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The automatic air traffic control system described in the report consists of automatic control centers for en route control and small satellite computers for approach-departure control. Each automatic control center is composed of 5 automatic sections providing the following functions: (1) position gathering and tracking, (2) internal communication, (3) manual input and display, (4) control, and (5) information storage. An automatic center is capable of controlling over 1000 aircraft simultaneously. Each satellite computer is intended to control approaching and departing aircraft for one airport and is capable of controlling 50 flights simultaneously. The goal in the design of the system is to provide a system that in no way hinders traffic flow and also is safe and simple to use. To achieve this goal, it is necessary to automate all processes in which information flows in large quantities or is rapidly changing. The most important process falling in this category is decision making; consequently, decision making has been automated. All processes in which information is slowly changing or infrequently exchanged are to be executed manually.
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I. INTRODUCTION

This report describes a proposed automatic air traffic control system. Despite its great influence and extensive application in other areas, automation has not as yet been seriously exploited in the field of air traffic control. One of the reasons for this is a reluctance on the part of designers to consider automation of the decision-making processes. In our opinion this is unfortunate, since it is difficult to visualize a significant improvement over the existing system in any system that does not include automatic decision-making. On the other hand, it seems evident from the work herein described that if automatic decision-making is accepted as an integral requirement, a relatively straightforward system design is possible.

The system described in this report consists of principles and devices that are well known in the world of digital computers and related automatic equipment. Each automatic system as described is equivalent to an air traffic control center of the existing system and is capable of automatically controlling over 1000 aircraft simultaneously. Any type of aircraft ranging in performance from the slowest to the fastest can be controlled with the same relative ease.

Automatic decision-making in air traffic control is a complicated subject worthy of study in its own right. The work done at the Coordinated Science Laboratory has, in fact, been devoted to devising a control logic for use in controlling air traffic with an automatic system. The actual system used for this work is a real-time system which simulates the control and tracking sections of the proposed system described in this report. In the process of devising and testing a control logic, the feasibility of automatic decision-making in air traffic control has been established. The results of this work will be reported in Part II of this report entitled "An Experimental Control Logic."

In the material following, a practical control system is described and the benefits resulting from automation of decision-making are outlined. A wide range of ramifications is discussed, including controller responsibilities and behavior of pilot and aircraft.
II. CONTROL SYSTEM REQUIREMENTS

Any air traffic control system must provide five basic functions:

1) information gathering, 2) information storage, 3) internal communication,
4) control, and 5) dissemination of control information. An efficient control
system is one that provides the five basic functions in such a way that air traffic
flow is limited only by air traffic and not by the control sytem. This statement is
taken as a basic premise in the analysis of the existing system and in the design
of an automatic system.

A. Existing System

For purposes of air traffic control, the continental U. S. is divided into
26 control areas each of which is under the jurisdiction of a discrete control
unit called the air traffic control center (commonly referred to as "the center").
Each control area is further divided into 10 or 15 sectors. The function of the
center is to control all IFR (controlled) air traffic in en route phase of flight.
The function is executed by a group of approximately 50 people working in a large
room usually centrally located within the control area. Two or three controllers
control each sector.

Within each control area there are a number of approach-departure control units
whose functions are to control traffic in arrival and departure phases of flight.
The area of jurisdiction of each approach-departure control unit extends to 4 or 5
thousand feet and approximately 30 miles in all directions from the airport it
serves. The control unit is located at the airport and employs from 1 to 8 people
depending on local circumstances. There are over 400 such units in the United
States.

Each air traffic control center has voice communication with all adjacent
centers and with all approach-departure control units within its control area. The
entire complex is referred to as the control system.
1. **Basic Functions**

All five of the basic functions listed earlier involve information flow (as in communication) or information change (as in control). If information flow and change cannot take place at a rate commensurate with the needs of air traffic, the air traffic itself will suffer delay or loss of safety or both. This property is prevalent in the existing system as described below. The description is intended to emphasize those elements of the existing system in need of automation.

**Data Gathering.** In the existing system, the primary medium for information gathering is the voice link. Because of the low data rate of this link, information can be exchanged only infrequently. This is adequate for slowly changing information but infrequent reporting of rapidly changing information is equivalent to reporting with large error. Air traffic positions are in rapid change so that in effect, the system maintains highly erroneous position knowledge of its traffic. Since position errors are large, minimum safe spacing between flights is large, and, consequently, the existing system makes inefficient use of airspace. Radar gathers positions much more frequently and therefore provides the system with position information with relatively small error. This fact is reflected in the rules which set much closer minimum spacings for traffic under radar surveillance. Unfortunately, a controller with radar must do his own tracking in addition to his primary function of control and consequently can work with only a small number of flights.

**Information Storage.** The primary storage device in the existing system is the flight strip. The flight strip is a piece of paper roughly 10 inches long and 1 inch high. Each controller's console holds up to 20 flight strips and each flight strip contains all information regarding one flight. Information is entered into storage by writing (with a pencil) and extracted by reading (visually). Thus, memory access time is determined by manual processes. Access time to total storage is even further restricted. Since there may be 20 or 30 consoles in a single
center, total storage is necessarily decentralized. As a result, each controller has a piece of the total storage at his console but his only access to the total storage is via voice link with other controllers. Consequently, the sorting process, from which all control decisions are derived, is limited by internal communication.

**Internal Communication.** Internal communication is communication within the system that does not involve direct communication with aircraft. All internal communication is via the voice link which is inherently slow. As described above, the sorting process takes place in such a way that it is slowed by internal communication. This is particularly true of sector to sector communication within each air traffic control center. It means that when traffic is heavy, there is delay either in holding or in delayed departure, because the internal voice links are busy. In the extremes, there can also be a loss in safety due to system communication lag.

**Control.** The weakest element of the present system is control. To maintain cooperation and understanding between pilots and controllers, it has been necessary to establish rules restricting air traffic behavior. Unfortunately, the rules reflect the limited abilities of human controllers much more strongly than they reflect air traffic performance capabilities. This is contrary to the basic premise, "air traffic flow should be limited by air traffic—not by the control system". Further limitations in traffic flow can be found in the difficulties confronting an air traffic controller. His problems are too complex, his air traffic moves too fast, and his console contains more information than he can handle. Any automation that does not include automatic decision making will aggravate the controller's problems by loading him with still more information from which he will be expected to make even more rapid decisions.
Dissemination of Control Information. In the existing system, transmission of primary control information takes place before a flight departs. Primary control information consists of a flight plan, submitted by a pilot, and a clearance which is issued by the center. A flight plan is a statement of the intended route and destination; a clearance is the center's approval of the flight plan. Flights frequently have to wait for long periods for their clearance but the delay is rarely due to overload in the communication channel for transmission of control information. Since the flight plan and clearance is comprehensive, not much auxiliary control information need be sent and dissemination of control information usually does not cause delay.

2. Advantages

Three important advantages of the existing system are: a) low cost, b) simplicity, and c) reliability. The cost is low because the system only requires people and very simple equipment. Equipment is simple because the only electronic device absolutely necessary for the system to function is the voice communication link. Reliability is excellent if considered in terms of total system failure. Cataclysmic failure can occur only if there is total communication failure or total failure of a group of 50 controllers. Either case is extremely unlikely because of redundance in communication and because of the inherent reliability of a group of people. If considered in terms of errors, the system is not so reliable, particularly under heavy load.

3. Limitations

The limitations listed below are operating properties of the existing system which are undesirable or destined to become undesirable as the traffic load continues to increase. They are essentially manifestations of the inherent limitations described in the analysis.
Limited Collision Avoidance. The present control system devotes its efforts to IFR traffic only (approximately 5 o/o of all flying); all remaining traffic (VFR) operates with "see and be seen" collision avoidance. Since the system takes no cognizance of VFR traffic, it also cannot provide controlled separation of its own IFR traffic from VFR traffic.

Poor Optimization of Flight Paths. In-flight conflicts are resolved by rerouting or holding. Since all traffic is restricted to airways, intersections, fixes, etc., these methods result in inefficient use of airspace.

Limited Ability to Accomodate Expanding Volume. The quantity and rate of flow of information will continue to increase as aircraft increase in numbers and improve in performance. The number of controllers that can be inserted is limited by internal communication problems.

Emotional Reaction. Fatigue, strain of continued concentration, or even headache can induce mistakes, which can end in tragedy.

Excessive Cockpit Load. Any pilot operating under the control of the present system (IFR) must accept responsibility for a) operation of his aircraft, b) navigation and c) maintenance of communications with the controlling agency. In a modern airliner, these tasks are sufficiently complex and time consuming as to justify a crew of three or four.

B. Automatic System

The basic goal in the design of an air traffic control system is that air traffic flow be limited by other air traffic and not by the control system. Furthermore, there must be no degradation in system performance if the number of active runways is increased to any practical number. (The number of active runways is the ultimate limit in traffic flow). This can be accomplished with automation. To do so, all processes in which information exists in large quantities or is rapidly changing must be automated. This includes tracking, decision
making and some communication.

1. Basic Functions

Automatic digital equipment is characterized by a) large fast access memory, b) ability to calculate at high speed, and c) high degree of flexibility in function. These properties are listed because of their value to automatic air traffic control. The system requirements for the automatic system are the same as those of the existing system and are briefly described below as affected by the imposition of automation.

Data Gathering. The most important information gathered is position reports from all traffic. This information exists in large quantities and changes rapidly. It should be gathered automatically. All other information changes slowly and can be gathered over voice links.

Information Storage. All information pertinent to the control of 1000 flights can be stored electronically in a 1000 word memory of 200 bits per word. Since electronic memory access time is infinitesimal compared to air traffic movement, it is possible to keep a memory filled with information that is never more than 2 or 3 seconds old.

Internal Communication. If the main storage device is an electronic memory, internal communication within each center (equivalent to sector-sector communication in the existing system) becomes a matter of memory access time instead of voice link conversations. Communication with adjacent control centers and with satellite approach-departure computers is essential and should be automated. The reason for automation in these channels is that system effectiveness is considerably increased if current air traffic positions are exchanged.

Control. An automatic control computer can execute control using any set of rules. In contrast to the existing system, an automatic machine is fast enough and flexible enough that the rules can be derived strictly from air traffic
performance. The net result will be that all delay in flight will be caused by other air traffic and never by inefficiency in the control system.

**Dissemination of Control Information.** Automatic control will be far more active than in the existing control system and consequently will need a high speed communication channel to all controlled flights. It is possible to supply all controlled flights with a heading, distance to the outer marker at destination, and the instruction "hold or cruise". This information is necessary and sufficient to provide safe arrival at destination for any controlled flight.

2. **Advantages**

The important operating properties of an automated system are listed below. It should be noted that all of the serious limitations in operation of the existing system have been eliminated or improved.

**Positive Separation for Controlled Traffic.** Any flight choosing not to rely on "see and be seen" collision avoidance in good weather could obtain positive safe separation from all other air traffic including uncontrolled.

**Optimization of Flight Paths.** Optimization is effected by the control computers; there is virtually no limit to the sophistication that can be wired or programmed into a flexible digital machine.

**Improved Expansion Capability.** System capacity is determined by memory size and computing speed. Memory size is easy to increase and computing speeds of today are sufficient for controlling over 1000 aircraft from each computing center.

**Reduction in Cockpit Load.** Flight under automatic control offers optimum flight path to destination with positive separation from all other air traffic. Such a flight can be sustained with no more complication than making the initial request for automatic control.

**Elimination of Sector Communication.** It is not necessary to "hand-off"
traffic as it progresses from sector to sector since all traffic within the area of control resides in one memory (there are no sectors).

**Expansion in Usable Airspace.** It is not necessary to restrict air traffic to airways since the control computer can navigate and resolve conflicts anywhere in the area of surveillance.

**Reduction in Pilot Training Requirements.** A pilot need only be able to maintain attitude and heading to be safe in his use of the system. To use the system in good weather, a pilot's competence requirements are identical to present day VFR requirements.

**Reduction in Work Load on Controllers.** Controllers would be used for identification, monitoring and manual control. All three functions are extremely important but are not nearly so demanding as present controller responsibilities.

### 3. Limitations

The major disadvantage of an automatic system is its high cost. It is estimated that each automatic control center would incorporate 2 million dollars worth of automatic equipment and each automatic approach-departure control area would be equipped with a satellite computer costing approximately $100,000. The entire country could be controlled by 10 automatic control centers.

Automation of dissemination of control instructions implies a digital data receiver aboard each controlled flight. The receiver is relatively expensive and its cost would have to be borne by the users of the system. (The data link receiver is necessary only to guarantee use of the system at any time. An aircraft not equipped with a data link receiver could receive control instructions via the voice link if the controllers involved were not too busy with other unequipped aircraft).
III. AUTOMATIC CONTROL SYSTEM

The automatic control system is to be designed so that air traffic flow is never hindered by the control system. In examining the control needs of air traffic, it is found that there are two distinct types of control required: one type for en route traffic and the other for traffic in approach and departure phases of flight. En route control needs are the same throughout the country but approach-departure control needs are partly determined by local conditions, such as wind direction, runway directions, location of outer marker, etc. It is impractical to incorporate the wide variety of local conditions in a single computer; therefore, approach-departure control shall be relegated to small satellite computers located at airports under their respective control. Airspace reserved for approach-departure control shall be the same as it is in the existing system (30 to 50 mile radius extending to 4 or 5 thousand feet). There will be as many approach-departure areas as traffic conditions demand, and the system shall be designed to accommodate additional satellite computers as they are required.

En route area is defined as all airspace not reserved for approach-departure control. If the system has complete air surveillance, there is no need for airways. This is quite an important factor as it constitutes removal of a serious restriction of air traffic. En route area throughout the continental United States is further divided into approximately 10 en route control areas. (Each control area can be as large as desired, provided that there is no chance of exceeding the center's capacity of some number over 1000 aircraft). Each of the 10 control areas is controlled by one automatic air traffic control center and as many approach-departure control computers as required. The entire complex of 10 automatic air traffic control centers and all approach-departure control computers is called the automatic control system.

The purpose of the automatic control system is to guide all controlled
traffic over the optimum path to any destination in the country. Guidance shall be provided so that all controlled traffic travels with safe separation from all other traffic and also with avoidance of severe weather. Automatic control is to be initiated or terminated as pilots choose. If a pilot chooses not to terminate automatic control, the control system will relinquish control automatically as the flight passes over the outer marker at destination. The flight will be sequenced and aligned for ILS or GCA approach at the time control is terminated.

Control of air traffic cannot be accomplished without imposing some restrictions on air traffic. In the system described below, controlled traffic is to be restricted to a heading and to the execution of one additional instruction to "hold" or "cruise". These restrictions are necessary and sufficient to accomplish control as described above without violating the original premise (traffic flow shall not be limited by the control system).

A. Major Components

The first major division of components is apparent from the preceding paragraphs. Approach-departure computers are separate and distinct from the equipment executing en route control. Approach-departure computers are relatively simple and therefore will not be described here.

The automatic air traffic control center consists of five sections of automatic equipment providing five basic functions. These functions are: 1) storage of information, 2) automatic tracking, 3) manual input and display, 4) internal communication, and 5) automatic control. All of these are continuous and independent processes and the last four need access to information in storage. These factors suggest the arrangement depicted in Figure 1.

As seen from Figure 1, all information is stored in a common memory and each of the four remaining sections has independent access to the common memory.
With this arrangement, the four functions can be executed simultaneously.

1. Memory

Memory requirements are nominal by today's standards both in capacity and in access time. The total space required is essentially determined by the two largest sections of memory: the airport directory and flight storage. The airport directory requires approximately 7000 words of 32 bits each and flight storage requires at least 1000 words of 200 bits each. The airport directory and flight storage are described below.

The airport directory consists of the coordinates of every possible destination in the country. Assuming 7000 airports, 16 bits for x and 16 for y. (1/8 mile resolution for the entire United States), the directory can be stored in 7000 words of 32 bits each. Besides being a potential destination, each airport within the immediate control area is a possible emergency field. Since some airports cannot accept all types of aircraft, it is necessary to store extra information descriptive of each airport within the control area. There may be 200 or 300 airports within each control area; four extra bits for each airport will suffice.

Flight storage is all information pertaining directly to each flight operating within the control area. The requirement is one 200 bit word for each flight. The information in flight storage consists of position and velocity, auxiliary information and control information. All of these quantities are inserted and used by one or more of the four automatic sections referred to earlier. Auxiliary information and control information are described in more detail in the following sections.

The capacity of an automatic control center can be increased by increasing flight storage capacity (one 200 bit word per aircraft). Increasing capacity by this means will eventually reveal the next system limitation which is
computation time. It is imperative that the control center never be overloaded in this respect as there is loss in safety under this condition. The time required for processing 1000 flights is a function of control philosophy and cannot be specified accurately at this time. Using worst-case estimates, however, there is no doubt that an automatic system would not be pressed for time in controlling 1000 flights simultaneously.

In addition to all of the information mentioned thus far, the common memory must store aircraft type parameters. Aircraft type parameters are such quantities as maximum speed, maximum acceleration, optimum cruise speed, etc. for each type of aircraft in existence. In terms of these parameters, all aircraft in existence can be categorized into about ten groups. Aircraft type can be converted to the proper category by controllers as they insert auxiliary information.

Aircraft type parameters and the airport directory are quantities in a state of extremely slow change. Coordinates of new airports and parameters for new types of aircraft can be inserted by manipulating special toggles reserved for engineering use.

The total contents of the common memory are listed below, along with the source of each quantity. All information listed is described in detail in the sections following.

a) position and velocity of all traffic in the control area (inserted by tracking section).

b) position and velocity of all pertinent traffic in adjacent systems (inserted by communication section).

c) auxiliary information on all controlled traffic in the control area (inserted by the manual section).

d) auxiliary information on all pertinent traffic in adjacent systems (inserted by communication section).

e) control information on all flights (inserted by control section).
f) severe weather avoidance areas (inserted by manual section).
g) coordinates of every airport in the country (permanent memory).
h) descriptive indices for emergency use of every airport in the area of surveillance (permanent memory).
i) performance specifications for every aircraft type (permanent memory).

2. Tracking Section

The purpose of the tracking section is to gather and process all air traffic positions and store all positions and velocities in the common memory (velocity is calculated in the process of tracking). The tracking section is made up of a position gathering network feeding an automatic tracking computer.

Data Gathering. The large size of the control area makes it necessary to postulate remote position gathering stations. Several different methods of position gathering can be used simultaneously as long as a position report for each aircraft is received about once every two minutes. Radar can be the primary mechanism for position reporting because of the following advantages:

a) minimum cost to users, b) all presently operating radars can be used, c) most existing radars have been installed in areas of heavy air traffic, and d) radar "sees" all uncontrolled traffic without requiring special airborne equipment. The chief disadvantage of radar is its fallability in target detection and this disadvantage is the weakest element of the entire automatic system.

A more reliable position gathering medium could be achieved with a "one dimension radar" system, i.e. one that measures range only. As will be described later, an airborne discrete address data link receiver is postulated for reception of control instructions. This receiver inherently has the coded response feature but normally does not respond with a transmitted pulse. If a tiny single pulse transmitter is included in the receiver, automatic range measurement is possible.
Instruction transmitters can be operated in pairs, geographically separated and time-sharing the same frequency, thereby gathering sufficient information from which to deduce position. The simple ambiguity resulting from the dual range measurement is automatically resolved by the tracking logic. Among the advantages offered by the one dimension radar are more reliable position reporting and a reduction in equipment at ground installations. The disadvantages are increased complexity of the airborne receiver and the fact that air traffic not equipped with receivers will not respond.

Regardless of the method or methods used for position gathering, position information must ultimately appear at the input terminals of the tracking computer. Data rate in transmission of position information from remote site to computing center is such that telephone line bandwidth is adequate.

**Tracking Computer.** Input to the tracking computer is all position reports from all position gathering stations. The function of the tracking computer is to make use of position reports in such a way as to insert the best possible position information in the common memory.

To describe the operation of a tracking computer, it is necessary to define several terms:

a) **Extrapolation:** The time interval between position reports for any given flight may be relatively large (several minutes). During this time interval, the tracking computer will advance the stored position on the basis of the flight's stored velocity. This is called extrapolation.

b) **Association:** An association if formed if a new position report falls within some specified small distance of an extrapolated position stored in the memory.

c) **Initiation:** If a new position report fails to associate with any extrapolated positions stored in the common memory, it is stored as a tentative track. If subsequently there is an association with the tentative track, a new track is initiated.
d) Track: A track exists at some specific address in the memory if there are repeated associations with position coordinates stored at that address. In an actual machine, it is necessary to establish time intervals to define "repeated associations".

In operation, each position report is checked for association with all positions stored in the common memory. If no association is found, the new position report is used for initiation. If an association is found, the checking process stops and the computer uses the new position report in the calculation of new position coordinates. (The new position report cannot be used directly because of intrinsic error in the position gathering devices). The calculated coordinates are the best possible coordinates (on the average) and are inserted in the memory.

By the definition given above, if a track exists, it resides at a specific address in the common memory (in the flight section). The fact that each track resides at a specific address is extremely important as it is possible to store velocity and auxiliary information at the same specific address. Auxiliary information is aircraft type, identification, destination, altitude, and control status. By definition, a track is identified if auxiliary information has been inserted.

Any memory address containing an identified track will contain accurate present position and velocity plus auxiliary information descriptive of the flight. Any address containing an unidentified flight will contain accurate present position and velocity with zero for auxiliary information.

3. Manual Section

The purpose of the manual section is to provide a communication link between the common memory and controllers. Information has to flow both ways with keysets providing for insertion of information and other electronic devices providing display of the contents of the common memory. Practically all of the information
stored in the common memory must be displayed. The quantity of information in storage is so large that it will have to be distributed among several people by establishing sectors within the control area. Each sector is to be attended by one controller operating a console. Aside from the controller's console, there will be a weather console and a computer monitor console all of which are described below. It is important to note that the manual input and display section is independent of the other three sections so that designation of sectors for display does not extend to any of the other automatic sections.

Controller's Console. The controller's console consists of an air situation display, keyset, flight monitor display, and voice communication link to controlled traffic. Each situation display is a large sized cathode ray tube scaled and centered to display the sector it serves. It displays a spot with velocity nose for each target position and velocity, and alpha-numeric characters for tracking address and auxiliary information. The operator of each console must be given the ability to select with switches the information and targets he chooses to display.

Auxiliary information is inserted in the common memory through the controller's keyset. With the keyset, controllers can select tracks by tracking address or by identification (wing or flight number), and insert aircraft type, identification, destination, altitude, and control status.

Flight monitor displays are simple electro-mechanical devices which in effect duplicate airborne receiver displays. Each flight monitor has an aircraft selection panel so that a controller can monitor the control instructions being sent to any selected flight. With the flight monitor and voice link, a controller can relay instructions to any controlled flight that cannot receive the digital data link.

Weather Console. The weather console consists of a keyset panel and a
cathode ray tube display for insertion and display of severe weather. Weather information is to be gathered in the usual ways, i.e. visual, radar, pilot reports, etc. In its simplest form, a cylindrical avoidance region can be specified by position coordinates, a radius, and two altitudes. Irregular shapes can be very well approximated by specifying several cylindrical avoidance areas as described above. Since severe weather does not prevail and is relatively slow moving, it is practical to ask that a controller with keyset keep the control computer informed on severe weather movement.

Computer Monitor Console. The purpose of this unit is to give human monitors as much information as possible regarding the computer's performance. Basically, it is a sector display that can be switched to duplicate any sector display in the system. In addition, the console displays the results of all calculations on selected targets and indicates the control computer's intentions regarding the selected flights. It should be manned by people who have good knowledge of the computer logic or who are well trained in interpreting the computer monitor display. Any anomaly observed by a sector controller is to be reported by voice to the computer monitor where it can be investigated thoroughly.

4. Internal Communication Section

The third independent input-output connection to the common memory must provide communication with adjacent automatic control centers and with satellite approach-departure control computers. There must be continuous exchange of tracking information on pertinent aircraft and occasional exchange of auxiliary information. Since tracking information (position and velocity) changes rapidly, the communication links must be automated. The internal communication section logic will be designed so that satellite computers can be added as needed with no disruption in system operation.

In effect, the automatic connection between adjacent control centers enables
Each center to "use" the position reporting network and tracking section of neighboring control computers. Each control center must retain control of all controlled traffic operating within its area of surveillance, but adjacent centers can make use of position and velocity in anticipation of transition into the adjacent control area. The communication section can decide which traffic will be traversing which adjacent control area and exchange information accordingly.

Similar factors apply to communication with satellite computers. All flights in approach or departure phases of flight will be tracked by the tracking computer at the automatic control center but they will be controlled by satellite computers in their respective approach-departure areas. The internal communication logic will be designed so that tracking information will be sent to appropriate satellite computers. In effect, the satellite computers "use" the tracking section of the center. In addition, auxiliary information has to be occasionally sent both ways.

5. **Automatic Control Section**

The purpose of the air traffic control system is to steer any controlled flight to any destination in the country. Guidance will be provided such that there is safety from collision and such that the route traversed is optimum, commensurate with air traffic.

The purpose of an en route control computer is to steer controlled traffic in en route phase of flight while in the immediate control area. If a controlled flight is not terminating in the immediate control area, it is adequate for the en route control computer to relinquish control as the flight passes into an adjacent control area. If a controlled flight terminates at an uncontrolled destination within the immediate control area, it is adequate for
the control computer to relinquish control as the flight passes over its
destination. If a controlled flight is terminating at a controlled airport
within the immediate control area, it is adequate for the en route control
computer to relinquish control to a satellite control computer as the flight
enters approach area at its destination.

The purpose of a satellite control computer is to steer all controlled
traffic in approach and departure phases of flight at the airport under its
control. An arrival will be safely steered to the outer marker in such a
way as to be sequenced and aligned with ILS. Under these conditions, it is
adequate for the satellite computer to relinquish control as the flight
passes over the outer marker. Departures will be steered until safely clear
of all approaching, departing and uncontrolled traffic at which time it is
adequate for the satellite computer to relinquish control to the en route
control computer.

Control information is all results of all control computer calculations
that must be saved for future calculations. It is descriptive of each
individual flight and consists of such information as heading, time intervals,
winds aloft (affecting the flight), etc. Since the information is pertinent
to each flight, it will be in the flight storage sections of memories and will
require approximately 100 bits per aircraft. Each control computer, whether
en route or approach-departure type, will have to have its own control infor-
mation store. At the automatic control center, control information will be
stored in the common memory and each approach-departure computer will store
control information in its own local memory.

In addition to all information in storage, each control computer has to
know the time, and must have some method of transmitting control information
to controlled traffic. The time is not difficult to provide since it is
adequate if all computers keep the same time to within 2 or 3 seconds. Communication of control instructions will be via digital data link or voice link depending on the airborne equipment.

**En route Control Computer.** In its role of decision maker, the control computer can make use of all of the information stored in the common memory. From our experience at the Coordinated Science Laboratory, it has been found that very elaborate control processing of a single flight can be done in approximately .01 second. In general, the degree of "elaborateness" necessary for processing a flight is a function of the traffic density so that in most cases the full treatment and consequently the full .01 second is not necessary. Typically, each target will be processed once every 10 or 15 minutes providing ample time to process and control over 1000 flights.

Briefly, control processing takes place as follows: During the time interval in which a flight is being processed, it is defined as the reference aircraft. The problem for the control computer is to find a path to destination for the reference aircraft such that the path is optimum and such that there is safe separation from traffic and severe weather. The problem can be solved by sorting the reference aircraft against the contents of the memory in several different ways (altitude sort, distance sort, etc.). If a good solution cannot be found or if congestion is compounding, the control computer can choose to "hold" the reference aircraft. Part of the solution to the control problem for the reference aircraft will include calculation of a time interval over which control processing of the reference aircraft will not be necessary. This time interval will range from 1 minute to 30 minutes depending on traffic.

The control computer could be a general purpose machine, but it appears to be far more economical to design and build a special purpose control computer. Solutions to the control problems are essentially logical reactions
to quantities such as \( \sqrt{x^2 + y^2} \), \( \sin \theta \), \( \text{arc tan } y/x \), etc. This suggests an arithmetic unit made up of 6 or 8 sixteen bit registers from which the common functions are calculated by modular units that can be plugged into the machine. Control circuitry for the control computer will cause the arithmetic unit to execute the air traffic control philosophy. The recommended machine would be a relatively small wired logic special purpose computer.

**Satellite Computers.** The purpose of the approach-departure control computer is to control approach, terminal sequencing and departure. The satellite computer has its own memory which is supplied with auxiliary information from local key-sets and position information from the automatic control center. The satellite forms and stores its own control information. The computer has an arithmetic or logic unit in which control decisions are made and a digital data link transmitter for transmission of control instructions. The messages that it transmits are identical to en route messages so that a pilot need only change frequency of his receiver to maintain uninterrupted control through transition from en route area to approach area.

The memory required for the approach-departure computer is smaller than that of the en route memory since there can only be up to perhaps 50 aircraft operating simultaneously in the approach area. (The machine must provide one 200 bit word for each aircraft). The word format of the memory is identical to that of the en route memory; consequently, standard display consoles can be used in conjunction with satellite computers. Consoles can be located in the approach-departure cab or the tower as local circumstances dictate.

The computer itself can be assembled from the same modular units used to assemble the en route computer. Its control logic is different, however, since its purposes are to steer to ILS with safe sequencing or steer departures to en route area. The computer must be designed so that local rules, runways, outer markers, etc. can be inserted with switches or plug-in units.
Dissemination of Control Information. Control computers must have the ability to transmit control instructions to any controlled flight. Since there may be over 1000 flights simultaneously under control, the total amount of information transmitted may be enormous. The proposed automatic communication link is a network of remotely located digital data transmitters fed by telephone lines emanating from the control computer. Each remote transmitter has its own memory capable of storing messages for all aircraft in its vicinity. The airborne receiver is a discrete address digital data receiver.

In operation, the control computer will process each target as often as traffic conditions demand. Typically, each en route flight will be processed every ten or fifteen minutes and frequently processing will result in the formation of a new message. The message will be sent via telephone lines to the most desirable remote sites where it will be inserted in the remote memories. (Distance to outer marker is part of the message and will be calculated and transmitted more often but this is not part of control processing). All messages sent over the telephone lines can be sent with error check digits to provide redundancy.

Remote transmitters can be dispersed so that any flight anywhere in the control area will find good reception above some reasonable minimum altitude. The number of flights in the vicinity of any one transmitter will probably never exceed 100, consequently, each remote memory need only store a maximum of 100 messages. Each transmitter will transmit the contents of its memory repetitively so that at typical data link rates each controlled flight will receive a message more often than once every second. Since the contents of each message remain unchanged for much longer periods of time, there is a high degree of redundancy in this communication.
The information to be transmitted is determined mostly by air traffic needs. It is desirable to minimize the quantity of information to reduce the cost and complexity of airborne equipment. It is also desirable to send information that is of greatest value to a pilot. These factors, plus the aircraft selection requirement (control computers must send messages to selected flights), determine the information content of control messages. Specific content of each message is described below in the airborne receiver section.

**Airborne Receiver.** The digital data link receiver is not an absolute necessity for all aircraft. Even when the traffic load is heavy, controllers will have time to relay instructions by voice link to some unequipped airplanes. Unfortunately, the voice link is inefficient and therefore easily overloaded. This sets a limit to the number of airplanes that can be controlled by this method. This point is discussed in more detail in manual control.

The airborne receiver is a tunable VHF or UHF discrete address digital data receiver. Discrete address means that the receiver will only accept messages addressed to it. The address is the same as the wing number or identification and is therefore unique for each aircraft. The number must be wired or set into each receiver at installation. Airliners identifying by flight number would have to be equipped with a slightly more elaborate unit in which the crew could set the current flight number into the receiver with switches.

Each receiver must display the following information:

1) **Heading** - the heading displayed is simply the heading that must be flown.

2) **Distance** - distance to the outer marker at destination. If destination has no outer marker, distance indicated is to the airport.
3) Hold-cruise - If the display indicates "hold" it means to enter a standard holding pattern on the indicated heading and maintain the hold until the indication changes to "cruise". Cruise means proceed on the indicated heading.

4) Red flag - If the red flag shows, the pilot is informed that he is not being controlled by the automatic system. The flag would normally appear as the flight passes over the outer marker on final approach but in all other cases, its appearance indicates an anomaly which should be resolved over the voice link if the flight is to proceed on automatic control. The flag is actuated by the receiver (not by the control system) if more than 5 seconds elapse with no receipt of a message.

5) Attention - Since the displayed heading may not change for long periods of time, it is desirable to incorporate a light or tone to call the pilots' attention to a new heading or new hold-cruise status. The indication should persist until manually reset.

The following is a list of a possible set of digit allocations for the messages transmitted to controlled aircraft.

<table>
<thead>
<tr>
<th>Identification</th>
<th>Bits</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identification</td>
<td>19</td>
<td>(524,288 airplanes)</td>
</tr>
<tr>
<td>Heading</td>
<td>7</td>
<td>3° increments</td>
</tr>
<tr>
<td>Distance</td>
<td>10</td>
<td>For indication of distance up to 999 miles</td>
</tr>
<tr>
<td>Hold-cruise</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Attention</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>38</td>
<td></td>
</tr>
</tbody>
</table>
B. Operation

The automatic system is not intended to be devoid of people -- in fact the staff requirements are about the same as those of the existing system. Humans are actually quite valuable to an automatic system but not for control. Control needs have become too complex and fast-moving to be satisfied manually.

If humans are to remain efficient and effective at any task, it is necessary that they do not become overloaded. To prevent overload in the manual functions, it will be necessary to divide control areas into sectors as has been done in the present system. Each sector will have assigned to it one console with built in display and keyset (described earlier) and each console will be operated by one or two controllers. Sector size is determined by the number of flights that one or two controllers can safely monitor.

It has been specified that control shall be done automatically but little has been said about how to control. There is an enormous amount of flexibility in control philosophy because of the flexibility of modern digital computing equipment. No attempt is made in this report to describe a control philosophy in detail but the important and basic aspects are given. This is done primarily to give the reader an idea of what can be done with automatic decision making and also to indicate effects on pilots and their behavior in making use of the system. The following sections describe automatic system operation in terms of controllers' functions, control philosophy and pilot behavior.

1. Controllers

The main responsibilities of controllers in the automatic system are identification, monitoring, and manual control. Identification occurs only once for each flight originating in the control area; monitoring consists of scanning the situation display for incipient collisions involving one or more controlled flights. The information exchange rate in these two functions is low enough that a sector controller can work with ease. The additional function of manual
control can be as time consuming or strenuous as the controller chooses to make it since he has choice in the number of flights operating under manual control. Controllers' stations are at sector consoles described earlier and their functions are described in detail below.

**Identification.** Any controlled flight entering a control area from an adjacent automatic control area will enter with identification preserved and so will not have to be re-identified. (His identification will have been automatically sent over the internal communication channel well in advance of his actual entry). Any flight originating within the control area, however, will have to be identified if it is to travel under automatic control.

Identification of a flight is always initiated by a pilot and cannot be completed unless the flight is airborne. The controller's function in identification is to insert all auxiliary information on the proper track in the common memory. Each track has a memory address (called tracking address) which is displayed beside each target appearing on the controller's air situation display. Auxiliary information will have been given the controller in the conversation with the pilot requesting control. The controller will have to establish radar identification so that he can observe which tracking address contains the flight requesting control. Having done this, the controller can insert auxiliary information at the proper address with his keyset. This action, in turn, enables the control computer to transmit messages to the newly identified flight since identification is part of auxiliary information.

An aircraft departing from a controlled airport will exchange all auxiliary information with the tower operator or ground controller. As the flight becomes a radar target and subsequently appears on the departure controller's situation display with a tracking address, the information can be inserted and identification completed. If the tower is not equipped with automatic satellite computer and console, the auxiliary information will have to be exchanged via telephone.
line to a sector controller and identification completed there.

A flight departing from an uncontrolled airport will have to maintain visual flight while uncontrolled, except by prior arrangement with a sector controller. The altitude to which the flight must climb to become a radar target is determined by local radar coverage and would be known to the sector controller. If the flight could not reach the altitude without entering the clouds, it would be necessary to obtain a clearance granting permission to climb to radar altitude. The clearance would be issued by a sector controller. As in the present system, the safety of this maneuver is dependent on uncontrolled traffic maintaining visual reference clear of clouds at all times.

In all cases in identification, a keyset operation is involved. If properly done, the pilot of the newly identified flight will observe the disappearance of the red flag in his receiver within seconds after the controller announces "identified". If the controller made a mistake in inserting wing or flight number in his keyset, the affected pilot would observe the red flag in his receiver display indicating no control. He should initiate corrective action over the voice link immediately. If the controller made a mistake in destination, the affected pilot would observe disappearance of the red flag indicating positive control (and safety) but he would observe absurd heading and distance. He should initiate correction. All other keyset errors are easily detected within the automatic equipment.

Monitor. When the traffic count is high, the amount of information appearing on a sector situation display may be considerable, however, not all of it is pertinent to the monitoring function. Each controller has the ability to filter the displayed data by manipulating switches. He can thus confine his attention to selected flights, selected altitudes, selected classes, etc. or whatever he may need to provide effective monitoring. If he finds any reason to doubt the
effectiveness of control within his sector, he can report his observations to the computer monitor where a very quick analysis can be made and special action taken if necessary.

**Manual Control.** The function referred to as manual control is actually manual communication. Any aircraft that cannot receive the digital data transmitters can still operate with automatic control subject to a limitation in the number of such flights. This applies to unequipped aircraft as well as those having receiver failure. The limitation in numbers occurs as a result of the low information exchange rate in the voice link.

As described earlier, a controller can duplicate any airborne receiver display he chooses with his flight monitor display. If he has several flight monitor displays at his console, he can select several flights. To execute manual control, he has only to relay control instruction over the voice link as they appear in the flight monitor displays. One controller could probably manually instruct up to 10 flights with no difficulty. (It is possible to devise a control philosophy such that each en route flight will receive a new heading less often than once every ten minutes. In approach area the instruction rate would be higher and in terminal area, headings would be changed at a rate equivalent to present day radar vectors to ILS).

Pilots intending to make use of the system under manual control would be expected to contact the automatic control center before take-off if flight conditions were below visual minimums. If controllers were busy because of heavy manual traffic, the request for manual control would be denied or the inquiring pilot advised of a departure time.

2. **Control Philosophy**

The general behavior of all controlled air traffic is determined by the control philosophy or control logic. In an experimental system such as that
used at the Coordinated Science Laboratory, it is possible to invent and evaluate any philosophy by simply programming a general purpose computer. In a practical operational system, the logic would be wired into the machine and consequently could not be changed easily. It is obviously important to devise a satisfactory logic before such a machine is built. The control philosophy must be built around certain basic elements so that there is safety, efficiency and acceptance by users. Some of the basic problems are discussed below.

Since the postulated control computer has the ability to transmit headings to all controlled aircraft, it becomes a matter of control philosophy as to whether it should do so throughout all phases of controlled flight. More specifically, should it provide guidance when there are no conflicts ahead or, in the language of the pilot, should the control computer navigate?

A common concept in air traffic control is that the air traffic control system shall provide separation—not navigation. Adherence to this principle in control philosophy could be achieved by transmitting two types of messages to controlled traffic. One message would be a command heading for conflict avoidance which must be obeyed, the other an advisory heading for navigation which could be obeyed or not as the pilot chose. This could be implemented at a cost of one more digit in the digital message which must be decoded in the receiver to indicate "command" or "navigate". Under conditions of congestion or high traffic density, however, most or all headings would be command headings which suggests that the common concept needs revision.

Congestion can be defined as existing if it is ever necessary to deviate a controlled flight to avoid conflict with any other flight. This definition and its role in control philosophy are important because there is always an optimum way to control congestion as defined above. Optimization in control of congestion is of little consequence if the number of aircraft involved is small but when considered in terms of today's air traffic volume, optimization becomes extremely important.
The control logic has two degrees of freedom with which to control congestion and provide optimized air traffic flow. It has complete freedom in choice of heading for each controlled flight and it can inject delay by instructing any flight to hold. Under automatic control, a typical flight in today’s high traffic volume would spend an entire flight following headings intended to optimize traffic flow. Unfortunately, the process of steering to optimize resembles navigation and is therefore in violation of the "provide separation—not navigation" concept mentioned earlier. In a logical sense, very high quality optimization is feasible and should be a part of the control philosophy regardless of whether it is referred to as navigation or optimization.

Expected errors in long range anticipation of air traffic behavior are of large magnitude. If traffic flow is to be optimized, the process must involve long range anticipation and consequently there must be some means of coping with large expected errors. The logic of optimization should be such that it favors small average error in anticipating traffic performance. If only small errors materialize, traffic flow will be near optimum. If large errors materialize and traffic enters into conflict as a result, the conflicts will be resolved by another system of logic described below. The logic of optimization should take into account the number of flights "lost" to conflict resolution, so that it can adjust the error threshold accordingly. (In conflict resolution, optimization of flight path is a secondary factor).

Conflict can be defined as existing if any controlled aircraft is destined to have a collision and a collision in turn is defined as a controlled aircraft very close to any other aircraft. The logic of conflict avoidance uses very short range anticipation (of the order of twenty minutes) and is therefore a relatively precise system of calculation. If the optimization logic is well
done, all conflicts will be quite easily resolved. All air traffic in conflict
takes priority over optimization; consequently optimization will tend to
deteriorate if it is such that it permits many conflicts. One of the most
important factors contributing to loss of optimization of any flight is poor
heading following.

Poor heading following is specifically defined as following a heading
that is different from the heading transmitted by the computer. This can
occur as a result of poor pilot behavior, poor compensation for winds aloft,
or erroneous compass. It is important to note that poor following can in
no way influence the accuracy with which the control computer knows air traffic
positions and velocities; consequently it is always possible for the computer
to detect impending uncontrollable collision and if necessary inform a control­
er so that special action can be taken.

Errors due to poor following are of unknown and varying magnitude, and they
are different for each flight. In spite of these properties, it is possible to
devise a collision avoidance logic such that controlled traffic will not collide
even under the influence of the worst case errors mentioned above. (It is only
necessary to calculate headings that are some function of the distance between
the two flights in conflict). The flight operating consistently under large
magnitude error in heading following will reach its destination safely but its
flight path will be non-optimum. The magnitude of departure from optimum will
be proportional to the magnitude of the error. (Long straight line segments of
the flight path will become curved paths resembling the uncompensated crosswind
homing flight path).

The most important contributor to poor heading following is wind aloft.
There is no difficulty in calculating a heading that is fully compensated if
the wind is known; the difficulty is in learning the wind. Several methods have
been suggested all of which use controlled traffic itself to deduce the wind (by comparing instructed track with actual track). The questionable aspect of the use of air traffic in this way is that one must assume that controlled air traffic is operating under no other heading following error. Errors in this assumption can be compensated by averaging or by using controllers in some way to help the computer learn winds aloft. In general, poor knowledge of winds aloft means poor optimization and nothing more.

3. Pilot Behavior

In his use of the present system, the pilot uses VOR receiver, charts, hand calculators, etc. from which he deduces a heading and ascertains his present position. His need for a heading is obvious but knowledge of present position is of little or no value to him except in emergency (discussed below).

Logically, the only information that a pilot must have to reach his destination is a heading and the distance to the outer marker at his destination. The postulated control system will send this information to each controlled flight. Each recipient of control headings can know that if he follows the headings, his flight will be safe from collision and will traverse the shortest route commensurate with other air traffic. Pilots also know that the voice link is open for relay of any auxiliary information (altitude changes, weather, etc.) or resolution of any anomalies. If a pilot should find need for his exact position he can get it very quickly from a controller. (The controller has only to manipulate a few toggles to cause his display to display the inquiring flight and no others).

In case of emergency aboard a controlled flight, the automatic system can be considerably more effective than the existing system. The pilot would have to declare the emergency over the voice link so that a controller with keyset could mark the flight as an emergency. In response, the control computer will
automatically change the destination of the stricken aircraft to the nearest acceptable destination. From that moment on the flight in distress will receive messages which contain heading and distance to the new destination.

The price paid for conflict avoidance can only be delay. If a conflict can be avoided by a heading change and resultant small increase in delay of the deviated flight, it should be done. However, as the air situation becomes more complicated and total delay requirements increase, it becomes more desirable to "hold" traffic so as to reduce compounding congestion ahead. The hold pattern can be identical to the present day race track pattern and it is reasonable to assume that all pilots have the ability to properly execute the pattern in response to the simple instruction "hold". The hold instruction would always be accompanied by a heading which a pilot must interpret as the inbound heading of the hold pattern. It is not necessary that air traffic hold on a fix or intersection as long as all traffic is under surveillance.

Holding on a heading without a fix presents no particular problem except for drift in the presence of winds aloft. As long as drifting hold patterns are under complete surveillance, there is no danger of collision but the drifting pattern is non-optimum as well as aesthetically unpleasing. It is possible to specify VOR-DME equipment on board each aircraft so that pilots could compensate but it is preferable to exploit the computing facility and let it compensate. The computer can completely specify a hold pattern by transmitting inbound and outbound headings. The headings can contain compensation for crosswind component and the time of transmission of each heading can contain compensation for head-tail wind components.
IV. SUMMARY

Three broad aspects of automatic air traffic control have been discussed: 1) system design 2) philosophy of piloting and 3) control philosophy. Of these, system design has been emphasized in keeping with the purpose of the report. The automatic system described in this report will virtually never become obsolete in its ability to perform the air traffic control function. This is true because the only important system limitation (capacity) can be increased as technology in computing circuitry improves.

Philosophy of piloting has been treated lightly because a pilot will find little or no difference between automatic control and present day radar vectoring. In the existing system, radar vectoring is used extensively both in approach-departure control and in en route control. The only difference proposed in this report is that radar vectors be sent automatically rather than verbally.

Control philosophy has also been treated briefly in this report to help emphasize the automatic system. Control philosophy is the most important aspect of the automatic system and, therefore, will be treated separately in another report. Actually, one of the main purposes of the work done at the Coordinated Science Laboratory was to devise and test a workable control philosophy and in the process to isolate the problems associated with automatic control of air traffic in the civilian environment. The control system used for the study was the Cornfield System described briefly below. Several control programs have been written and are operational. They have served the purposes mentioned above and in the process have established the feasibility of automatic decision making in air traffic control.

Part II of this report, called "An Experimental Control Logic" (CSL report R-146), describes the control philosophy that has been devised at the Coordinated
Science Laboratory. The problems associated with the formation of the control philosophy are discussed in detail with solutions where they have been found. This control philosophy is not optimum but is well understood and can serve as a basic framework from which better logic can be derived. An additional report, "Optimum Landing Order of Planes" (CSL report R-142), deals with optimization of the landing order which is a necessary part of the approach-departure control philosophy.

The Cornfield System is described in detail in CSL reports R-35, R-63, and R-114. Very briefly, the Cornfield System is a real time system using two separate computers; one is a special purpose tracking computer (TASC) and the other a general purpose (ILLIAC) acting as control computer. The two computers are connected together through a rather elaborate network of automatic equipment providing a highly flexible system. The displays use 19 inch Charactrons (C19-K) with P-19 phosphor and were designed and built at the Coordinated Science Laboratory specifically for the Cornfield System.
Fig I. Automatic air traffic control center showing one satellite computer.