of communication with his operations office and he is permitted a great deal of freedom in selecting flight altitudes, in making his ascent to cruising altitude, and in making the initial approach for landing. On the other hand, when flying under an IFR flight plan the pilot must obey the instructions of the traffic control center and must stay on the airways. This requires that the pilot must continuously check upon his flight path, either by aural tones in a headset or by visual indications on a meter. The pilot must make careful reports upon passing the various reporting points, and the ascents and descents must usually be carried out in accordance with procedures specified by the control centers. All of these requirements do not in any way simplify the otherwise difficult task of piloting during inclement weather. For these reasons, pilots prefer to fly as little as possible under IFR conditions. It is also because of these reasons that the work of the control centers virtually ceases during periods of fair weather. Some airlines do, however, require their pilots to file IFR flight plans and conduct the flights under center supervision even during VFR conditions.

Another important consideration is that of the unpredictable nature of the weather and the resultant changing conditions along the routes and in the various areas. Because of this fact, it is sometimes possible to plan a trip under VFR conditions and later find that changes in the weather requdire a switch to IFR control. This is especially true of long flights. For these reasons and those mentioned in the previous paragraph, provisions are made so that IFR clearances are given for only those portions of the flight over which they will be needed. Despite this fact, some pilots prefer to travel an initial VFR portion of the flight under an IFR flight plan for the whole trip, rather than securing the IFR clearance while en-route. On the other hand, when it becomes apparent that the approach or landing of a previously IFR-cleared flight can be made under VFR conditions, pilots do not hesitate in cancelling their IFR flight plans.

The desire to restrict IFR flights and clearances insofar as is possible also exists for the center controllers, and hence they tend to cooperate with pilots in planning altitudes and points of ascent and descent so that flights can be conducted under VFR conditions for as long as is possible.

With the foregoing considerations in mind, it is now possible to list the standard conditions under which the computer will initiate or terminate control over aircraft:

Initiation of Control

a) An aircraft coming from an adjacent area, upon coordination with that area.

b) An aircraft already in the air within the computer's area which desires an IFR clearance due to a deterioration of weather or because it has just joined the airways from an off-airways, non-controlled flight.

c) An aircraft on the ground in the computer's area, desiring an IFR clearance from takeoff.

d) An aircraft on the ground in the area, desiring an IFR clearance over a reporting point in the area.

Termination of Control

e) An aircraft proceeding into an adjacent area.

f) An aircraft cancelling his flight plan while still in the air in the computer's area because of VFR conditions or because of leaving the airways for an off-airways flight.

g) An aircraft landing within the area.

In the case of initiating control and issuing a clearance to an aircraft already airborne within the computer's area, it should be noted that a pilot must, if possible, maintain his aircraft under VFR conditions until he receives an IFR clearance. As a basis for establishing the clearance, the pilot is usually asked to estimate his current position and to estimate his time of passing the next reporting point. The only change required for the computer-controlled system would be that the position given to the computer be specified in terms of two adjacent reporting points.

3. Application of Program

The approval Request Program will be utilized preparatory to the four conditions of initiation listed above. The program is message-ordered, and for purposes of simplicity the various messages which result in its operation will all be termed Approval Requests.

Approval Requests dealing with initiation of control over aircraft entering from an adjacent area will be of two types: one in which a flight plan is relayed from an adjacent area, the second in which the flight plan arrives from an operations office as a result of a request by the computer. In this case, as well as that of initiation of control over flights initially on the ground and desiring clearances at takeoff or at a certain point in the area, no immediate action will be undertaken after the completion of the Approval Request Program. Succeeding action in these cases will be undertaken as a result of time or message-ordered programs.

When the aircraft desiring a clearance is already in the air (condition b on page 94) or if the computer receives a flight plan forwarded by an adjacent area, following the completion of the Approval Request Program the computer will continue action with programs which obtain the necessary clearance.

There are no fixed regulations concerning the times at which Approval Requests for aircraft initially on the ground may be filed: an Approval Request may be followed almost immediately by the Clearance Request or the interval between the two may be as much as several hours. The latter case generally results from unforeseen delays on the ground before takeoff permission is requested from or granted by the tower. Since there is no particular premium on flight progress strip storage space in the suspense bays, long delays between the Approval Requests and Clearance Requests in the present-day system offer no special problems, and it is not uncommon for the strips for a long-delayed flight be to unused for a period of several hours. Long delays and the resultant tieup of storage space would be intolerable with the use of the computer. For this reason it does not seem unreasonable to require that Approval Requests be cancelled if flights are delayed beyond a specified period of time, say 15 minutes. It should be the duty of the various operations offices to make these cancellations, but as noted, a time-ordered check should also be made by the computer.

4. Message Form

In accordance with the discussion of this and previous chapters, it appears that the following standardization of items can be assumed for the Approval Requests. As will be noted, the main body of the message consists essentially of the flight plan data.

a) Message Identification
This item not only will identify the message as requiring action by the Approval Request Program, but will aid this program in sorting out the various conditions of initiation and termination.

b) Flight Number
This will correspond to the present-day flight identifications, usually consisting of several letters and numbers.

c) Communication Routing
A number or code word will be specified, this number or word serving as a communication routing indication for all messages destined for the particular flight. (At the present time, controllers must know how to dispatch messages to all aircraft under their control. The circuits used frequently change as the flights progress.)

d) Aircraft Type
If the aircraft is not of a standard type whose performance characteristics are stored in the computer, these performance figures should be included as a supplement to this item.

e) Proposed Airspeed

f) Type of Initiation (see page 94.)
If the Approval Request is relayed, this item should contain the altitude and estimated time at which the flight will pass the first reporting point. For aircraft already in the air in the area, the message should contain the present position and altitude of the aircraft as well as an estimate of the time at which the aircraft will pass the next reporting point. If the aircraft is on the ground, the altitude, position, and estimated time at which control should commence as well as desired cruising altitude are to be specified.

g) Reporting Points
All reporting points over which the flight passes are to be given. In case the flight leaves the control area, the boundary point should be listed.

h) Type of Termination (see page 95.)
An appropriate indication should be given of whether control is to be terminated (at least insofar as is then known) by cancellation of the flight plan, leaving the airways, leaving the area, or landing. In the case of an aircraft leaving the area, and indication should be given of which of the points of item g) above is a boundary point over which control will be exercised by another computer.

5. Flow Diagrams

The general flow diagram for the Approval Request Program is shown in Figure 17. As noted, five main functions are blocked out and numbered in this figure: more detailed flow diagrams for three of these functions are given in Figures 18, 19, and 20. Throughout the diagrams certain functions are specified which begin with the word "check." In all such cases it is implied that if the computer discovers an error, the program will be interrupted and the computer will proceed to another program used to notify the appropriate authorities of the error(s) discovered.

A1 Preliminary set up and storage

A2 Perform preliminary operations associated with initiation of control

A3 Check and store flight plan data

A4 Perform preliminary operations associated with termination of control

A5 Prepare for succeeding action

General Flow Diagram for Approval Request Program

Figure 17

Start

Inspect Message Identification and prepare to use it in guiding the course of action of program.

Find a free register in the flight data assignment table (see flow diagram of Figure 14). Store the Flight Identification in this register, and prepare for the storage of the flight plan data.

Store a void time for Approval Request in present-status-information register.

Store Communication Routing

Does message specify a standard type of aircraft?

no

Convert and store aircraft performance characteristics

yes

Check proposed airspeed with standard stored value.

Store proposed airspeed.

to A2

Flow Diagram for Block A1 of Approval Request Program

Figure 18

from A2

Prepare to deal with first reporting point specified in message.

Convert reporting point designation to pure binary form. (See flow diagram of Figure 11.)

Check correspondence with preceding reporting point (see flow diagram of Figure 12: this check is not made when dealing with first reporting point).

Check desired altitude of aircraft with minimum permissible flight altitude along path between present and preceding reporting point.

Check for conflict with any known restrictions at reporting point.

Commute approximate time at which aircraft will pass reporting point.

Store reporting point binary designation and appropriate time calculated above.

Have all reporting points given in message been dealt with?

no

yes

Is next specified point one which belongs to section of flight plan to be relayed?

no

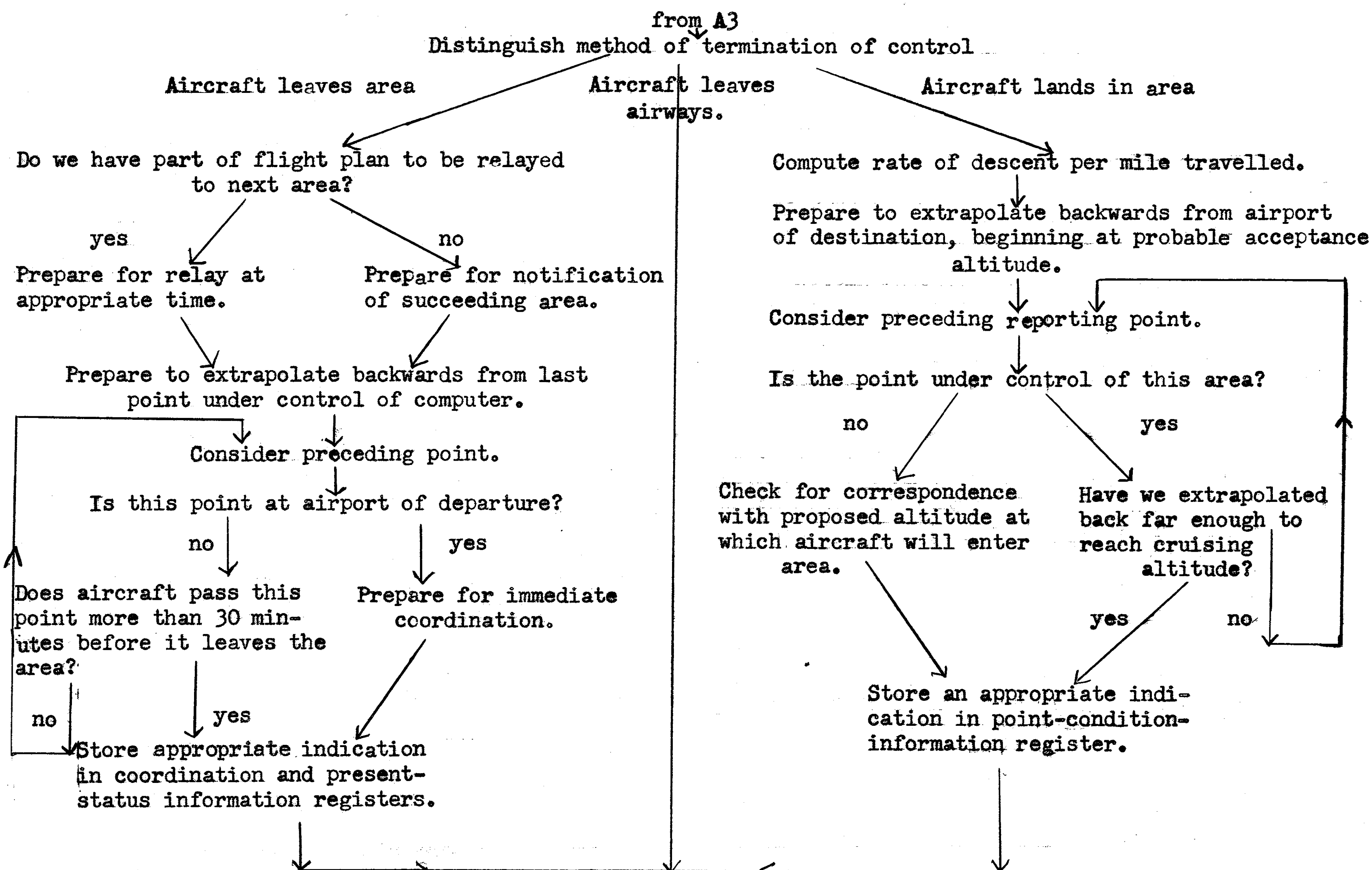
yes

Prepare to deal with next reporting point

Store temporarily the part of flight plan to be relayed.

to A4

Flow Diagram for Block A3 of Approval Request Program
Figure 19



Flow Diagram for A4 of Approval Request Program

Figure 20

Section A2, which has not been diagrammed in detail, will handle and check the method by which initiation is to occur. The Approval Request will also be checked for conformance to the coordination regulations of page 81. At this time the computer will make arrangements for relaying the flight plan to a succeeding area or for notifying that area to secure its section of the flight plan data. The program will make appropriate indications in the present-status-information and coordination-information registers according to the various conditions which exist.

Section A5 is used in initiating any further action required after the Approval Request Program. In those cases in which the aircraft is already in the air and needs immediate action on a clearance, the computer would proceed to the Clearance Program to be discussed in Chapter IX. In other cases, the computer would prepare to dispatch an acknowledgment message to the originator of the Approval Request.

CHAPTER VIII

Separation Program

Before a clearance can be given for an aircraft to proceed along a section of its flight, it is necessary that careful checks be made to determine whether there is any possibility of a conflict between that aircraft and any other aircraft flying along the same section of the airways. This chapter discusses and illustrates by means of flow diagrams the Separation Program which will be used in carrying out these checking operations.

The Separation Program will actually be an auxiliary part of the Clearance Program of Chapter IX. As will be mentioned in that chapter, the Clearance Program will have the responsibility for formulating the initial clearance for aircraft as well as extending these clearances as becomes necessary during the progress of the flights. Clearances will usually extend ahead of the actual position of the aircraft by several reporting points, but the basic unit of distance in dealing with clearances and separations will be the flight path between successive reporting points. The Clearance Program will supply to the Separation Program the identification of a particular aircraft and the two successive reporting points between which a separation check is desired; the latter program will then proceed to investigate the separations which exist or will exist between that aircraft and all other aircraft whose flight plans have been stored by the computer.

The end result of the use of the Separation Program will be an indication either that separation does or does not exist insofar as the available data stored by the computer is complete. In this sense, the Separation Program serves only to perform a checking function; the decision as to what action should be taken as a result of the discovery of the existence or lack of separation will be the function of the Clearance Program. As an aid in formulating the plan of action which must be undertaken, the latter program will also be supplied with all available information regarding the conditions which are discovered to lead to a possible conflict.

It is a suprisingly simple task for an experienced human controller to scan a number of flight progress strips and decide whether or not proper separation will exist between aircraft. The ease with which this can be done is to a large degree attributable to a human's ability to visualize a four-dimensional system -- geographical relationship of airways, distance along the airways, altitude, and time. This ability is not inherent to the computer, and it is rather interesting to note in this chapter how the action of the computer in investigating separations resolves itself into a veritable maze of comparisons and checks.

In accordance with the discussion of Chapter I, it is not to be implied that the flow diagrams of this chapter handle all possible situations which might conceivably arise in practice; an effort has been made, however, to make these diagrams accurate and realistic, the limiting factor being the author's knowledge of the operation of the current system.

A. Separation Standards

1. Fixed and Moving Block System

The present scheme of air traffic control is what is generally termed a moving block system. Each aircraft flying with an IFR flight plan is considered as being surrounded by a volume or block of airspace; the aircraft is at the center of the block and the block moves along with the aircraft. The size of the block is chosen so as to take into account the degree of accuracy with which the position of the aircraft can be determined. Under such conditions, there is no danger of conflict as long as no two blocks overlap. The three dimensions of the moving block are measured by the separation standards -- longitudinal, lateral, and vertical. The condition that two blocks shall not overlap is that either the longitudinal, or the lateral, or the vertical distance between two aircraft shall exceed the corresponding separation standard.

Under consideration for future traffic control systems and presently being employed in railroad operation is a fixed block system. In such a system the available airspace would be divided up into a number of stationary or fixed blocks. The effective separation of aircraft would then be based on provisions which do not permit two aircraft to occupy the same block at the same time, and certain restrictions which ensure that aircraft on adjacent blocks do not approach too close to each other.

A number of studies have been made of the relative advantages of these two systems and of their requirements in regard to block size and traffic handling capacity.[1] The flow diagrams of this and following chapters are based on the existing moving block system; mention is made here of the fixed block system because of major differences between it and the present system as regards the ease with which a computer can check for the separation between aircraft. The moving block system is essentially dynamic in nature inasmuch as the major item of interest is the dynamic movement and separation of these blocks. The fixed block system, on the other hand is concerned only with the static positions of blocks and questions of whether or not particular blocks are occupied. It is not too difficult to see that this static nature offers a certain degree of simplicity in checking for separations. Similar advantages also arise in determining

1. References 44-49.

what action should be taken to resolve or avoid any conflicts which are discovered; further comments on this fact are made in the next chapter.

2. Types of Separation

According to the CAA regulations:

> longitudinal, vertical, or lateral separations shall be provided all aircraft operating on IFr traffic clearances.[1]

The longitudinal separation is further defined as:

> The longitudinal spacing of aircraft at the same altitude by a minimum distance expressed in units of time, so that after one aircraft passes over a specified position, the next succeeding aircraft will not arrive over the same position within the minimum number of minutes.[2]

The minimum time separations are not fixed, but are varied to meet certain conditions which arise. The details of longitudinal separation are discussed in detail in Section C2 of this chapter.

Vertical (altitude) separation of aircraft is fixed at 1000 feet except in the special case of long transoceanic flights where a reduction of vertical separation is necessary due to the limited range of cruising altitudes at which fuel economy is achieved and at which there is no need for continuous use of oxygen equipment.

Lateral separation is defined as:

> The lateral spacing of aircraft at the same altitude by requiring operation on different routes or in geographical localities as determined by visual observation or by use of radio navigational facilities.[3]

For the most part, lateral separation is achieved by flight along different airways. Each airway in itself is considered as having the width of only one aircraft, and generally speaking there cannot be any passing at the same altitude of aircraft flying in the same direction. As previously noted, the ranges or courses of each range station are wedge-shaped and about 3° wide. Because of this fact and because of the regulation requiring pilots to fly to the right of the center of the beam, the CAA rules do permit opposite-direction aircraft

1. Reference 16, page 7.
2. Reference 16, page 8.
3. Reference 16, page 9.

to pass at the same altitude. For the most part, this right-side separation is applied only to opposite-direction aircraft which are changing altitudes, but it may also be used for cruising aircraft in emergencies. This type of separation is not used in the immediate vicinity of a radio range station due to the narrowness of the beam; no specific rules are used in deciding how close to the range station right-side separation may be employed and a figure commonly used by controllers is that such separation should not be used within five minutes flying time of the range station. Controllers do not like to use this type of separation at large distances from the range station, due to the poor definition of the radio range, and they are very wary about using right-side separation with other than experienced commercial pilots.

3. Exceptions to Use of Normal Separations

As has been mentioned in Chapter VII, the desire of the traffic controllers and pilots alike is for a minimum amount of strict regulation of flights conducted under an IFR flight plan. In an attempt to avoid strict regimentation as much as is possible, three major exceptions to the normal control and separation of aircraft are permitted.

The first exception is when aircraft are flying at least 500 feet on top of a cloud, haze, or smoke formation and the ceiling is unlimited above that formation. If the flight visibility is at least three miles and a definite top of the formation is known to exist, no separations are required for en-route traffic and during daylight hours no separations are required for holding aircraft. When aircraft are operating "500-top" they must still transmit progress reports, and flight progress strips are maintained for all the reporting points on the flight since IFR clearances are required to get the aircraft above the clouds or other formation on the ascent and to bring them down on a descent in preparation for an approach and landing.

The second situation in which the normal IFR separations need not be applied is under marginal weather conditions. In such cases when it is expected that an aircraft can climb to or descend from his cruising altitude with VFR visibility conditions, a VFR restriction can be applied to the ascent or descent if normal longitudinal, lateral or vertical separations are not possible. The restriction requires the pilot to supply his own separation as long as he will be under VFR visibility conditions: in the event that this may not be possible, alternative procedures are given to the pilot so that normal separations can be achieved. The specific regulations dealing with the ascent are:

> Departures may be cleared to maintain VFR until a specified time or location if reports indicate that aircraft can continue with 3 miles visibility and can remain 500 feet vertically and 2000 feet horizontally from all clouds.[1]

The determination regarding the possibility of VFR restrictions as well as the possibility that the aircraft can be permitted "500-top" separation will not be made in the Separation Program, but is handled as a part of the

1. Reference 16, Page 14.

action of the Clearance Program prior to reference to the Separation Program.

In general, the strictness with which a flight is controlled is directly dependent upon the density of the traffic. Under heavy densities the flights may be required to make their ascents and descents in a carefully specified manner. In less dense conditions, the flight may be given a certain amount of leeway, as for example "to descend past point A so as to reach altitude Z by point B". Under other conditions in which there is no other possible conflicting aircraft on the airways, the pilot may be allowed to decide where and when he shall make his descent or ascent on the basis of his convenience and wishes. Inasmuch as this is a desirable state of affairs from the point of view of the pilots, one of the steps in the Separation Program will be the determination if an unrestricted ascent or descent can be made.

B. General Provisions of Program

1. Path and Point Separation

As noted, the input to the Separation Program will consist of the aircraft to be checked, the two reporting points involved in the check, and the characteristics of the flight of the aircraft between these two points. There are two general phases to the separation check: one check must be made along the path between the two reporting points -- that is, along the airways --, the other must be made with respect to aircraft crossing the paths at the reporting points or aircraft holding at or near these points.

It is possible to perform a check both along the path and at each of the end-points, however, such a method of checking becomes redundant when applied to successive pairs of reporting points due to the duplicate checking at the points for crossing or holding aircraft. As a means of eliminating the double checking at these points, the Separation Program will operate so as to check only at the first reporting point and then along the path to the next reporting point. The check upon this second reporting point will be performed when the program is requested to check the next pair of points. Any danger arising from the fact that the further point in each case is not checked immediately is circumvented by always having the Clearance Program keep well ahead of the present position of the aircraft. The fact that most flights will terminate along the airways at a special marker where they will be turned over to Approach Control will, in general, bypass the need for a check at a final point of the path.

In checking along the path between two points, the check will usually not attempt to determine any lack of separation or conflicts which will occur just beyond that path on some adjacent path. This will be left until a check is requested along that path. One exception to this procedure will be necessary when dealing with an aircraft departing from a point adjacent to a reporting point. In checking the separations at the various points, however, it will, of course, be necessary to investigate the traffic along the connecting airways.

2. Broken Flight Paths

The flight of an aircraft along the path between two points P_1 and P_2 can be respresented by algebraic expressions containing the variables of distance, time, and altitude. The flight may also be pictured graphically as in Figure 21 where distance and altitude are plotted against time. With these plots, the checking procedure would be to superimpose one at a time the flights of all other aircraft travelling between the points P_1 and P_2 and then supply the separation criteria.

Figure 21 assumes that the speed and the rate of change of altitude are constant. The more general case which must also be considered is that of broken flight paths in which aircraft will cruise and then descend or ascend, or vice-versa. In these cases the plots of Figure 21 will be composed of broken lines with each part having different slopes corresponding to variations in speed or rate of change of altitude. (It appears that the separation standards are sufficiently large to consider the changes in slopes as immediate rather taking place slowly with a rounding of the plot at these points.) Either the aircraft that is to be checked or any aircraft against which it is to be checked may have such broken flight paths. As a means of convenience in checking such paths for separation, the general procedure will be to individually check all parts of the broken flight path of one aircraft against the individual parts of the flight path of the other aircraft.

C. Details of the Separation Program

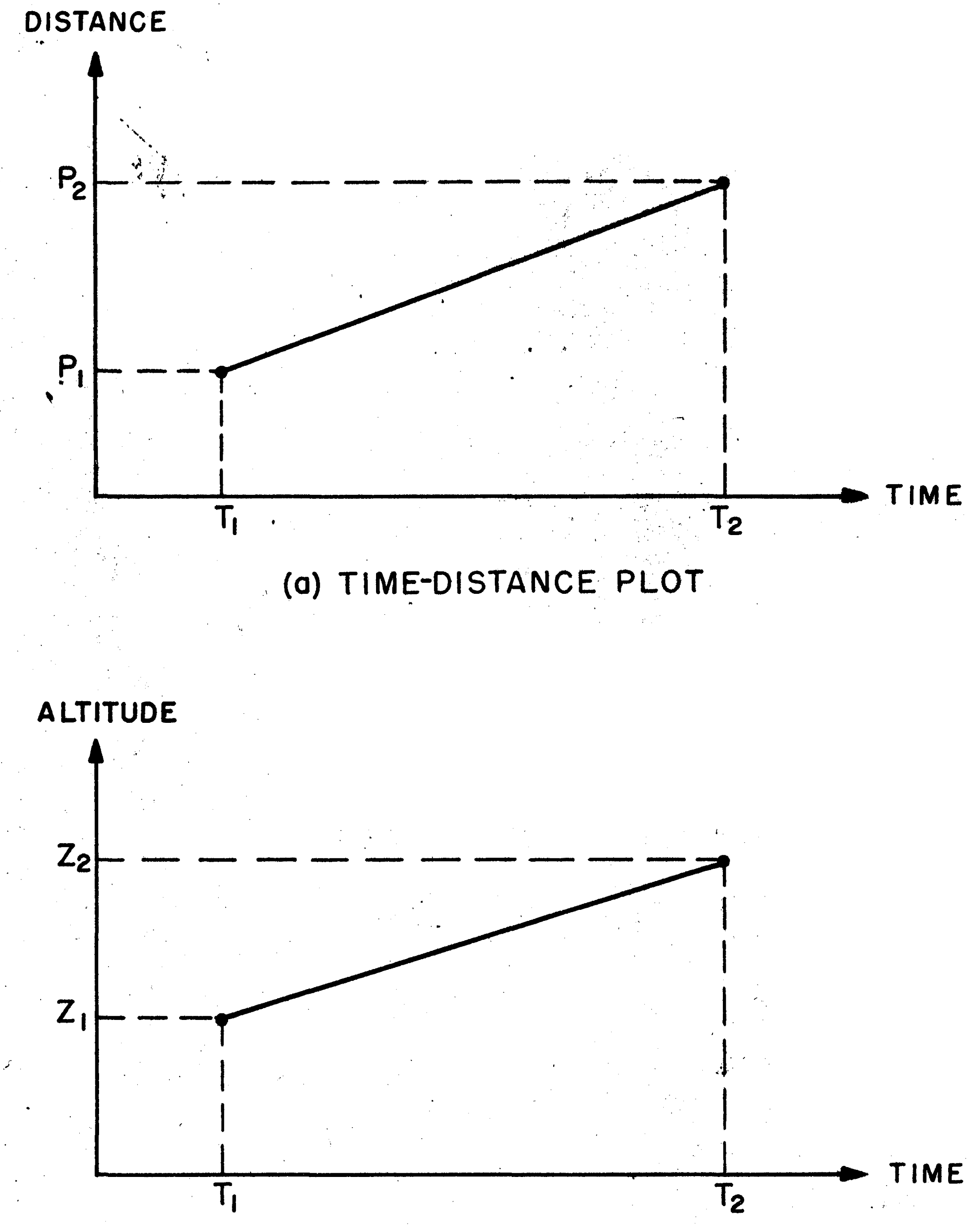
1. General Flow Diagram

The general flow diagram for the Separation Program is given in Figure 22. The three parts of the flow diagram which are outlined at the bottom of the figure are each discussed in more detail in succeeding sections of this chapter.

The first step in the program is to prepare to carry out the check for separations between reporting points P_1 and P_2 with the characteristics of the flight of the specified aircraft. This initial step must prepare the program to handle a broken flight path as well as aircraft departing from airports.

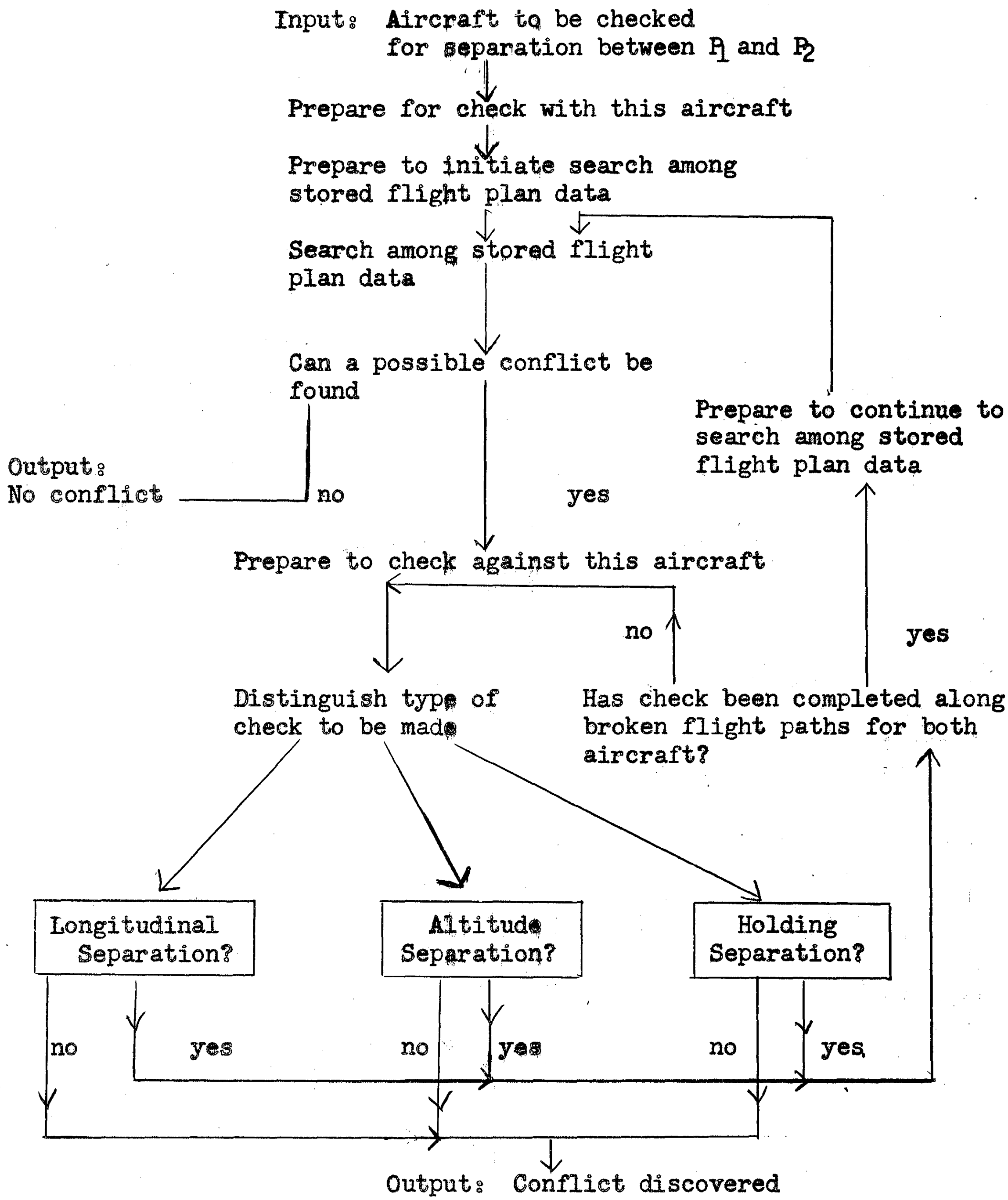
With the initial preparation completed, the program will proceed to investigate all of the stored flight plan data. If an aircraft is found which crosses or holds at point P_1 or travels along the path between P_1 and P_2, that aircraft is considered as a possible conflict and the program will proceed to prepare to check against it. Similar steps as above must then be taken to prepare to check against the possible broken flight path of this aircraft as well as the possibility that it is a departure.

For the sake of convenience, the actual checks for separation are divided into three categories -- Longitudinal, Altitude, and Holding -- each with a separate subprogram. The preparation for these checks will be such that an orderly procedure is used in dealing with the various sections of broken flight paths for each aircraft. As is shown in Figure 22, if no conflict is found on a passage through one of the three subprograms, a cyclic process is



GRAPHICAL REPRESENTATION OF PATH OF AIRCRAFT BETWEEN TIMES T_1 AND T_2

A-45289



General Flow Diagram For Separation Program

Figure 22.

set up until all sections of the flight paths of both aircraft have been checked. If no conflict is found anywhere along the paths, the program will return to continue a search among the stored flight plan data. The ultimate result in any case, regardless of intermediate action, will be either the discovery of a conflict between the input aircraft and an aircraft from the stored flight plan data or else the confirmation that no danger of conflict exists.

2. Longitudinal Separation

The regulations governing longitudinal separations specify the following separation standards:

Aircraft flying on the same or converging courses:

1) Ten minutes if radio facilities permit frequent determination of position and speed; otherwise 15 minutes.

2) Five minutes if a preceding aircraft has filed an airspeed at least 25 miles greater than that of a succeeding aircraft.

Aircraft flying on crossing courses:

Ten minutes if radio facilities permit frequent determination of position and speed; otherwise 15 minute.[1]

A flow diagram for this longitudinal separation check is given in Figure 23. The two aircraft to be checked are denoted by A and B, where it is assumed that A, the aircraft being checked for separation, leaves point P_1 at time T_1 and arrives at P_2 at time T_2. The ΔT's indicated in the diagram refer to the time separations of either 10 or 15 minutes as noted above. The letters OK and X are used to indicate whether separation does or does not exist.

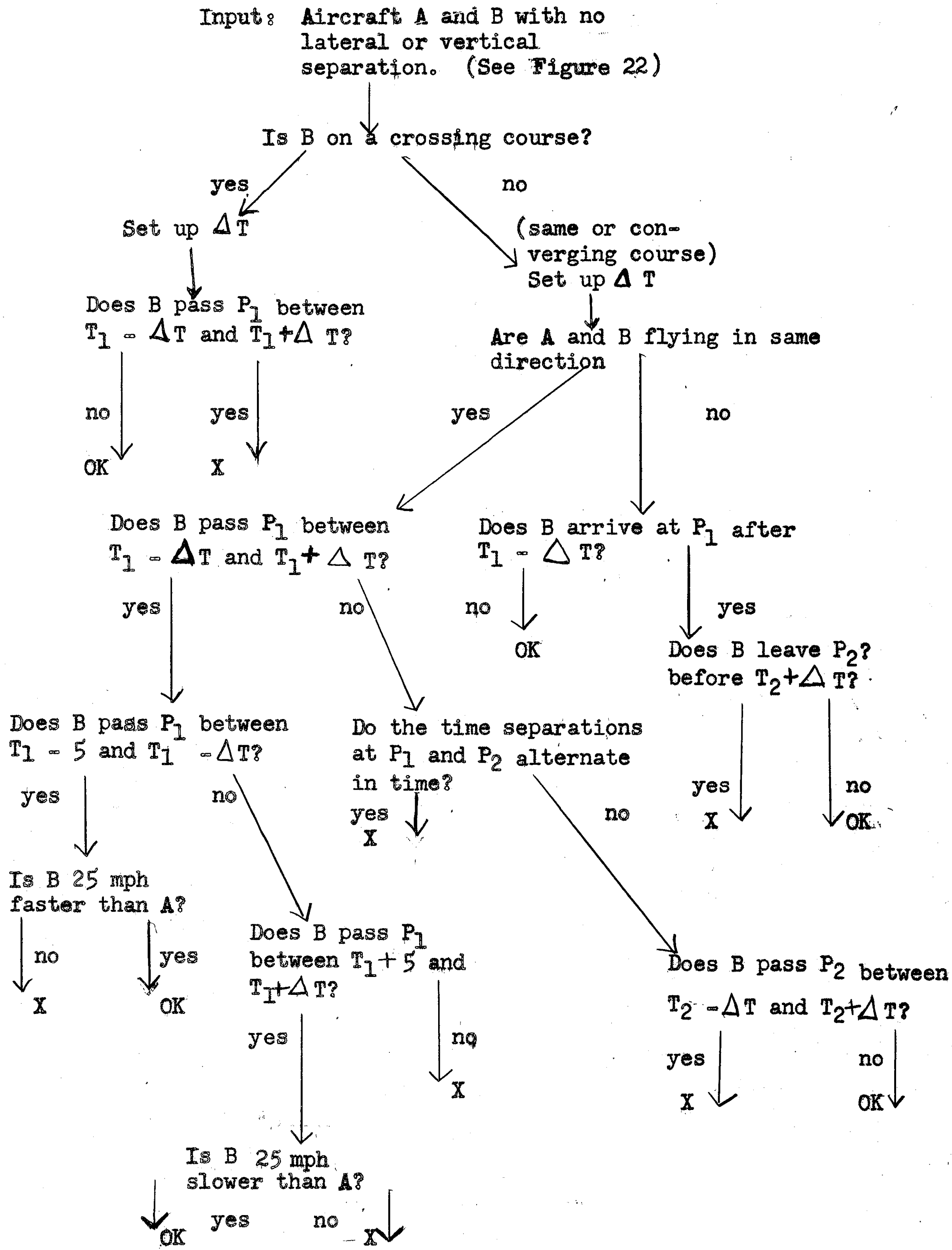
There are a number of ways in which the computer could go about the task of determing if the separations listed above exist. Basically the problem is that of determining if the paths of the two aircraft in a time-distance plot as in Figure 21 cross or are separated by less than the specified minimum. Several attempts at different methods of programming seem to indicate that the procedure illustrated in Figure 23 is the simplest.

3. Altitude Separation

The general program for checking altitude separations is given in Figure 24. The first steps in this program are to distinguish three separate cases; crossing paths, departures, and aircraft which have been permitted to make a non-restricted altitude change.

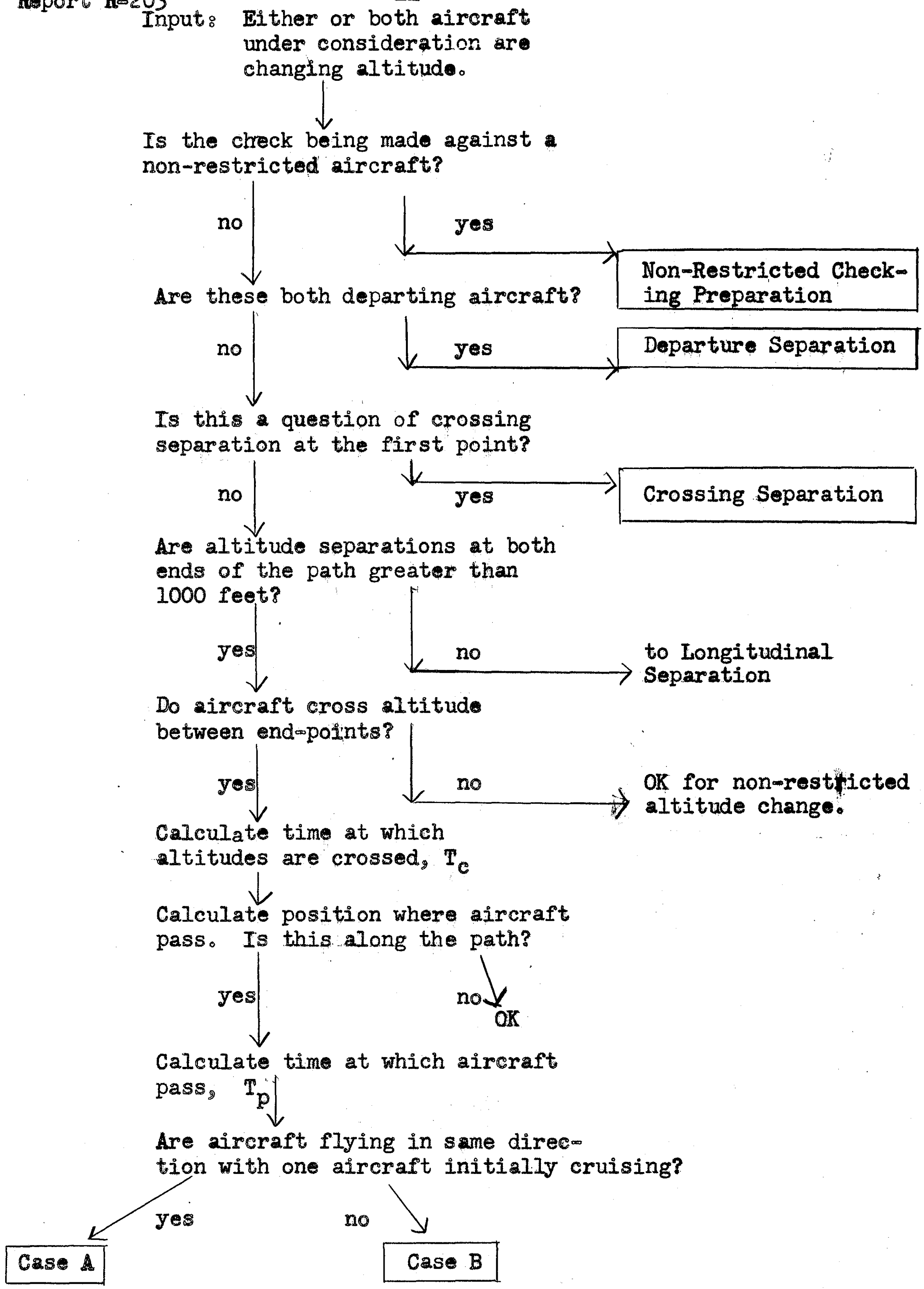
---

[1] Reference 16, page 8.



Flow Diagram for Longitudinal Separation Subprogram.

Figure 23.



General Flow Diagram for Altitude Separation Subprogram.

Figure 24.

After eliminating the three special cases, the program proceeds to determine if there is an actual conflict of altitudes. If there is a lack of separation at both end points, then both aircraft are following the same path in an altitude-distance plot and the situation reverts to one of longitudinal separation; if altitude separation exists at both end points and the aircraft cross altitudes in between, the time that these altitudes are crossed, T_c is calculated. A check is then made to see if the aircraft actually pass each other, and if so, the time at which they pass, T_p, is calculated. (These steps basically consist of determining if paths cross in the plots of Figure 21.)

The separation standards regarding altitude changes are as follows:

> Altitude Change--Same Direction Traffic:
> When lateral separation is not provided and an aircraft will pass through the altitude of another aircraft, the following longitudinal separation shall be provided:
>
> (1) Five minutes at the time that altitude levels are crossed, and provided that such separation is authorized only when:
>
> (a) The vertical separation at the time of the commencement of change is 2000 feet or less; and
>
> (b) A leading aircraft is being cleared for descent through the altitude of a following aircraft, or a following aircraft is being cleared for climb through the altitude of a leading aircraft; and
>
> (c) The altitude change is commenced within ten minutes after the time the second aircraft has reported over a reporting point.
>
> Altitude Change--Opposite Direction Traffic:
>
> (2) Where lateral separation is not provided, vertical separation shall be provided for at least ten minutes prior to and after the time the aircraft are estimated to have passed. If reports are received that aircraft have passed each other, this minimum need not apply.[1]

In view of these provisions, a division has been made into two checks: one which deals with the more specialized case in which both aircraft are proceeding in the same direction and in which the first provisions listed above apply, and the second dealing with the more general case listed immediately above. These cases are noted as Case A and B, respectively, and are shown in more detail in Figures 28 and 29.

When it has been discovered that the aircraft against which the check is to be made is being permitted to make a non-restricted altitude change, the computer will proceed with the action diagrammed in Figure 25. In such a case the aircraft making the non-restricted altitude change may be anywhere

---

1. Reference 16, Page 8.

Input: Aircraft against which check is to be made is on a non-restricted altitude change

Is non-restricted aircraft already on this section of the path?

no

yes

Has a recent report been received of the altitude of this aircraft?

no

yes

Prepare to dispatch a message to aircraft to determine his altitude.

Set up time-delayed action

Send message

Prepare return to check against two imaginary aircraft: one cruising at initial altitude, one cruising at final altitude.

Prepare for future action that will take place if conflict is determined with either of imaginary aircraft.

To main section of Separation Program to determine type of action.

Flow Diagram in Preparation for Checking Against a Non-Restricted Aircraft.

Figure 25.

between its initial and final altitudes. The first step is to determine if the non-restricted aircraft has begun that portion of his flight; if so, an effort is made to determine his present altitude as a means of more closely restricting the region of altitude uncertainty. The computer proceeds by making two checks, one against an imaginary aircraft cruising at the initial altitude and one against another aircraft cruising at the final altitude. If no conflict is discovered with either of the two imaginary aircraft, it is safe to assume that there will be no conflict with the non-restricted aircraft.

The pertinent separation standards with regard to separation of departures are as follows:

a) Five-minute separation at the time altitude levels are crossed if a departure will be flown through the altitude level of a preceding departure and both departures propose to follow the same course. Action must be taken to ensure that the five-minute separation will be maintained or increased when altitude levels are crossed.

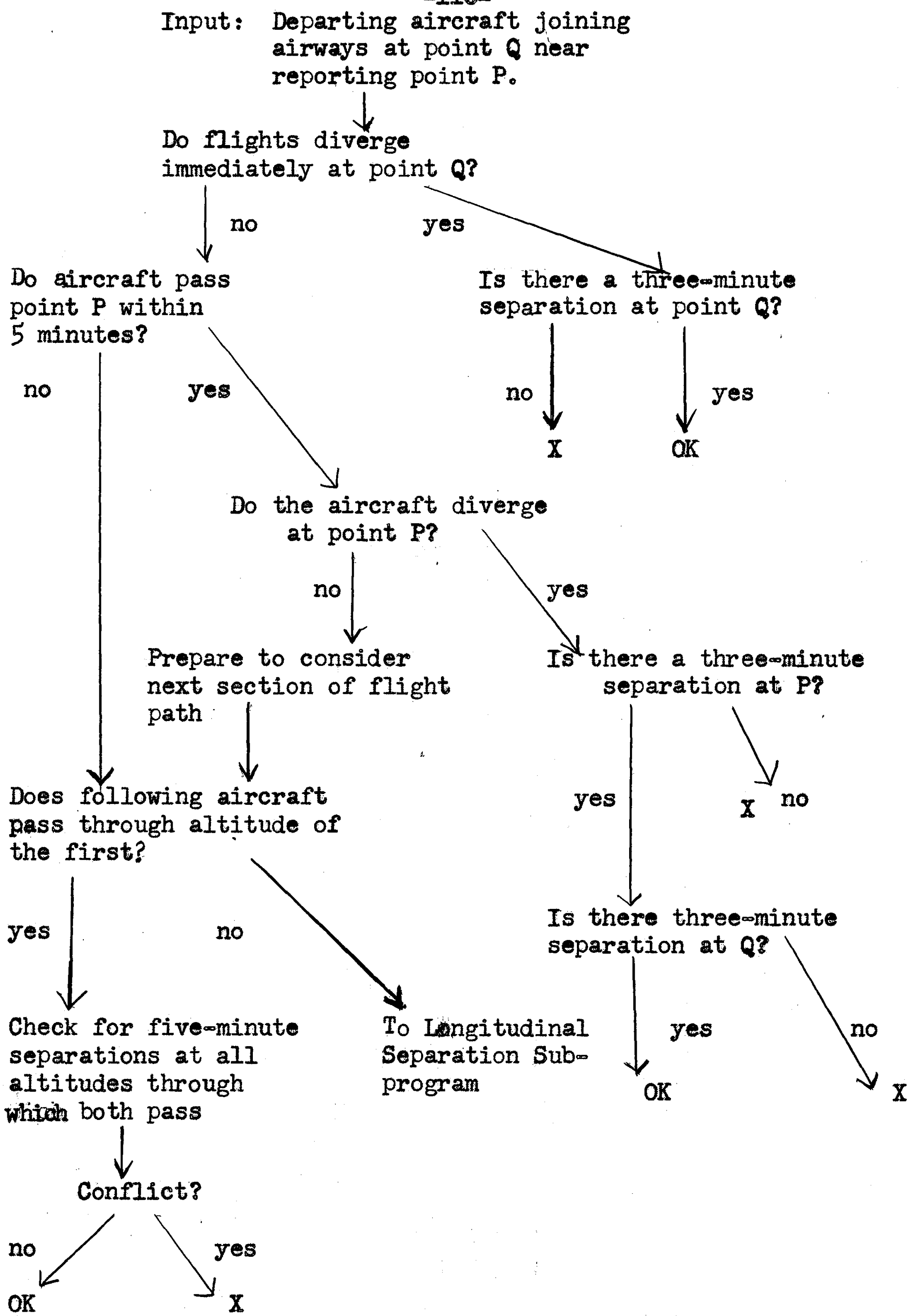
b) Three-minute separation at the time courses diverge if aircraft propose to follow the same course immediately after take-off and then follow different courses, provided aircraft will follow diverging courses within five minutes after take-off. Action must be undertaken to insure that the three-minute separation will be maintained or increased during the period the aircraft are following the same course.[1]

The flow diagram for the course of action in checking the separations of departing aircraft is shown in Figure 26. It is assumed that both aircraft will join the airways at a point Q near a reporting point P, and that both aircraft will pass point Q at altitudes differing by less than 1000 feet. (In some cases P and Q may be at the same point.) As indicated in the flow diagram, a check is first made to see if the aircraft are going in different directions at Q. If this is not the case, then it is determined if they are proceeding to the point P where they diverge. If the two aircraft diverge there, then the three-minute separations are put into effect. In the other cases where both aircraft follow the same courses the separation is handled in the Longitudinal Separation Subprogram, or else in a special manner if the following aircraft flies up through the altitude of the first.

The manner of handling crossing aircraft where either or both are changing altitudes is indicated in Figure 27. The chief consideration here is that if the aircraft pass the point in question with less than 10-minutes difference, an altitude separation of 1000 feet must exist for at least ten minutes before and after one of the aircraft crosses the point.

---

1. Reference 16, Page 14.



Flow Diagram for Departure Separations.
Figure 26.

Input: Two aircraft whose paths cross at reporting point P_1.

Find the time at which one aircraft passes over P_1. Call the time T_a.

Find the time at which the second aircraft passes over P_1. Call the time T_b.

Is $|T_a - T_b| < 10$ minutes?

yes — no → OK

Is there a 1000-foot difference in altitude at $T_a - 10$?

yes — no → X

Is there a 1000-foot difference in altitude at $T_a + 10$?

yes — no → X

Do the altitudes cross?

no → OK — yes → X

Flow Diagram for Crossing Aircraft When Either or Both Are Not Cruising.

Figure 27.

The flow diagrams for Cases A and B of the Altitude Separation are given in Figures 28 and 29. The action in these cases corresponds to the provisions listed on page 113.

4. Holding Separation

The relevant provisions for the separation of holding aircraft are given as follows:

> When aircraft are being held in flight, the appropriate vertical separation minimums shall be provided between holding aircraft and en-route aircraft while such enroute aircrafts are within 5 minutes' flying time of the flight path of holding aircraft.[1]

The flow diagram for the Holding Separation is given in Figure 30. This diagram considers the action necessary when either of the two aircraft under investigation will be holding. In general, an aircraft will hold along one of the airways, with the holding pattern anchored on a reporting point P_1. The standard holding pattern is to fly along the specified airways inbound to the point, make a 180° standard rate turn (3° per second) to the right, fly a parallel straight course outbound for two minutes, make another 180° standard rate turn to the right and again fly towards P_1. As noted, if aircraft are holding during the daylight hours at "500-top" altitudes, there is no need for any separation. If both aircraft are holding and the 1000-foot separation or "500-top" altitude conditions do not apply, there will be a conflict; if only one aircraft is holding a check must be made for separation at each end of the holding pattern and special consideration must be made for the case when the non-holding aircraft passes along the holding pattern or when it only crosses it at P_1.

1. Reference 16, page 11.

Input: Two aircraft proceeding in same direction, one aircraft cruising.

Is the initial separation less than 2000 feet?

yes

no → Case B

Is speed of leading aircraft greater than that of following aircraft?

yes

no → Case B

Will altitude change be commenced within 10 minutes after following aircraft will pass over reporting point?

yes

no → Case B

Is leading aircraft above and descending?

yes

no → Is following aircraft below and ascending?

yes

no → Case B

Is $|T_c - T_p| \geq 5$?

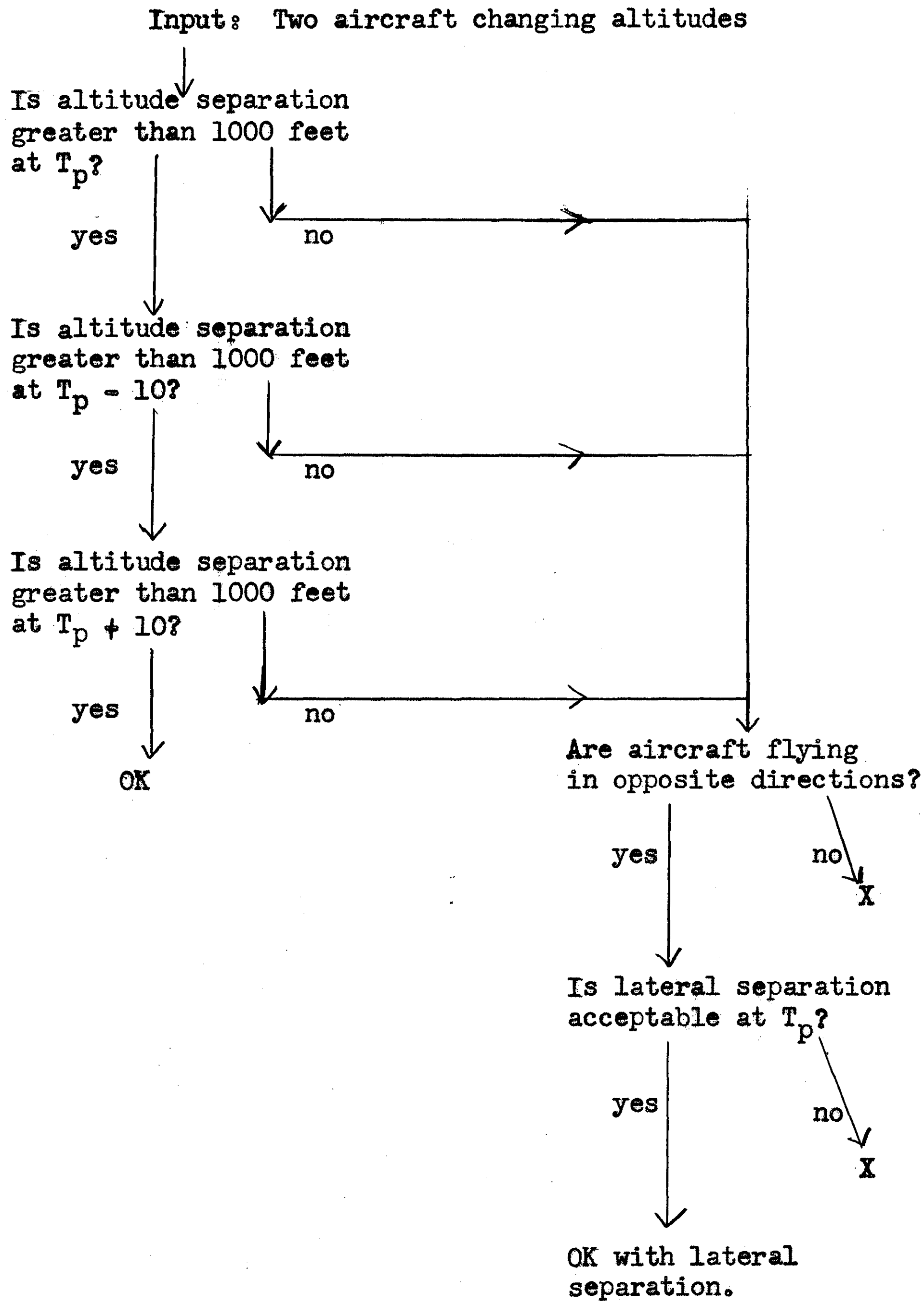
no → X

yes → Set up time-delayed check to see if aircraft passes over reporting point in time.

→ OK

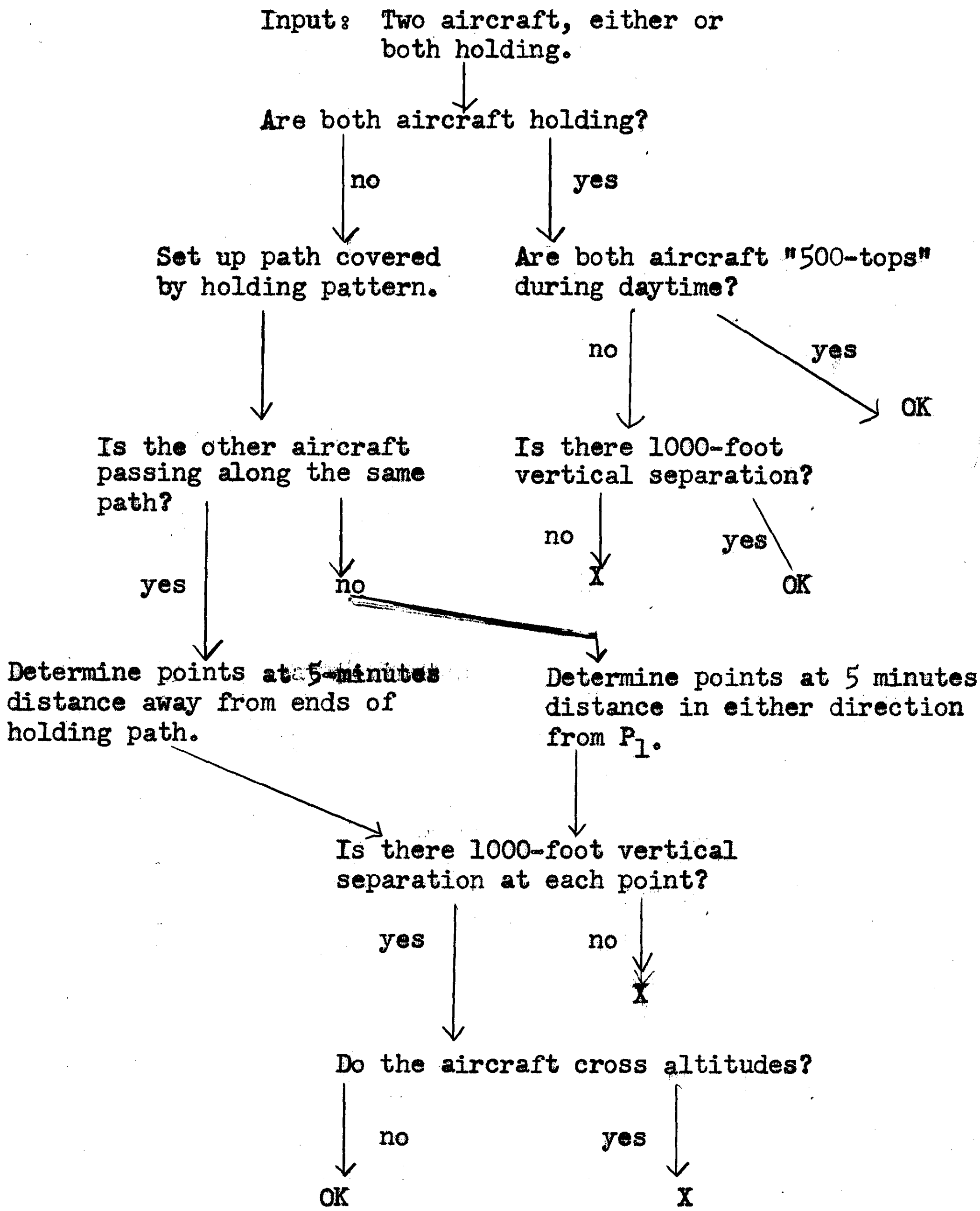
Flow Diagram for Case A of Altitude Separation.

Figure 28.



Flow Diagram for Case B of Altitude Separation

Figure 29.



Flow Diagram for Holding Separation.

Figure 30.

CHAPTER IX

Clearance Program

An air traffic control clearance is defined as:

> authorization by air traffic control, for the purpose of preventing collision between known aircraft, for an aircraft to proceed under specified traffic conditions within a control area.[1]

This chapter discusses a number of considerations which deal with the general subject of clearances, and sets forth an outline of the method by which the computer would proceed to process and issue clearances to the aircraft under its control. Because it is felt that further and more exacting study must be given to ways in which a moderate amount of human intervention may be applied, certain aspects of the Clearance Program of this chapter are not diagrammed and are limited only to discussion.

A. Processing of Clearances

1. Present-Day Methods

In general, the philosophy of the present system is to permit the pilots or operations offices to select the times of takeoff and cruising altitudes for their flights. Within this framework the controllers must provide the necessary control instructions to permit the aircraft to safely reach these cruising altitudes and later to descend safely on their approach at the airport of destination. Of course, if it arises that the use of a particular cruising altitude or time of takeoff will lead to a specific lack of separation with one or more other aircraft on the airways, the control centers must be able to suggest alternate flight plans.

Unfortunately, it is impossible under the present system operation to adequately determine at any one time whether a particular flight plan will permit safe separations at all points along the remainder of the flight. As noted, this is primarily due to the fact that the traffic control centers do not have adequate forewarning of all conditions which will prevail over the remainder of the flight; this is not only true of the weather conditions, but the traffic conditions as well. As regards traffic conditions, it should be noted that under present operation all the traffic information is not concentrated at one point or with one person, rather the information is spread out among the controllers for the different sectors and among the centers controlling the different areas.

---

1. Reference 16, page 5.

It should also be realized that it is rather difficult to fly an aircraft at a constant ground speed, and hence it is difficult to accurately estimate times at which aircraft will pass over future reporting points. Pilots can fly at a fairly constant speed relative to the air mass, but the winds may cause rather sizable changes in the true ground speed. Since the knowledge of the winds aloft is at best only of a sketchy nature, future arrivals over the reporting points can hardly be estimated with an accuracy of better than a few minutes, thus making it rather futile to base separations on time estimates of aircraft at points some distance ahead of their present positions.

Another contributing factor which effects the accuracy of time estimates of aircraft is the probable lack of synchronization between watches of pilots and the clocks in control centers. For this reason and those above, and in the general interests of safety, controllers make every attempt to ensure that separations do not deteriorate to the bare minimums of the previous chapter; whenever possible a leeway of several minutes is provided as an operating margin. In this way, safe conditions are possible even if there is a slight deviation in the times that aircraft pass reporting points.

As a result of the factors mentioned above, no attempt is now made to provide or check for a safe channel or path for an aircraft from its point of departure clear through to its point of destination before the aircraft departs along its flight; rather a flight plan is only carefully checked at one time for separations over a section of its flight corresponding to a few reporting points. The exact number of points depends upon the geographical layout of the sectors, traffic densities, weather conditions, etc. For the most part, then, any planning is of a short rather than of a long term nature. This means that controllers must be able to decide upon and use alternate procedures at any time if traffic is to flow smoothly and safely.

2. Standardized Computer Procedures

In using the computer to process clearances, it would be desirable to give a clearance for the aircraft over a fixed number of reporting points ahead of its present position. It would also be desirable to give a single and complete clearance to cover all sections of an ascent or descent, rather than splitting up each of these sections of a flight;[1] the single-clearance handling of an ascent and descent will permit a complete and coordinated decision to be made as to the best ascent or descent path (see page 137). A single-clearance procedure is made possible through the feature of the provisions for coordination between areas which give complete control over an ascent or descent to either one or the other of the two adjacent centers.

As a means of satisfying the requirements of a standardized procedure for handling clearances, the computer will always provide an aircraft with a three-point clearance extending through the succeeding two and up to the third reporting point ahead. As the aircraft passes from one reporting point to the next, upon receipt of a progress report over the second point the computer will proceed to extend the clearance. When the third reporting point in a

---

1. As used in this chapter, ascent and descent refer to the altitude change on departure or arrival, not altitude changes made en route.

clearance is on part of the aircraft's descent, the clearance will be extended ahead another point, if necessary (see page 79), to give complete coverage of the descent; for an aircraft initially departing from the ground, the three-point clearance is sure to cover the complete ascent and at least a single section of the cruise.

It will be desirable to pattern the behavior of the computer after the practices of the human controllers and have the clearances checked for separations somewhat greater than the bare minimums. This can be accomplished either by increasing the minimums of the Separation Program or by checking separations not only for the true time estimates of the aircraft but for values increased and decreased by several minutes. When the progress reports from the aircraft indicate that the aircraft are within a permissable margin of safety about the previously checked estimates, there is no need to recheck separations for the existing clearance and the computer will proceed merely to extend the clearance; if the aircraft does not pass over the reporting point within a specified margin about the checked estimate, the computer must proceed to recheck and possibly revise the remainder of the previous clearance, as well as extend the clearance by another point.

It might prove to be advisable, from considerations of safety and reduction of computer operations, to store with the flight plan of each aircraft the variation in time permissible at each reporting point within which the actual time of passage can fall without danger of conflict. This is another of those situations in which the expenditure of a large amount of storage space can shorten the overall amount of computer operation.

Although clearances for aircraft flying "500-top" need not be checked for separations, it will still be necessary to proceed in advance of the aircraft by the three-point clearance distance so that appropriate action can be taken to obtain a descent clearance to bring the aircraft down through the clouds on its approach. It also appears that in the interests of reducing complication without imposing severe and undue restrictions on the system, no flights should be dispatched with a "500-top" clearance unless the clearance appears to be valid for the entire flight on the basis of current weather reports.

3. Handling Coordinated Clearances

As discussed in Chapter VI, it will be necessary for computers of adjacent areas to coordinate clearances, this coordination to be accomplished by having one computer suggest a clearance and the other computer accept or reject it. One possible method of implementing this action would be to have the second computer independently devise and process a clearance which could then be checked against the details of the other proposed clearance. Such a procedure would be possible inasmuch as the details of handling inter-area flights require the storage of the same data in both computers; it would be necessary, however, that the standardization of the procedures be such that both computers would be likely to arrive at the same clearance. A somewhat simpler approach would be that of having the first computer supply the details of the proposed clearance to the second computer. This second computer would check the time estimates of this clearance and would then process it in almost the same fashion as it would a normal clearance in checking for separation. In referring to the flow diagrams presented later in this chapter, it will be seen that only relatively minor modifications are necessary to perform this coordination action.

B. Conflict Elimination

A most formidable problem is that which deals with making decisions on how to direct aircraft when it is revealed, as for example by the Separation Program of Chapter VIII, that there will be a conflict between two aircraft. A realization that a conflict exists will generally be discovered in the Separation Program when the computer is preparing an original clearance or when it is attempting to readjust a clearance because an aircraft has not met the conditions of a previous clearance. The desired action in such situations is the determination of a new clearance which will not only provide for safe separations, but which does not introduce long delays or inconveniences in the flight. As regards these latter points, it is obvious that although in most situations it would be possible to have one of the aircraft involved in a lack of separation situation hold over a specific point for a certain length of time until the danger of conflict had passed, it would be more desirable to use as the means of conflict elimination an action such as an altitude change which would not impose any excessive delays on the flight. It is also clear that in any system in which the planning and conflict elimination is carried out only over a limited section of aflight, there is little guarantee that the measures taken will be such that they involve a minimum amount of delay with respect to unknown conditions which may exist later in the flight.

As stated in the previous chapter, the computer will retain and store a number of flight plans for aircraft which have been successively checked against each other for separation. The question then arises as to how to proceed to eliminate the conflict when a new flight plan or revision of a previously accepted flight plan does not give a proper check against the others. One possible answer would be to consider the accepted and checked flight plans as being fixed, with the only variable being a flight plan for the aircraft which does not check. In this case, this aircraft alone must have its flight plan altered so that it provides no conflict.

This "one-variable" scheme is by far the easiest from the programming and decision-making point of view, and it is probably quite satisfactory when traffic conditions are not heavy and there is a good deal of available air space. The ideal solution, on the other hand, would be to consider all aircraft as variables which could have their flight plans altered in accordance with the desire for proper separation with a minimum of inconvenience and delay for all aircraft concerned. The mechanization of such a scheme is rather complex, however, and it becomes a question as to whether the cost of such mechanization in terms of computer storage and operating time is worth the end results, especially when the computer action is balanced against the ability of a human controller in such a situation.

The difficulty of the mechanization is quite apparent, especially in view of the moving block system presently employed. With a fixed block system there are a limited number of variations which can be made in the flight plans of the aircraft; that is, there are a definite number of blocks and a definite number of aircraft and the problem in a limited sense is to pick the proper blocks. Such is not the case with the moving block system in which there are essentially an unlimited number of changes which can be made in the positions and movements of the blocks.

A consideration of the use of the fixed-block system as a means of performing and carrying out scheduling functions for all flights will mentioned in Chapter X. In view of the difficulty in the use of the computer in effecting conflict elimination for a pure moving block system, it does seem that as a means of easing the problem it might be possible to reach a compromise between the two extremes in such cases; one such compromise might take the form of artificially dividing the airspace into small volumes which could then be used in determing what types of changes a moving block system might employ as a means of conflict elimination.

Another problem in the mechanization of conflict elimination is the choice among the rather large number of alternative procedures which can be employed. As an example of these possibilities, consider the following partial list:

a) Cruising aircraft

i) Holding

(The aircraft can be held at a particular marker, although such action should be carefully considered in light of delays and in possible consequence of impeding other traffic by holding at a busy reporting point or intersection of airways)

ii) Ascent or Descent

(Care must be taken that any ascent does not set the aircraft at an altitude inconsistent for approach or transfer to a holding stack; the aircraft cannot be sent up to an altitude too high for its operating conditions. Similar considerations apply to descents: the aircraft should not be dispatched to an altitude below the stack acceptance level or to an altitude unsafe due to the terrain conditions.)

iii) Right-Side Separation

(This is normally only applicable to opposite direction traffic when the aircraft are properly situated in respect to distance from the range station. As noted, it is probably best only to use this type of separation for experienced pilots).

b) Departing Aircraft

i) Holding on the ground

ii) VFR Restrictions

(This can be used if weather conditions are favorable)

iii) "Stepping"

(Aircraft can be despatched to ascend, cruise, ascend, etc., so as to permit safe separation. Care must be taken to get the aircraft above the terrain minimums)

iv) Non-Restricted Ascent

(These procedures can be used in full, or the aircraft can be requested merely to reach an altitude at a specific time or to pass a point at a specific altitude)

v) Right-Side Separation

c) Approaching Aircraft

i) Holding

ii) Right-Side Separations

iii) "Stepping"

(Certain procedures of cruise, descend, cruise, descent, etc, can be utilized. Care must be taken so as not to place the aircraft too low for the holding stack, if any exists)

As already noted, it is not unusual at the present time for several controllers to arrive at different solutions when faced with the same conflict problem. An important aspect is the previously stated fact that the choice of variation or procedure must be consistent with convenience and a minimum amount of delay. Hence, in fact, while controllers will put certain procedures into effect with only the desire to effect safety over a limited section of the flight, they will choose procedures which offer a reasonable assurance that the flight is not put into a condition where it will be handicapped later, as for example by being at an inconvenient altitude for transfer to approach control or for landing.

A true appreciation of the flexibility and comprehensive nature by which the human mind operates in a decision-making situation such as conflict elimination can probably only be gained when one has tried to outline in a flow diagram the mental processes which must be carried out. The author has spent a good deal of effort in considering the most simple form of the problem in which the flight plan for only one aircraft was considered as variable. The resulting flow diagrams, even with the most stringent of conditions and a strict standardization of procedures, were highly complex and lengthy. In view of this result, it is the opinion of the author that the general problem of conflict elimination is one best suited for a certain degree of human intervention and control.

There are a number of forms that the introduction of the human controller might take. He might be presented with all the relevant information and then be permitted to propose a procedure which the computer would then carefully check for accuracy and lack of conflict. The Approval Request Program calculated time estimates for all of the reporting points over which a flight will pass; these tentative estimates should provide to a human a fairly good idea of the expected traffic conditions and should be useful in guiding his decision. As an alternative, the human might be consulted by the machine in only the most difficult of cases. The author hesitates to decide the extent to which the human element should be introduced; in particular it is felt that a good deal more experience in the actual operation of the system and a study of where standardizations could be made without undue restrictiveness would be necessary before a proper decision could be reached. It is strongly felt that it would be necessary to determine how efficiently, accurately, and rapidly a human operator can make decisions concerning conflict elimination when all the pertinent data is presented to him in a suitable form. The degree of efficiency would have to be gauged in respect to the handling of all types of separations as well as accelerated traffic conditions. From a cursory examination, it appears that a scheme in which the human made the basic decision as to how the conflict should be resolved, coupled with the use of the computer for supplying details and for checking, would hold a good deal of promise.

For the reasons described above, in succeeding sections wherein flow diagrams are presented, blocks labelled <u>Conflict Elimination</u> will be used in lieu of specification of the exact means by which this action shall be carried out.

C. Altitude Assignments

A problem closely related to that of conflict elimination is the assignment of cruising altitudes for aircraft. Although pilots and operation offices are permitted to initially request a cruising altitude, in many cases it is not desirable to permit the flights to proceed at the requested altitude. The problem is basically that of assigning aircraft to altitudes so as to permit the optimum handling when it later becomes necessary to land them. Officially stated:

> Insofar as practicable, cruising altitudes of aircraft flying to the same destination shall be assigned in a manner that will be correct for an approach sequence at destination.

> The first aircraft estimated to arrive over the point from which approaches are commenced will normally be the first aircraft to approach. Other aircraft will normally have priority in the order of their estimated arrivals over such point.
>
> Altitudes at holding points shall be assigned in a manner that will facilitate clearing each aircraft to approach in its proper priority. Normally the first aircraft to arrive over a holding point should be at the lowest altitude, with following aircraft at successively higher altitudes.[1]

The situation which these regulations are intended to prevent are those in which the first aircraft to land arrives at a higher altitude than a following aircraft, and must be brought down through the altitude of the second aircraft. If the two aircraft will arrive over this point at about the same time, then it is seen that this changing of the altitude becomes a rather difficult task. It is not hard to envision situations more complex than that above, situations in which it is imperative that proper assignment of altitudes be made beforehand.

The most desirable state of affairs would be that in which an optimum assignment of altitude had been made when each aircraft entered the control system. For the reasons noted in the preceding sections of the chapter, such preassignment is rather difficult to achieve. The only convenient situation in which it can be successfully accomplished is when the aircraft in question are both dispatched from the same airport, in which case the action could be undertaken by the Approval Request Program. In other cases a controller handling the sector including a particular airport will either make an attempt to properly sequence aircraft when they enter that sector or will request the controllers of adjacent sectors to change the altitudes of aircraft in their sectors so that the proper assignment will have been achieved. The method by which clearances for arrivals are handled will permit the computer to make such a check on the altitude assignments of all aircraft at least three reporting points before they begin their descent.

Basically, the altitude assignment has all the aspects of the conflict eliminations discussed in the previous section, and the discussion there applies to a great extent here. As for the mechanization, it would appear that it might be carried out in part by the Approval Request Program, and in part by the section of the Clearance Program dealing with arrivals. However, as in the case of conflict elimination, a number of questions arise as to how the reassignments of altitudes should be made. It is felt that this again is an appropriate spot for human intervention, and although the author has drawn up several flow diagrams for the optimization of altitudes assignment by the computer, here, again, the action will be represented in the flow diagrams by only a single block.

---

1. Reference 16, page 10

D. Subdivision of Program

1. Relationship of Subprograms

The Clearance Program logically divides itself into four main subprograms: Progress Report, Ascent Clearance, Cruise Clearance, and Descent Clearance. The subprograms are schematically represented in Figure 31 in which the general plan of action of the Clearance Program is illustrated.

As the names imply, the Ascent, Cruise, and Descent Clearance Subprograms handle the clearance for those three major sections of a flight. Initial clearances for flights are obtained via the Approval Request Program or upon receipt of a Clearance Request message. Depending upon the condition of the aircraft -- on the ground or in the air -- a three-point clearance is then processed and issued. These clearances may be extended or revised in accordance with the results of the progress reports received from the aircraft. The three subprograms may also be entered as a result of a request for coordination on a clearance by another area.

2. Progress Report Subprogram

The outline of action for the Progress Report Subprogram is shown in Figure 32. Action of the subprogram will commence upon the receipt of progress reports when aircraft pass en-route reporting points; departure notices, holding passages, or messages from aircraft "stepping" up through altitudes will not be handled in this program.

As previously outlined, the main function of the program is to determine whether the aircraft is within an allowable deviation from the time it was estimated to pass the reporting point. If so, action is taken to extend the clearance, otherwise the program determines what section of the flight is being handled and a return is made to check for separation and possibly revise the clearance.

3. Cruise Clearance Subprogram

The Cruise Clearance Subprogram will be used for the following purposes:

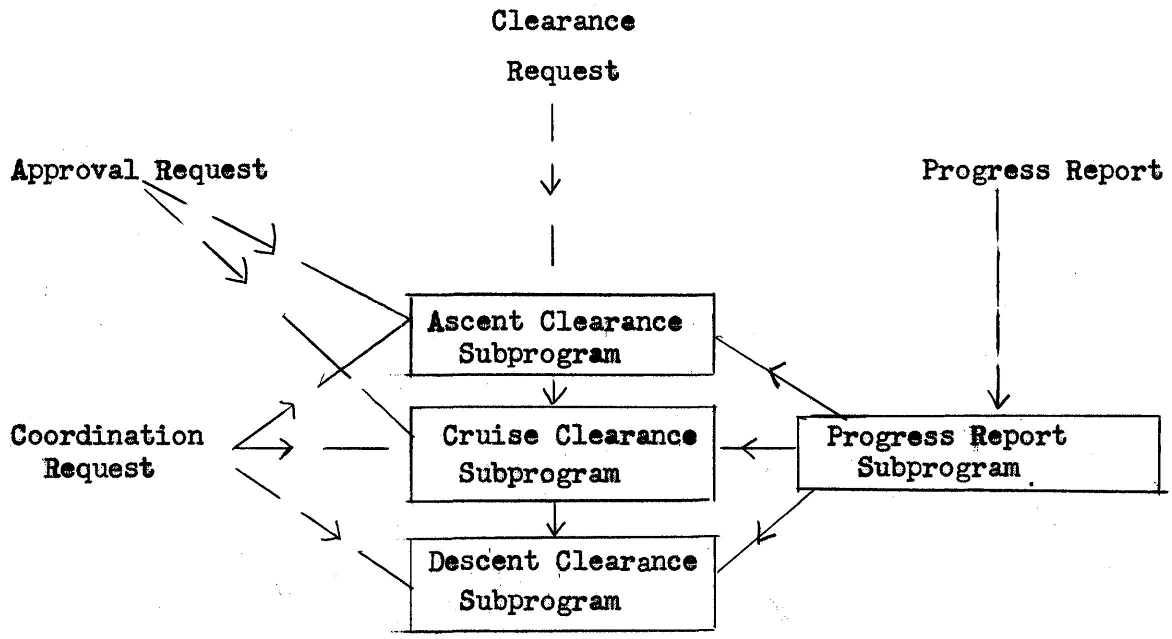
a) processing a clearance following an ascent to cruising altitude.

b) processing a clearance for an aircraft entering area at cruising altitude.

c) processing a clearance for an aircraft entering IFR control while cruising.

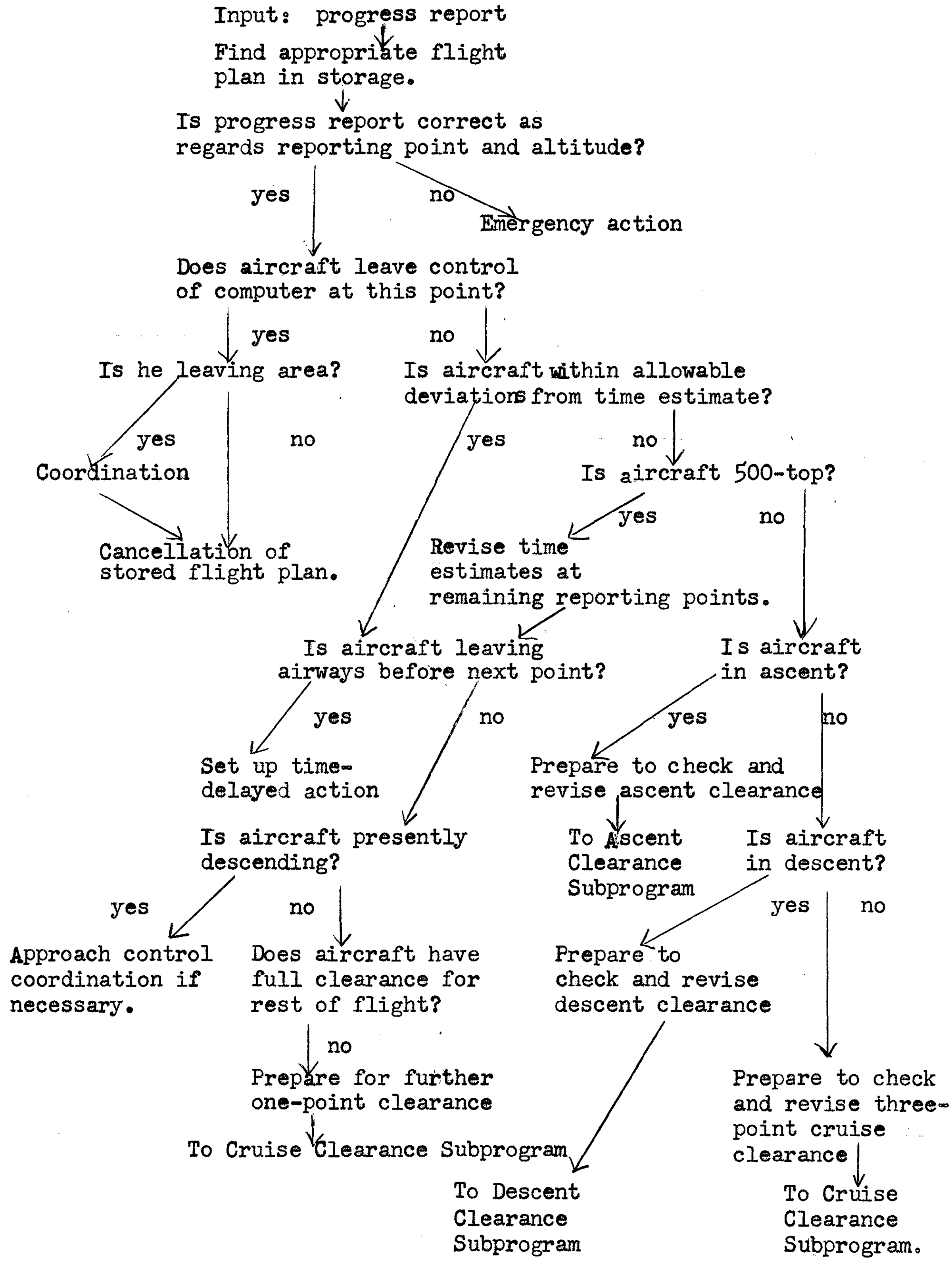
d) extending a clearance following a progress report.

e) checking and revising a clearance following a progress report.



Plan of Action for Clearance Program

Figure 31.



Progress Report Subprogram

Figure 32.

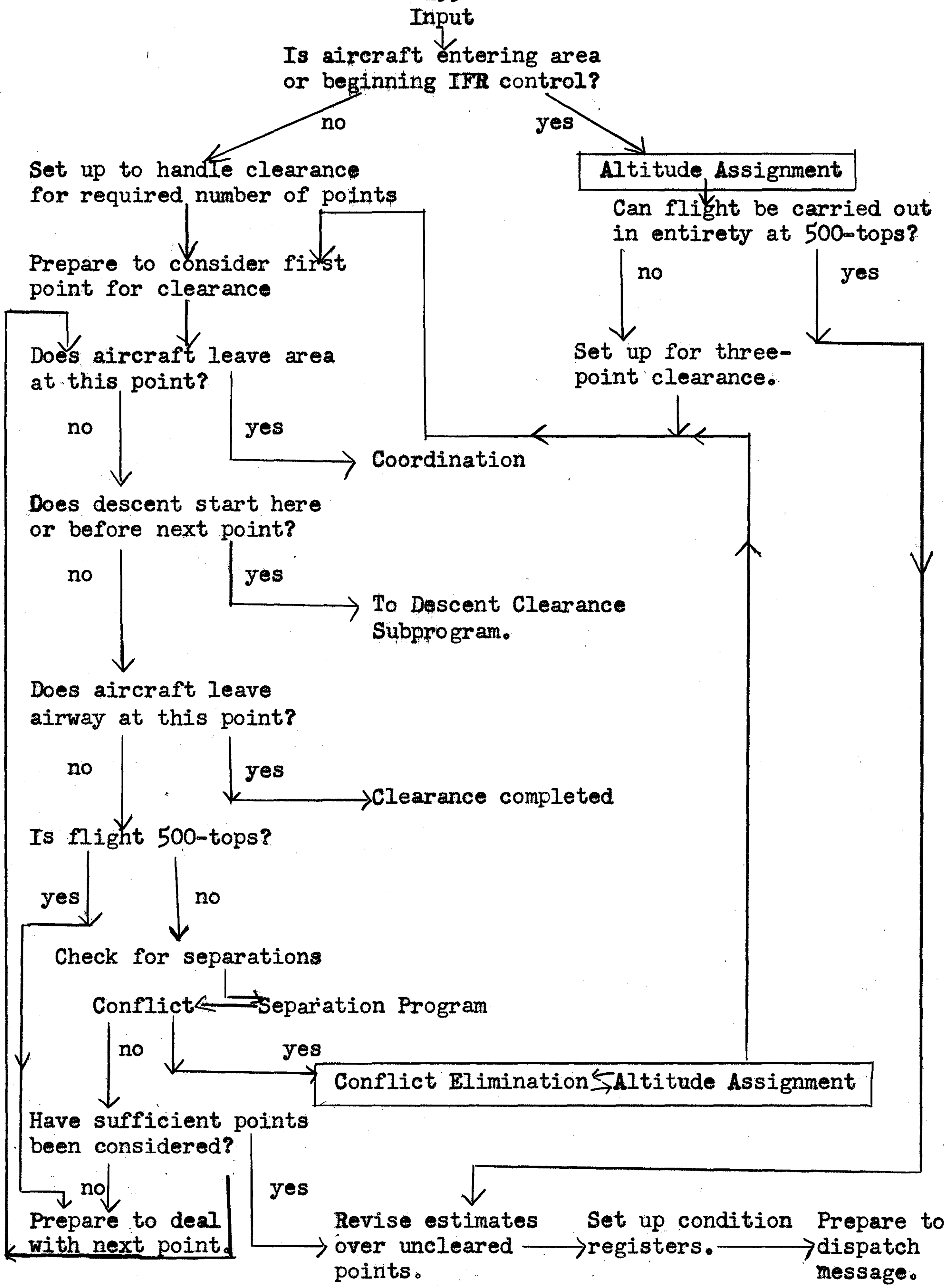
The action of the subprogram is outlined in general form in Figure 33. Cases b) and c) are first distinguished in the subprogram and are handled separately; the other cases enter directly into the cyclic part of the action which will handle a clearance of one, two, or three reporting points depending upon the purpose for which it is used. After all of the special conditions are distinguished and isolated, a check for separations is made with the Separation Program. When a conflict is discovered it is assumed that proper elimination of conflicts and assignment of altitude will be made. Following the processing of a complete clearance, the computer makes appropriate changes in the time estimates over the uncleared points, sets up the condition registers, and prepares to dispatch the clearance.

In this subprogram, as well as those for the ascent and descent clearance, when preparing for the use of the Separation Program the times at which the two reporting points will be passed will be estimated. This estimate will use the current wind conditions as well as the airspeed of the aircraft. In accordance with current practice, the observed deviation of the aircraft as determined in a previous progress report, if any, will be used to obtain a better estimate; such a process is equivalent to having calculated the actual ground speed of the aircraft and used it for the new estimate. Little or no use is made at the present time by the controllers of knowledge of the actual winds which can be calculated by determining the true ground speed and subtracting from it the reported air speed of the aircraft; the author has at times been amazed at the accuracy with which controllers estimate times using only the cruder methods described above, and there appears to be little to be gained by using a more sophisticated method.

Ascent and Descent Clearance Subprograms

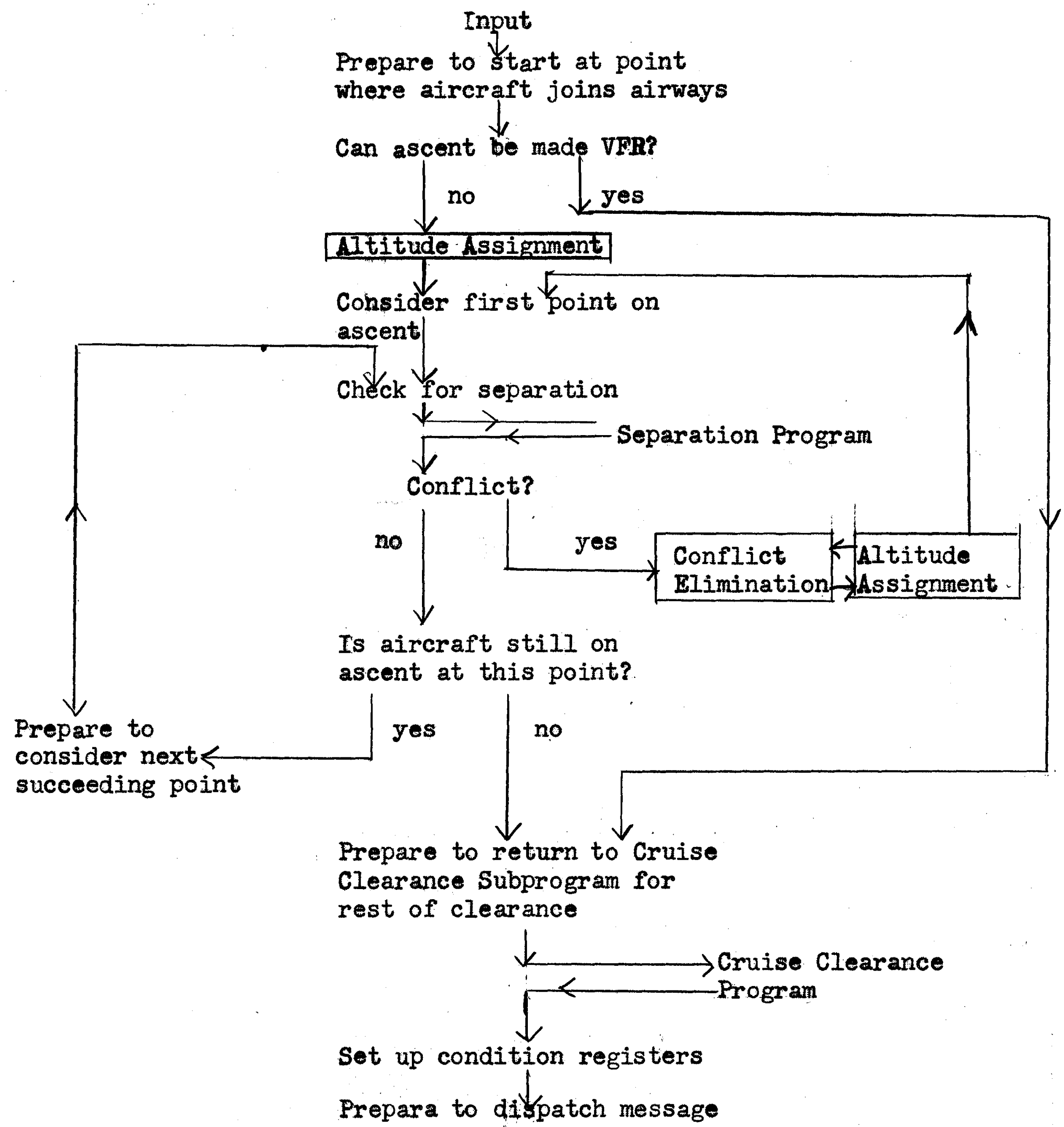
Flow diagrams for the Ascent and Descent Clearance Subprogram are presented in Figures 34 and 35. The general action of the Ascent Clearance Subprogram will be to process the clearance up to the point of the flight at which the cruising altitude is reached; at this point the clearance is taken up and handled by the Cruise Subprogram. The Descent Clearance Subprogram similarly handles only the descent portion of the clearance with suitable coordination being made with the Cruise Clearance Subprogram.

As already noted, it will be the duty of the computer to decide upon the manner in which aircraft will be dispatched to or from the cruising altitudes when on ascent or descent. The most desirable paths, in either case, are straight-line ascents or descents at maximum rate of change of altitude. This line of maximum altitude change represents one boundary on the ascent or descent, the other being the terrain considerations. If a conflict is discovered on the path of maximum altitude change, it will be the function of the computer to find some other acceptable path between the two boundaries; a path with a slower rate of change of altitude or one which follows the maximum path for only a certain distance can be tried. As a means of implementing the conflict elimination and altitude assignment functions, in processing an ascent clearance the computer will proceed in a forward direction along the flight path, starting at the point at which the aircraft joins the airways; and in processing a descent clearance the computer will consider points proceeding back up the descent path from the point at which the aircraft will join the



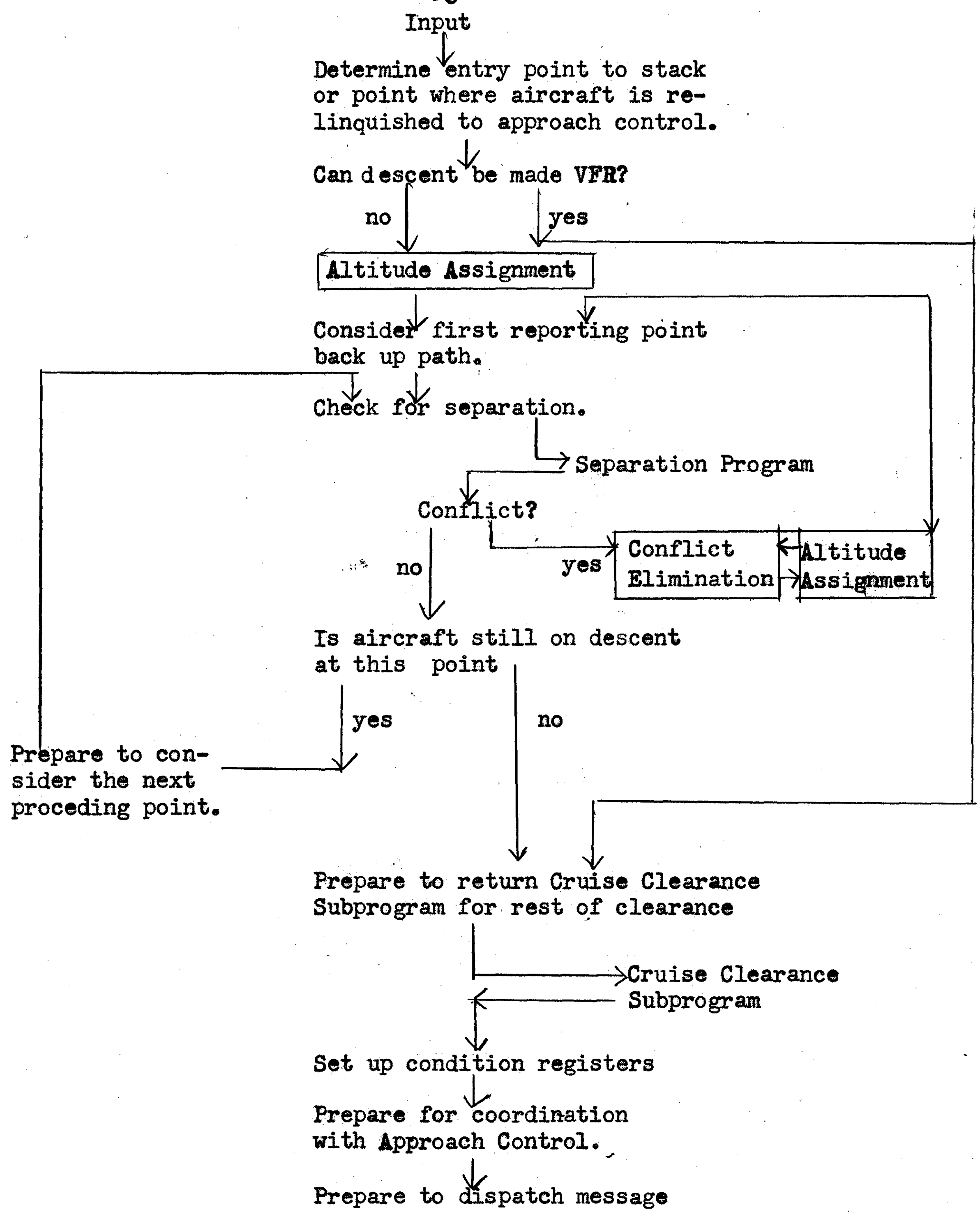
Cruise Clearance Subprogram

Figure 33.



Ascent Clearance Subprogram

Figure 34.



Descent Clearance Subprogram

Figure 35.

stack or be transferred over to approach control. Because of these reasons, there is a great degree of similarity between the ascent and descent subprograms; with careful programming it might be possible to combine the action of the two programs with the exception of the function of conflict elimination and altitude assignment.

CHAPTER X

General System Improvements With Use Of Computer

A. Introduction:

The previous chapters have dealt exclusively with the use of a computer within the specific framework of the existing system of control. As noted in these chapters, the present procedures and methods have been predicated upon the assumption that human operators are the central controlling elements of the system, and in several instances specific situations were pointed out where it appeared that more standardized procedures were desirable for mechanization with the computer. As a concluding chapter to this study, several rather general remarks will now be made in regard to certain advantages which might accrue if one considered the use of a computer in a system not planned for or restricted to the abilities of the human controllers. These remarks are not intended to be comprehensive or to include considerations of extremely futuristic systems in which the mechanization not only involves personnel on the ground but extends to the use of airborne equipment for flight control of the aircraft; rather the remarks are merely included as an illustration of the fields to which the use of a computer for air traffic control can be extended.

B. All-Weather Control

Present regulations require the strict control and supervision of only those aircraft travelling along the airways during IFR flight conditions; although as noted, it is not unusual for pilots to request an IFR clearance when flying under VFR conditions. The safety record for aircraft flying with IFR clearances is extremely high, and stands as a tribute to the little-publicized efforts of the air route traffic control centers and their personnel. At the present time, the large majority of mid-air accidents or collisions occur during good visibility conditions when pilots are responsible for their own safety and separation. Of a similar nature is the fact that some of the most difficult situations for the traffic controllers occur in what might be termed as "border-line" weather conditions. In such conditions when the weather and visibility are apt to change rapidly, it is not unusual to have a number of en-route aircraft file IFR flight plans within a short span of time. The coordination of information and the establishment of appropriate separations between these aircraft and those already under traffic control presents a taxing and difficult problem. The situation may become rather dangerous if the deterioration of the weather and visibility is so sudden and complete that the aircraft are not able to maintain VFR flight while awaiting the IFR clearance.

The above-mentioned situations might be averted if all flights, VFR and IFR alike, were controlled by the centers; it is probable, however, that the present control centers could not handle the large numbers of aircraft that fly in fine weather. The use of a digital computer probably offers a satisfactory solution to the problem and the extension of the use of a computer to an all-weather control system would not differ radically from the discussion in the main body of the thesis. Clearance based on appropriate separations would be required for all aircraft, and certain exceptions to control such as VFR restrictions or flights 500 feet above clouds would probably be modified or eliminated. The much larger bulk of traffic which would be handled by the system might lead to the employment of different data-handling and storage procedures than have already been mentioned, but the general nature of the computer work would be similar to what has already been described except that it would be at an increased tempo.

If an all-weather system were adopted, it would be possible to consider variations in separation standards. The present separations would be retained for IFR flights -- it is conceivable that the accuracy or reliability of the computer in the system might even ease and reduce these separations -- while a separate and less strict set of standards could be adopted for VFR flights in the daytime and another set for VFR flight at nights. The provisions noted in Chapter VIII for non-restricted altitude changes could be used in an all-weather system to give VFR flights as much freedom as is consistent with safety.

C. All-Area Control.

An extension to all-weather control over the airways would be but a first step in the establishment of a complete overall system of control. The second step would be to eliminate the restriction to the control of aircraft only on the airways. At the present time this would be impossible due to the limited extent of the navigational system; however, the Civil Aeronautic Administration is now developing and installing new navigational aids[1] which will essentially provide an unlimited number of flight paths and markers in a traffic control area. With appropriate airborne equipment[2] and in conjunction with the new ground equipment, pilots will be able to continuously determine positions and bearings with respect to a ground station and will be able to navigate a straight path between any two chosen geographical points.

The present methods of control, based as they are on the fixed airways and the fixed reporting points, are certainly not applicable to an all-area control system, and for this reason in the early stages of the use of the new equipment the pilots flying under IFR conditions will still be restricted to a small fixed number of paths. Such restrictions could be eliminated with a digital computer, and it would be possible to use the computer as the control element in a system which permitted aircraft to select optimum flight paths anywhere in the area. Such a system might be of the moving block type; however in view of the large amount of available air space a fixed block system could probably be used without drastically reducing the traffic-handling capacities. The methods of checking for separation in such a system might require fixed blocks of airspace; however, a compromise between fixed and moving blocks might be reached in view of the feature of being able to determine the positions of the aircraft more accurately, as well as being able to obtain position

1. Reference 39 and 40
2. Reference 41

reports whenever they are desired.

D. Use of Radar

It will take a number of years before navigation equipment of the type described above can be put into full operational use for all types of aircraft. The major deterrent to its widescale use will be the fact that a certain amount of the equipment must be airborne; this, plus its expense, places a burden on commercial carriers as well as the large number of private aircraft.

It is possible to envision a ground-based navigation system using only surveillance radar. Such a system has the advantage of requiring no special equipment in the aircraft, while still permitting almost continuous position measurements. It should be realized, however, there are a number of difficulties connected with the efficient use of radar as an aid to navigation or to traffic control; among these difficulties are those technical problems associated with:

a) discerning moving targets in the presence of fixed targets
b) discerning aircraft in the presence of storm clouds
c) discerning small aircraft at long ranges
c) determination of altitude

A large amount of engineering effort has been put into efforts at curtailing these limitations, and with improved ground equipment as well as a small amount of airborne equipment it has recently been possible to achieve more satisfactory operation. This is evidenced by the successful use of surveillance radar during the Berlin Airlift in 1949-1950[1] and by the recent decision by the Civil Aeronautics Administration to use radar as an aid and monitoring device for Approach Control.[2]

There are also a number of operational limitations which restrict the use of radar for navigation and traffic control purposes. The major of these is the fact that the radar data contains no identification of the target other than its position. This means that once one has established which of the radar echoes corresponds to a particular aircraft, the aircraft must be "followed" or "tracked" during the succeeding scans of the radar. This tracking procedure can become fairly difficult when a number of aircraft are flying close together or if the radar returns contain a good deal of errors or extraneous noise.

The normal presentation of radar data on a <u>plan position indicator</u> (ppi) does not include any provisions for indicating altitude, and the geographical positions of the aircraft must be measured from the scope face. In view of the information-handling and data-processing nature of the problem, it would seem that a computer could be conveniently used for the purposes of tracking and data presentation. In performing the former of these tasks, the computer might be programmed to utilize

---

1. Reference 33
2. Reference 14

the same criteria and types of judgment applied to the tracking problem by a human; in the latter task, the computer by virtue of its internal storage could not act as a filter and would provide as an output -- on paper tape, typewriter, etc. -- the data of interest.

E. Scheduling and Planning.

In the previous chapter mention was made of two of the more difficult problems of air traffic control: conflict elimination and assignment of optimum altitudes. These are actually scheduling problems; one is associated with the safety of the traffic, the other with the orderly and expeditious movement of the traffic.

There are a large number of ways in which the idea of scheduling can be applied to the control of air traffic. As was explained in the previous chapters, pre-scheduling and planning plays but a little part in the present system. Aircraft are dispatched with a certainty only that no conflict will exist during the first section of the flight, and with little or no assurance that they will not have to be delayed in the air at their destination. It is not that there is no desire to do pre-scheduling or a lack of desire to utilize the time schedules of commercial aircraft, rather it is the difficulty of taking such factors into account. In contrast to the current system, one can envision a system in which each aircraft before it leaves the ground has a complete schedule which is predicated on adequate separations, proper assignment of altitude, and a minimum of delay. With such a properly devised schedule which took into account small en-route delays and weather changes, the traffic control function for the most part would merely be one of monitoring all aircraft to make sure that they kept to their schedules.

Of course, between the two extremes of the present system and the optimum system there are a number of possibilities. A first step in the direction of complete scheduling is that of <u>flow control</u> in which an attempt is made to regulate the flow of traffic towards each airport to an amount which can be handled and landed without excessive delay. One principle which has often been discussed is that of not giving an aircraft a clearance until it is assured that it will have an available landing time at its destination. In its crudest form this type of flow control would consider only the points of arrival and departure, and would assume that the aircraft would not suffer en-route delays such that it could not make its scheduled arrival time. Plans have been formulated for <u>Airport Time Utilization Equipment</u>[1] which will accomplish the necessary "booking" and reservation making tasks. It is fairly obvious that this type of work could be carried out rather easily by a computer; essentially, however, this flow control would be but an inherent part of a completely scheduled system.

1. Reference 50

The problem of making out a complete and adequate schedule for other than but a small number of aircraft is of sufficient difficulty that a high-speed computer would be required. The problem is not merely that of setting up a single master schedule; the characteristics of commercial air passenger and freight travel, private flying, and military demands are such that one could not expect that it would be possible to create a strict schedule and follow it. Rather the schedule-making duties will be of such a nature that they must be carried out almost continuously, as unscheduled aircraft file flight plans or as scheduled aircraft deviate sufficiently from the schedule so as to require further action. Because of the fact that a sizeable amount of traffic does follow a fairly regular daily and weekly pattern, it would probably be possible to have a standard core to the schedules around which other schedules would be fitted. As noted, all schedules, if they are to be effective and not require a frequent amount of change, should be made with sufficient leeway so as to be able to take care of sudden changes in weather or small delays or advances which aircraft might encounter en-route.

The initial scheduling or rescheduling of aircraft is quite similar in nature to mathematical problems of maximization or minimization. There are certain boundary conditions -- desired time of departure, route, speed, etc., -- and there are certain restrictions enforced, chiefly those of safe separation; the desired result is a schedule which is not only safe, but which entails the least amount of inconvenience and delay for all flights. Of course, while the minimization of inconvenience and delay principle should be applied to all aircraft collectively, care must be taken so that the inconvenience and delay for a single aircraft does not become excessive.

The basic needs of a computer in handling such a problem are three-fold:

a) a means of proposing a schedule to be tested
b) a means of testing such a schedule for separation
c) a means of evaluating a schedule from the viewpoint of maximum convenience and minimum delay.

Need c) involves the setting up of some sort of criteria by which an otherwise safe schedule can be evaluated. For this purpose it might be possible to establish some sort of a merit or demerit system which would assign certain point values for delays, number of altitude changes, amount by which schedule deviates from wishes of pilot, etc. Each proposed schedule could be graded, and the schedule with the best grade selected as the optimum.

It would seem that in performing the functions of proposing and testing a schedule, a form of fixed block system would be the simplest. As already noted, the determination of safe separations in such a scheme is fairly simple -- far simpler than the methods which had to be employed in Chapter VIII -- and the fixed blocks readily lend themselves to schemes for altering the various flight plans in an attempt to obtain new and better schedules. There are a number of other and less obvious factors which would have to be discussed in a detailed consideration of the general subject of scheduling and how the problem might be handled by a computer. In particular, complete study of the subject would include an investigation and critical analysis of just what could and would be gained by using a computer to find the optimum schedule. After all, the saving in time and convenience introduced through the use of the schedule selected by the computer might not be significant over a schedule which could be selected by human planners. This consideration will, of course, become more critical in the future. Under heavy traffic conditions, there seems but little doubt that only a high-speed computer capable of trying and testing a number of possibilities would permit the desired efficient operation of the system.

APPENDIX I

Whirlwind Order Code as of January 1951

A. Notation: AC = Accumulator, AR = A-Register, BR = B-Register, x is the address of a storage register, n is a positive integer, k designates an external unit.

B. Notes on the Order Code:

Effect of operations. The functions of the various orders are described below. It is to be assured that AR, AC, BR, and the register whose address is x are undisturbed unless the contrary is stated.

AR. AR is primarily a buffer register for passing words into AC. After orders ca x, cs x, ad x, su x, sa x, and ao x it contains the number originally contained in register x. After orders cm x, mr x, mh x, and dv x it contains the magnitude of the contents of x. The effect of sp x and cp x is stated below. No other order changes the contents of AR.

BR. A number stored in BR always appears as a positive magnitude, the sign of the number being assumed to be that indicated by the sign digit in AC. This convention has no effect on the logical result of the operations involving BR except that when BR contains a number that will be used later it is necessary to retain the appropriate sign digit.

Alarms. If the result of an arithmetic operation exceeds the register capacity (i.e., if overflow occurs), a suitable alarm is given except as mentioned in connection with orders sa x and sl n.

Shift orders. A multiplication overflow in sl is lost without giving an alarm, but an overflow from round-off gives an alarm. Orders sr 0 and sl 0 only cause round-off, an alarm being given if an overflow occurs. The integer n is treated module 32, i.e., sl 32 = sl 0, sl 33 = sl, 1, etc.

Scale factors. If all the digits in BR are zero and AC contains $\pm$ 0, the order sf x leaves AC and BR undisturbed and stores the number 33 in the last 11 digit positions of register x.

Division. Let u and v be the numbers in AC and register x when the order dv x is used. If $|u| < |v|$ the correct quotient is obtained and no overflow can arise. If $|u| > |v|$ overflow occurs and gives an alarm. If $u = v \neq 0$ the dv order leaves 16 ones in BR and round-off in a subsequent sl 15 would cause overflow and give an alarm. If $u = v = 0$ a zero quotient is obtained.

Check order. This order cannot be used for anything but an identity check. It is intended primarily for use in special test problems and in spot-checking to assure reliability, especially in handling film units.

Display orders. The qh operation sets horizontal deflection of all scopes and leaves it set until the next qh. A new vertical deflection must be provided each time a spot is displayed by qd or gf. The qd or qf operations can be used without a qh operation by allowing the horizontal deflection to be provided by a linear time-base sweep generator in one of the display scopes, in which case computed values can be synchronized with the sweep by allowing each new sweep to cause the computer to start over at the beginning. The temporary display orders will be replaced later by using an operation like rf to select the device and operation re to put the number into it.

C. Orders:

Order	Operation		Function
	Name	Binary Code	
ri --	read initially	00000	Take words from external unit until internal storage is full.
rs --	remote unit stop	00001	Stop external unit
rf k	run forward	00010	Prepare to use external unit k in forward direction.
rb k	run backward	00011	Prepare to use external unit k in backward direction.
rd x	read	00100	Transfer to register x a word supplied by external unit.
re x	record	00101	Arrange for transfer of contents of register x to external unit.

Order	Operation		Function
	Name	Binary Code	
qh x	h-axis set	00110	Transfer contents of AC to register x; set the horizontal position of all display scope beams to correspond to the numerical value of the contents of AC.
qd x	display (D-scope	00111	Transfer contents of AC to register x; set the vertical position of the beams of the display scopes to correspond to the numerical value of the contents of AC; display (by intensifying) a spot on the face of the D-display scopes
ts x	transfer to storage	01000	Transfer contents of AC to register x.
td x	transfer digits	01001	Transfer last 11 digits from AC to last 11 digit positions of register x.
ta x	transfer address	01010	Transfer last 11 digits from AR to last 11 digit position of register x.
ck x	check	01011	Stop the computer and ring an alarm if the contents of register x is not identical with the contents of AC; otherwise proceed to next order.
---	---	01100	Unassigned.
qe x	exchange	01101	Exchange the contents of AC with the contents of register x (original contents of AC to register x, original contents of register x to AC).
cp x	condition program	01110	If number in AC is negative, proceed as in sp; if number is positive disregard the cp order, but clear the AR.

Order	Operation		Function
	Name	Binary Code	
spx	subprogram	01111	Take next order from register x. If the sp order was at address y, store y+1 in last 11 digit positions of AR.
ca x	clear and add	10000	Clear AC and BR, then put contents of register x into AC. If necessary, add in carry from previous sa addition.
cs c	clear & subtract	10001	Clear AC and BR, then put complement of contents of register x into AC. If necessary, add in carry from previous sa addition.
ad x	add	10010	Add contents of register x to contents of AC, storing result in AC.
su x	subtract	10011	Subtract contents of register x from contents of AC, storing result in AC.
cm x	clear and add magnitude	10100	Clear AC and BR, then put positive magnitude of contents of register x into AC. If necessary add in carry from previous sa addition.
sa x	special add	10101	Add contents of register x to contents of AC, storing result in AC and retaining any overflow for next ca, cs, or cm order. Only orders 1 through 15 may be used between the sa order and ca, cs, or cm orders for which the sa is a prepa ration.
ao x	add one	10110	Add the number 1 x 2^{-15} to the contents of register x. Store result in AC and in register x.
qf x	F-scope	10111	Same as operation qd, except display a spot on the face of the F-display scopes.

Order	Operation		Function
	Name	Binary Code	
mr x	multiply and round off	11000	Multiply contents of register x by contents of AC; round off result to 15 numerical digits and store in AC. Clear BR.
mh x	multiply and hold	110011	Multiply contents of register x by contents of AC and retain the full product in AC and the first 15 digit positions of BR, the last digit position of BR being cleared.
dv x	divide	11010	Divide contents of AC by contents of register x, leaving 16 numerical digits of the quotient in BR and ± 0 in AC according to sign of the quotient. (The order sl 15 following the dv order will round off the quotient to 15 numerical digits and store it in AC.)
sl n	shift left	11011	Multiply the number represented by the contents of AC and BR by 2^n. Round off the result to 15 numerical digits and store it in AC. Disregard overflow caused by the multiplication, but not that caused by round-off. Clear BR.
sr n	shift right	11100	Multiply the number represented by the contents of AC and BR by 2^{-n}. Round off the result to 15 numerical digits and store it in AC. Clear BR.
sf x	scale factor	11101	Multiply the number represented by the contents of AC and BR by 2 sufficiently often to make the positive magnitude of the product equal to or greater than 1/2. Leave the final product in AC and BR. Store the number of multiplications as last 11 digits of register x, the first 5 digits being undisturbed.

Order	Operation Name	Operation Binary Code	Function
qr n	read/ shift right	11110	Perform two logically distinct functions: 1) Cause the interim tape input reader to read one character from tape into digits 0 through 6 of FF Register #3. 2) Shift the contents of AC and BR to the right n times. The sign digit is shifted like any other digit and zeros are introduced into the left end. (no round off, no BR clear, no sign control.)
qp n	punch/ shift right	11111	Perform two logically distinct functions: 1) Cause the interim paper tape output equipment to record one character corresponding to the contents of digits 9 through 15 of FF Register #2. 2) Shift right as in operation qr.

BIBLIOGRAPHY

1. Air Traffic Control; by David R. Israel, Electrical Engineering Seminar, Mass. Inst. Tech., 1950

2. Monthly Summary of Air Traffic Control Operations; Internal Memorandum of Civil Aero. Ad., Washington, D.C.: November, 1949.

3. "Air Transport Facts and Figures;" Aviation Week, Vol. 50, No. 12, p. 35, March 21, 1949.

4. Survival in the Air Age; a report by the President's Air Policy Commission, U.S. Government Printing Office, Washington, D.C.: 1948

5. Air Traffic Control, Paper 27-48/DO-12; prepared by Special Committee 31, Radio Technical Commission for Aeronautics, Washington, D.C.

6. "Berlin Airlift;" by Charles J. V. Murphy, Fortune, Vol. XXXVIII, No. 5, November, 1948.

7. Air Traffic Control Implications of Aircraft Evolution: Cornell Aero. Lab. Inc., Buffalo, New York, Report No. JA-654-G-1, 1949.

8. "British Jet Transports;" by Albert Douglas, Harper's Magazine, Vol. 200, No. 1198, March, 1950.

9. "Economic Factors in Civil Aviation;" by P. G. Masefield, Journal of Royal Aero. Soc., Vol. 52, No. 454, p. 575, October, 1948.

10. Traffic Control Requirements for Jet Transport Aircraft; by W. T. Dickinson; talk presented at SAGE National Aeronautics Meeting Los Angeles: October, 1947.

11. Sutdy of Air Traffic Control: Reports 1-6; Washington, D. C.: 1943-45.

12. Teleregister Automatic Aids for ATC; Teleregister Laboratories, New York: 1947.

13. Traffic Control Without Pilot Effort: Teleregister Corp. New York: 1947.

14. Airport Approach Control; General Railway Signal Co., Rochester: Pamphlet 644, 1947.

15. Marginal Checking: Preventive Maintenance for Electronic Equipment; by George C. Sumner, Servomechanisms Laboratory, Mass. Inst. Tech., Report R-185, 1950.

16. AEC Procedures for the Control of Air Traffic; U. S. Government Printing Office, Washington, D. C.: 1950

17. Air Route and Airport Traffic Control Study Guides; Civil Aero. Ad., Washington, D. C.: 1948, 1949.

18. Digest of Airways Operations Service. Vol. I - History; Civil Aero. Ad., Washington, D. C.: 1948.

19. Digest of Civil Air Regulations for Pilots; Bulletin No. 22; Civil Aero. Ad., Washington, D. C.: 1943.

20. Airways Operations Training Series; Bulletins 1-7; Civil Aero. Ad., Washington, D.C.: 1948.

21. Resume of U. S. Planning in Air Navigation, Traffic Control, Communication: Radio Technical Commission for Aeronautics, Washington, D. C., Paper 85-48/DO-19, 1948.

22. Federal Airways Manual of Operations; Civil Aero. Ad., Washington, D. C.

23. Airport Planning; Airline-Travel Distances; Washington, D. C. 1948

24. Airport Planning: Peak Air Carrier Movements at Airports; Civil Aero. Ad., Washington, D. C.: 1949.

25. Introduction to Coding; David R. Israel, Servomechanisms Laboratory, Mass. Inst. Tech., Report E-2000, 1949.

26. Functional Description of the Whirlwind I Computer; John M. Salser, Servomechanisms Laboratory, Mass. Inst. Tech., Report R-180, 1950.

27. Notes from Course 6.535 --- Introduction to Digital Computer Coding and Logic; given at Mass. Inst. of Tech., by W. Gordon Welchman, 1950-51

28. M. I. T. Electrostatic Storage Tubs; S. H. Dodd, H. Klemperer, and P. Youts; Servomechanisms Laboratory, Mass. Inst. Tech., Report R-183, 1950

29. MEDIS (Message Diversion); Airways Operation Training Series Bulletin 8, Civil Aero. Ad., Washington, D. C. : 1945.

30. Magnetic Drum Storage for Digital Information Processing Systems; Engineering Research Associates, Inc., St. Paul: 1949.

31. Summary of Characteristics of the Magnetic Drum Binary Computer, Engineering Research Associates, St. Paul: 1948.

32. Radar Procedures --- Operating Procedures for Control Tower Surveillance Radar and Ground Controlled Approach; Civil Aero. Ad., Washington, D. C.; 1948

33. "What We Learned from the Berlin Airlift;" by H. A. Chaffee and R. B. Corby, Electronics, Vol. 22 No. 9, August, 1949.

34. Air Traffic Control and the National Security; Air Coordinating Committee, U. S. Government Printing Office, Washington, D. C.: 1950

35. Navigation and National Security; prepared by Ad Hoc Committee on Navigation, The National Military Establishment, Research and Development Board, Washington, D. C.: 1948.

36. Radar Aids to Navigation; by J. S. Hall, et al., Mass. Inst. Tech., Radiation Laboratory Series, McGraw Hill Book Co., Inc., Vol. 2, 1947.

37. Radar Beacons; by A. Roberts, et al., Mass. Inst. of Tech., Radiation Laboratory Series, McGraw-Hill Book Co., Inc., Vol. 3, 1947.

38. "Surveillance Radar Deficiencies and How They Can Be Overcome;" J. Wesley Leas, Proceeding of the IRE, Vol. 36, No. 8, p. 1015, August, 1948.

39. Distance Measuring Equipment; Civil Aero. Ad., Washington, D. C.: 1949.

40. "The Operation of VHF Omni-Range in the Transition System;" F. L. Mosely, Inst. of Aero. Sci. Reprint 240.

41. "Development of a Course Line Computer for the Air Navigation System;" C. W. Watts, Sr., and F. J. Gross, Inst. of Aero. Sci. Preprint 232, 1949.

42. Initial Flight Tests and Theory of an Experimental Parallel Course Computer; F. J. Gross and H. A. Kay, Civil Aero. Ad., Washington, D. C., TD Report No. 83, September, 1948.

43. Navigational Functions of Air Traffic Control; General Railway Signal Co., Rochester, N. Y., Pamphlet 659, 1948.

44. Evolution of the Integrated System of Air Traffic Control; General Railway Signal Co., Rochester, N. Y., Pamphlet 652, 1948.

45. The Application of Existing Techniques to the Development of an Improved System of Air Traffic Control; W. D. White, Airborne Instruments Laboratory, Mineola, N. Y., Report 524-1, 1947.

46. The Application of a Moving Block System to RCA Teleran; W. W. Felton, Franklin Institute, Report 354, 1947.

47. Interlock Features of a Moving Block System for Selective Assignment and Control of Air Traffic; W. W. Felton and R. S. Grubmeyer, Franklin Institute, 1948.

48. Investigation of Capacity of Moving Block Traffic Control System; A. B. Faunce, J. N. Marshall, R. W. K. Smith, Radio Corporation of America, 1947.

49. An Evaluation of the Traffic Capacity of a Fixed-Block Traffic Control System in the Approach Zone; W. R. Rambo and R.C. Wheeler Jr., Airborne Instruments Laboratory, Mineola, N. Y., Report 514J, 1947.

50. A Preliminary Analysis of Technical Problems Involved in the Development of Airport Time Utilization Equipment, ANDB Technical Memorandum No. 1; L. R. Philpott, 1949.