AN APPRAISAL OF PROBLEMS IN THE AIR TRAFFIC CONTROL SYSTEM

William B. Rouse

DSR 70283-12

Engineering Projects Laboratory
Department of Mechanical Engineering
Massachusetts Institute of Technology

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NASA Grant
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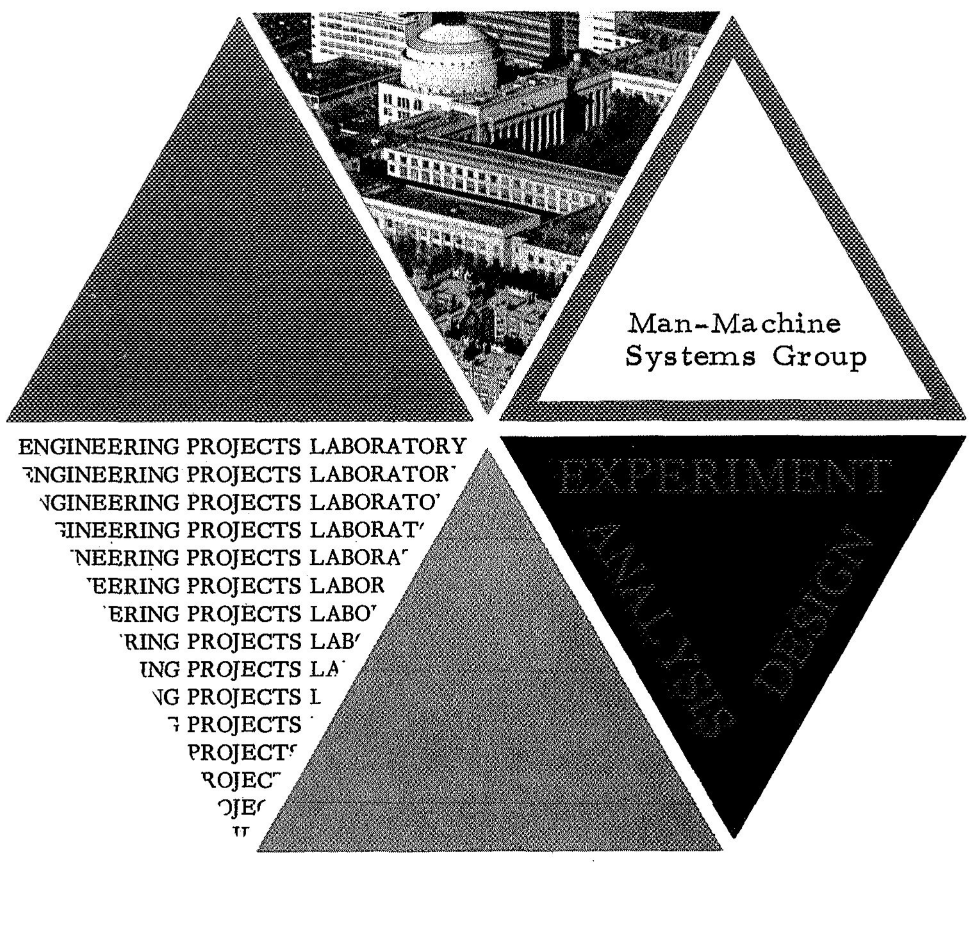

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ABSTRACT

This report presents a study of the air traffic control system with emphasis on the areas of management, operations research and design. The current system is described and research work that has been performed is discussed. A discussion of the need for a decision-making model is presented and used to conclude how future air directions for air traffic control research should be determined.

ACKNOWLEDGEMENTS

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I. INTRODUCTION

A recent magazine article [4] is entitled "If You've Time to Spare, Go by Air!" The nation's air transport system has not yet reached the point where this statement is a reality, but delays experienced during peak loads at the busiest airports indicate that unless the air transport system receives some doctoring, it will lose its significant role in our economy's growth.

While the number of aircraft (A/C)* has increased by approximately 15% annually over the past two decades and the system has provided an increasing annual contribution to the GNP, the air transport system has been dangerously neglected. Solutions to problems have been provided only in a "do or die" situation and the result has been a patchwork system which works, usually, although not very well.

Air transportation problems can be classified into two broad areas [20]. The first area of problems is associated with terminal operations. These problems include getting passengers, cargo, etc. to the airport, the handling of baggage and automation of ticket systems. The second problem area is related to general movement of A/C on the ground and in the air.

While both areas are in dire need of help, the area concerned with movement of A/C appears to be pushing the system towards the brink of catastrophe. This statement may not seem obvious, but if one considers that any work started now toward correcting the current situation will actually not be implemented until at least 1980 [3], the seriousness of the problem becomes astounding.

The purpose of this report is to study one of the primary considerations in moving A/C. This consideration is the air traffic control (ATC) system. ATC has been on the lips of many politicians, executives, and technologists over the past several months. Such interest has been motivated by the

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*A glossary of abbreviations and jargon appears in the appendix recognition of a tremendous need for refurbishing an out-moded ATC system.

The need is both aesthetic and economic. While aesthetic considerations are sometimes ignored by an industrial society, the aestheticians may provide pressure in this situation because they often have a choice between airlines they use, resolving this choice only by choosing the airline that provides more comfortable travel. Airline executives realize this and are making every effort to assure that their customers will have efficient, smooth, and pleasurable dealings with the airline. They realize that a lack of respect for the traveler's comfort will send him elsewhere. An airline does not have a monopoly on its services as a utility company may have, and so the problem of offering comfortable travel is one of economics. The turbo-train is now available and automated highways are on the horizon, so this problem is becoming even more urgent. Therefore, at least in spirit, the airlines are entirely backing efforts to update the ATC system.

An increasing portion of society that uses the air system is also enthusiastically supporting ATC efforts, and such organizations as NASA are realizing that "inner space" still has quite a few challenging problems. Industry in general is organizing to attack these problems. While this tends to produce an over-abundance of priorly unknown "experts," it has the benefit of motivating the economy towards a goal and substantially increasing the chances of finding a solution.

The research work accomplished and presently being conducted can broadly be called "systems engineering." Systems engineering will be broken down into three categories:

1) General management
2) Operations research
3) Design

Most of the available literature that concerns ATC can be put into one of these categories.

General management includes such general tasks as deciding that a problem exists, indicating some possible areas of study and motivating the funding of such studies. Operations research (OR) theoretically and experimentally investigates the problem area and determines some causal relationships. Design uses all of the above and produces a system to meet the desired applications.

ATC problems have received attention from all three of these categories. Work in the general management area has tended to be redundant, but some important concepts have come forth. Operations research work has been scarce, but what has been accomplished has been excellent. Design work has also been fairly limited; however, more importantly the "state-of-the-art" has advanced tremendously and new technology is now readily available to be applied to ATC problems.

All-in-all, the purpose of this report is to study the ATC system as it currently exists, evaluate research performed to date, and provide some criteria for future work.

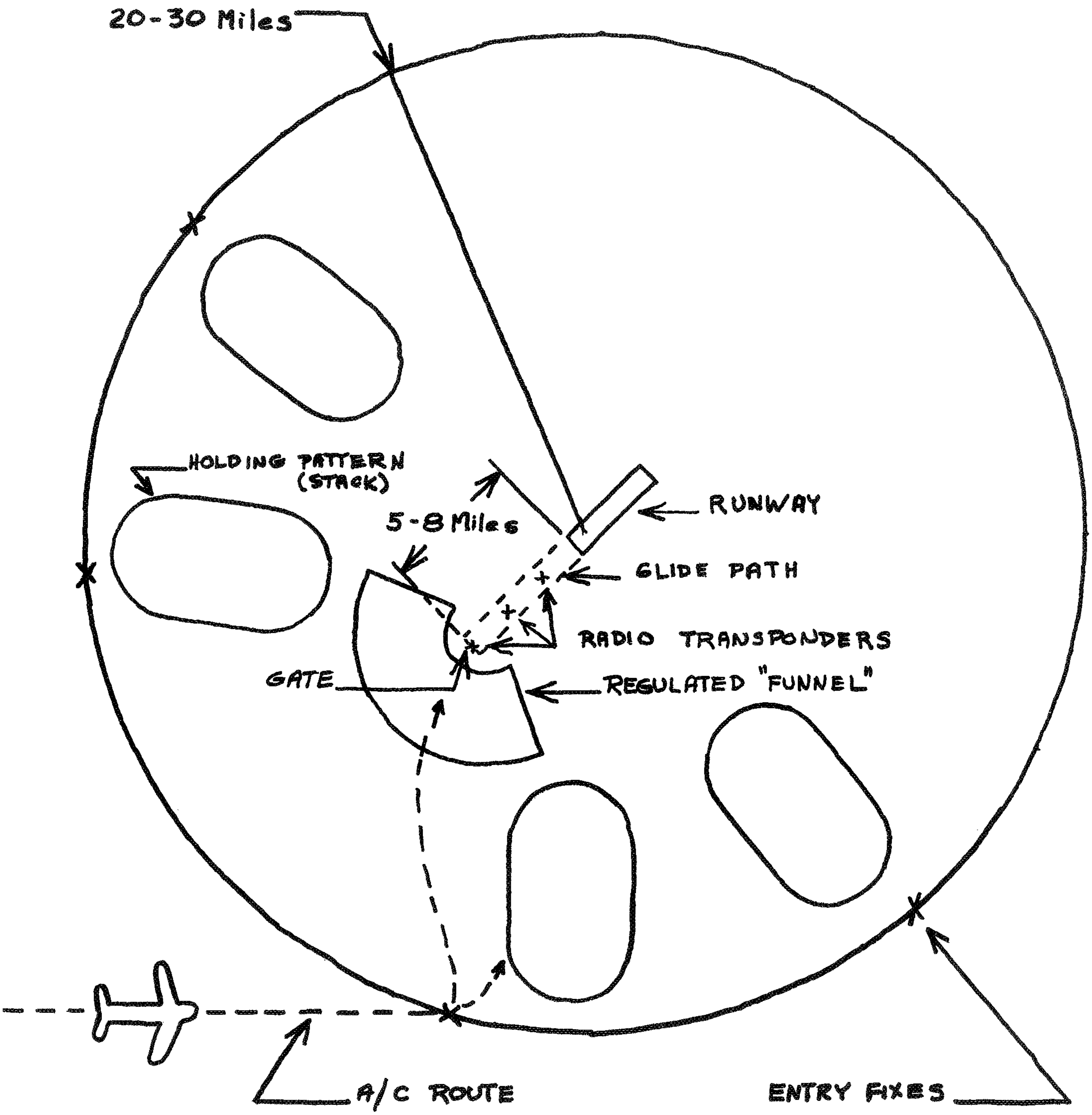
II. THE CURRENT SYSTEM

The national system of air routes and airports as it currently exists is fairly well organized. This organization of the air system was basically accomplished between 1919 (when ATC rules were first considered) and 1945 [17]. Minor changes have occurred in the past 20 years, but innovation has seriously lagged behind growth.

The air system consists of several hundred thousand miles of airway defined in the sky by VOR and VORTAC, which are VHF omni range beacons. Currently, enroute A/C use the radial beams emitted by these beacons and fly from beacon to beacon along these radial paths. A/C flying in opposite directions are separated by 1000 feet in altitude.

The U.S. is divided into many Air Route Traffic Control Centers (ARTCC). Each of these has control of a geographical area, e.g., New England. The ARTCC monitors all A/C in its area via radio and radar. When an A/C leaves one ARTCC and enters another, the controller of the area which the A/C is leaving "hands-off" the A/C to the controller of the next area via telephone. The A/C then communicates with the new ARTCC and receives such information as communication frequencies, etc. The above procedure applies to enroute A/C (those in transit and away from airport) only, which limits the ARTCC control to those A/C at altitudes over 18,000 feet.

As a subset of each ARTCC and around each airport are Terminal Areas (TMA) which have responsibility for A/C at all altitudes in an area that extends radially for 20-30 miles around the airport. Figure 1 is a sketch of a TMA. An A/C may enter the TMA through one of several entry fixes which are defined by radio beacons. At these points, the ARTCC controller hands-off the A/C to the TMA approach controller. The approach controller is aware that the A/C is due to arrive because he receives the flight plan of that A/C from its point of departure. This flight plan contains such information as estimated time of arrival (ETA), cruising altitude, speed, etc. The flight plan is



TERMINAL CONTROL AREA

Fig. 1.

updated enroute if any great changes occur in data originally sent to the TMA. However, since the ETA is by definition only an estimate, the controller actually experiences random arrivals of A/C into the TMA.

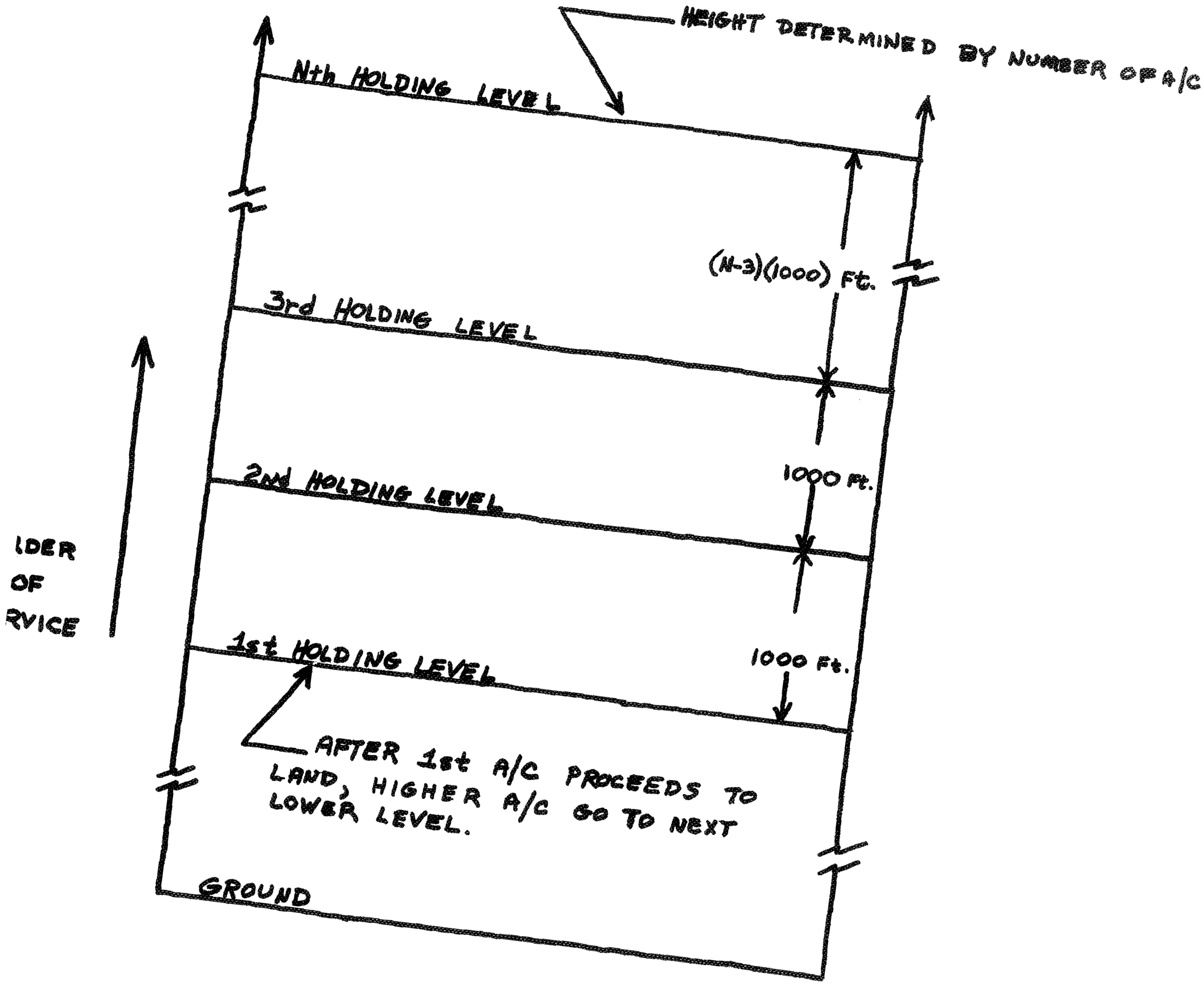
Upon entering the TMA, the A/C can be instructed to do one of two things. Either the A/C can be advised to proceed to land, or can be instructed to join one of the holding stacks and wait to be cleared to land.

If he is told to proceed to land, he enters the regulated "funnel," enters the glide path and descends to the runway.

If he is ordered into a holding pattern, he joins the highest level of the appropriate stack, as shown in Figure 2, and cycles down the stack as the A/C in the lower levels leave the stack to land. When he reaches the lowest level of the stack, it then becomes his turn to land.

There are two basic situations in which an A/C will use an airport. Visual Flight Rules (VFR) are such that A/C fly on a "see and be seen" basis. Instrument Flight Rules (IFR) indicate that A/C are being guided onto the runway with use of various equipment. IFR requires a great deal more use of the ATC system since it must in effect control the A/C. In the past, IFR use was limited to weather conditions of poor visibility, but increased density in airspace has resulted in most commercial carriers using IFR all the time when using high density airports. This accelerated use of IFR is one of the biggest problems in ATC [4]. Naturally, this does not mean that IFR use should be reduced, but that the system should be developed so as to have the capability of handling an ever-increasing IFR use.

When using the TMA under IFR, several aids enable the controlling of traffic. Holding patterns are established using radio beacons. Upon proceeding to land, the A/C uses an Instrument Landing System (ILS) to guide



HOLDING STACK

Fig. 2.

itself to the runway. Radio transponders define the glide path so as to enable the A/C to determine its position.

When an A/C is departing from a TMA, he flies a flight plan with departure control, as previously mentioned. Departure control clears the A/C to use a taxiway. When a runway is available, the A/C is cleared to depart. Departure control remains in charge of the A/C until it is handed-off to the next control area as it leaves the TMA.

There are many safety standards which complicate the above procedures. In the air, A/C are required to maintain a 3 mile horizontal and 1000 foot vertical separation from all other A/C. When A/C reach the runway, a minimum separation of 1.5 minutes is usually required to allow the runway to be cleared for the next landing [4]. For enroute A/C the minimum spacing requirements are somewhat greater (5 miles) because the greater amount of airspace allows a larger margin of safety. Thus, all of these standards as administered by the FAA are for safety's sake.

There are also departure separation standards. If two A/C are planning to fly the same course, their departure must be separated by at least 3 minutes. If their courses will diverge after 5 minutes in the air, the standard is 2 minutes, and, if their courses are completely different, the separation is 1 minute [20].

A/C could physically be flown much closer than these standards require, but equipment that the ATC system uses has some inherent uncertainty. Radar is the main system used by ATC in controlling A/C. The accuracy possible with this equipment is $\pm$ .333 nautical miles for distance and $\pm$ 2° for bearing [31]. Using this data and a little trigonometry yields the result that at 20 miles from the airport, the controller knows only that the A/C is somewhere in an area of space 1.40 miles by .77 miles. ATC knows the A/C altitude only by what the A/C tells them. Using these figures, the separation standards seem quite realistic for A/C traveling at a couple of hundred miles per hour.

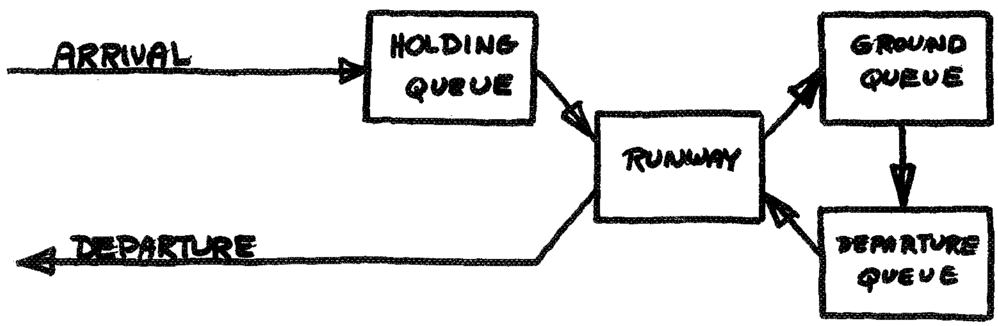
Often the controllers are skillful in avoiding situations where separation standards hinder operation. An example might be a faster A/C following a slower A/C. Here it is impossible to maintain the minimum standard constantly. When arriving A/C are too close or appear to be heading for that situation, the controllers instruct them to take courses which will delay them for a certain length of time. In other words, the A/C flies some pattern off course for a period of time so that when it rejoins the normal pattern, it has lost a desired amount of time and/or distance and thus has not violated the separation standards. Simpson [31] explains these various delaying patterns and their effectiveness. With respect to departures, the controllers usually sequence the departing A/C on the taxiway so that planes going in the same direction do not follow each other. This eliminates needless delay in meeting time separation standards.

There are many other pieces of navigational equipment in use today that are not discussed here. Basically, they are simply variations of the equipment previously explained.

Communications between ATC and A/C is via radio. During IFR situations at peak times, the frequencies available become dangerously overloaded. As an example, on an average flight from Washington to New York with a flying time of 39 minutes, there are 55 separate two-way voice communications on 11 different frequencies [3]. Telephone and teletype are used to communicate between ARTCC's and TMA's. The teletype is used to process flight plans. These are sent on paper "flight strips" which the controller manually handles and arranges in order of expected arrival. As previously mentioned, the telephone is used during the hand-off procedure.

Operation of the system is based on a "first-come first-served" basis with landings given priority over departures. Landings have priority because of the increased costs for delays in the air as opposed to those on the ground, and also for safety reasons. In communications, ground transmissions have priority over A/C transmissions. When the system is extremely busy, A/C are reduced to simply being listeners since there are no channels available [31].

The system may be modeled as a series of queues. The holding, ground and departure queues are displayed in Figure 3.



TERMINAL FACILITY QUEUES
Fig. 3.

In this context, 'ground' means all those activities which take place on the ground exclusive of landing and departing, such as loading and unloading passengers, fuel, and baggage and performance of any necessary maintenance.

Thus far the discussion has been limited to airports that have only one runway. With a few exceptions, all the rules and procedures are the same regardless of the number of runways available.

Many times multiple runways exist simply because of the variations in wind direction. If parallel runways are 5000 feet apart, then they can be used independently for departures and arrivals or for a mixture of both. Under IFR, the runway must have an ILS, but only a few of the busiest of the nation's airports have more than one. Therefore, capacity is lowered considerably when IFR is used in many airports that normally have multiple landing capability.

The ATC system as it currently exists with its many variations (i.e., geometry, number of runways, etc.) at different airports is fairly well-defined, but it is difficult to produce a complete understanding in a few pages. Some of the discussion that will follow in the next chapters is the result of research directed at comprehending the ATC system and its problems.

III. GENERAL MANAGEMENT

The publications in the previously defined general management area provide a clear definition of many of the broad problems as they currently exist.

As with most concerns in the public domain, the problems are more than technical. Schiever [29] indicates that society has a right to have a say in the way in which their transportation systems are designed. This is an extremely important concept because society must know how to use its systems. An airport is often built on the outskirts of a city so that the effect of noise will be limited. There is a need for some way of keeping people from building their homes next to the airport for convenience and then complaining about the noise of the A/C. With respect to ATC, a priority system can be designed so that faster A/C always are allowed to land first. This increases the capacity of the airport, but provides such uneven service that the owners of slower A/C will vigorously protest [22]. More and more, the taxpayer is having the final say on where the government money will go.

Many experts such as Kressner [19] feel that the SST (supersonic transport) and the other "jumbojets" are the answers to all of the ATC problems. It would seem that these A/C will only forestall the problem as the advent of the first jet carriers did in the early sixties [31].

A great deal of clamor is currently focused on automating the ATC system. Many of the routine clerical tasks performed by the controller can certainly be automated [1], [5]. Taylor [32] has indicated that automation is to be utilized in the future if the planners have their way. Holden [26] indicates that the computer might be used for tasks a great deal more sophisticated than flight strip processing and scheduling. He feels that manual conflict detection may no longer be feasible. It is important to realize that a system is not automated overnight and intermediate plans are needed [10]. A beginning might possibly be the simple use of computerized scheduling and a little coordination. As the FAA points out [26], such automation would smooth out some of the peak situations that occur when all flights are scheduled on the half-hour, on the hour, and during obviously overloaded periods.

Such general discussions of the ATC system as those in Gilbert [17] and in Schiever and Seifert [28] provide a background regarding the problems of the ATC. They have not changed to any great extent in the past 25 years. The basic reason for the situation as it currently exists is that the system simply evolved; it was not planned. Systems planners are coming to realize that a big management drive is going to be necessary to get the ATC system into shape.

Now that the U.S. is finally admitting that the ATC system has serious problems, some funding is being provided to help remedy the situation, but sometimes initiative is slowed by bickering and politicking [3]. The support source is far more limited than it was for such a task as Apollo, however, and general management has the problem of solving the ATC troubles in a more efficient manner than they are used to doing.

In the past, needs were indicated and then forgotten [17]. If they are forgotten this time, it may be the last time thay they need be mentioned [3].

IV. OPERATIONS RESEARCH

OR often has the difficult task of defining problems and possible solutions before much interest or funding exists for research in a specific area. This is especially true of public systems work, which has only recently gained the attention that was once given weapons systems planning. This is perhaps the reason why a lot of OR work has not been done in ATC.

OR began studying ATC in England soon after World War II. Bell, Bowen and Pearcy [6,7], English authors, published several papers basically concerned with a probabilistic analysis of ATC delays. England's problems are not so severe as those of the U.S. airports, but she has been supporting research in the area for over 20 years. They have a government-supported professional group composed of OR specialists and others whose sole responsibility is evaluating the total spectrum of ATC problems [2].

OR work in the U.S. was initiated by Blumstein in the late fifties. Several researchers have done some interesting work since then.

In general, OR studies performed have been of two types. Analytical investigations have been accomplished which for the most part involve many extensive mathematical derivations that would be above the comprehension or interest of the non-OR reader; however, such works will be discussed in this report in a simplified manner to facilitate understanding and point out important assumptions and results. Simulation is the other type of OR study that has been produced. This is easier to discuss, but unfortunately not many simulations have been performed.

Research has been directed into three general areas of study:

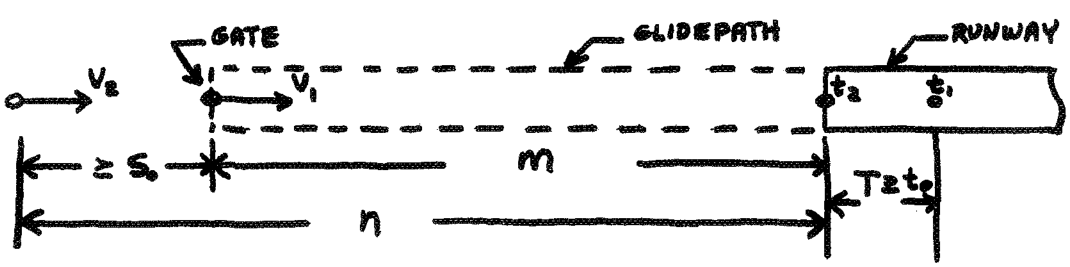
1) Runway capacity
2) Delays
3) Effect of different priority schemes.

Capacity

Runway capacity studies had their beginning in England with Bowen and Pearcy [7]. They simply defined capacity C as equal to the reciprocal of the minimum time separation standard at the runway, t_o. This is somewhat optimistic in that it assumes 100% efficiency. However, they qualify the statement by including that A/C using airports that are operated at capacity will experience infinite delays. This study concluded that capacity is very definition-dependent and that the actual average number of A/C that can use an airport is dependent on the distributions of velocities, types of A/C, arrivals, and service times. Blumstein was the first in the U.S. to consider runway capacity [9]. He makes several limiting assumptions for this analysis:

1) A/C land in the order that they appear at the gate
2) A/C arrive independently and randomly
3) A/C maintain distance/time separation standards
4) The runway is used for landings only
5) A/C maintain constant velocity once they enter the gate

Figure 4 will be used to explain his approach.



where S_o = minimum distance separation,

t_o = minimum time separation,

V_i = velocity of i^{th} A/C,

t_i = time i^{th} A/C reaches runway.

Blumstein's Capacity Model
Fig. 4.

The time between landings is given by

$$T(V_1,V_2) = \begin{cases} \frac{n}{V_2} - \frac{m}{V_1} , & V_2 \leq V_2^* \\ t_0 , & V_2 \geq V_2^* , \end{cases}$$

where V^* is such that

$$T = t_0 ,$$

and

$$V_2^* = \frac{nV_1}{V_1 t_0 + m} .$$

Assuming a velocity distribution

$$f(V_1 , V_2) = \begin{cases} \frac{1}{(b - a)^2} , & a \leq V_1 , V_2 \leq b \\ 0 , & \text{otherwise} , \end{cases}$$

the average time interval between landings becomes

$$\tau = \int_{V_2}\int_{V_1} T(V_1 ,V_2) \; f(V_1 , V_2)dV_1 dV_2 = \frac{S}{b - a} \ln\left(\frac{b}{a} \right) .$$

The average landing rate λ is then given by

$$\lambda = \frac{1}{\tau} = f(\overline{V}, m, t_0, S_0) ,$$

where $\overline{V}$ = the average velocity.

Using the above, he concludes that

1) λ decreases as m increases

2) λ is only effected by t_0 if $m \leq 2.5$ mi., $S \leq 3.0$ mi.

3) λ increases with increasing mean velocity $\overline{V}$

Basically, the best improvement in λ occurs with decreases in S_0 and decreases in the variance of the velocity distribution.

Odoni [20] carries Blumstein's work farther by eliminating the assumption that A/C maintain distance separation standards. The time between landings then becomes:

$$T(V_1,V_2) = \begin{cases} \dfrac{m+x}{V_2} - \dfrac{m}{V_1} & \text{if} \quad \dfrac{m+x}{V_2} - \dfrac{m}{V_1} - t_o, \\ t_o & \text{otherwise} \end{cases}$$

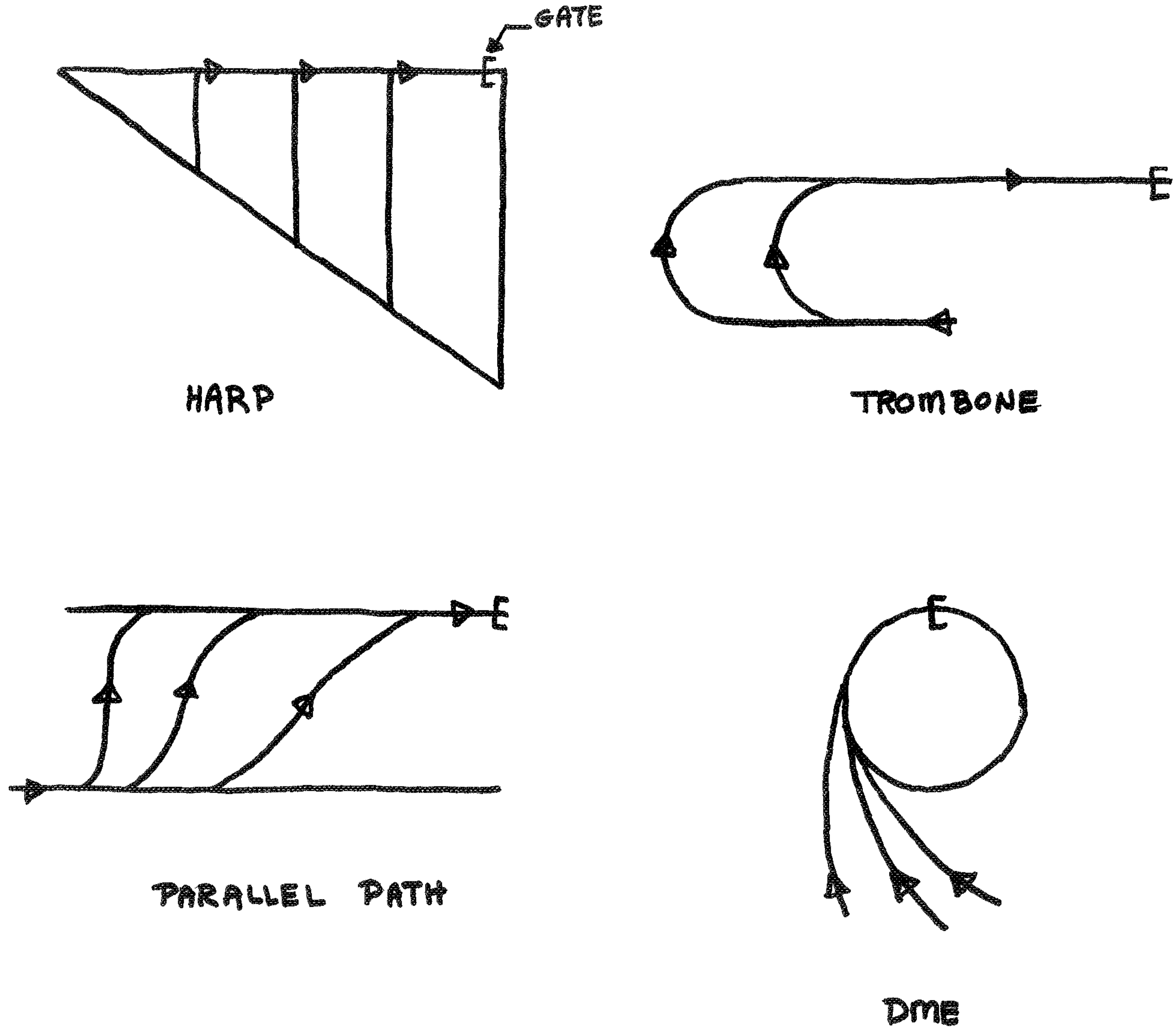
where x is a random variable measuring the error in separation distance. Odoni uses several possible distributions for x and the results are somewhat complicated, but his conclusion is important. Runway capacity is more sensitive to x than any other parameters, such as runway geometry and velocity distributions. He also develops capacity models for runways with departures only, alternating landings and departures, and interposing departures whenever gaps in the arrival pattern occur (i.e., priority to arrivals).

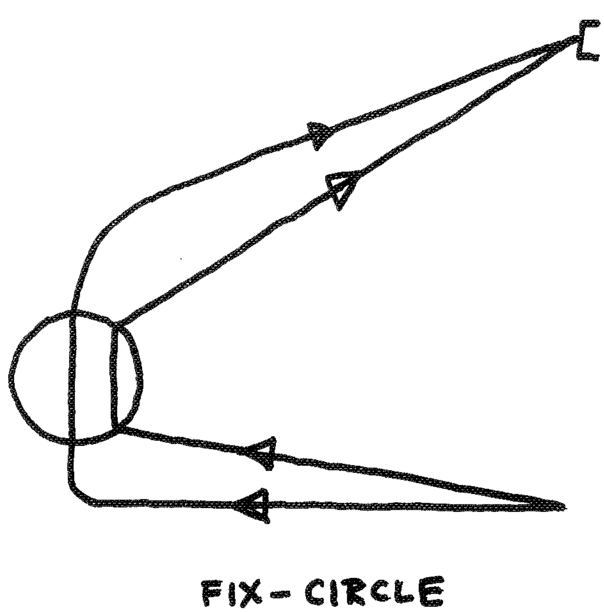
Jackson [18] has developed a simulation to study the error at the gate for landing A/C. He uses several approach geometries as shown in Figure 5. He presents no numerical results, since they depend on many factors, but the availability of a model that measures the variance of schedule error at the gate with respect to varying approach geometries would seem pertinent to Odoni's work.

A graphical explanation of how separation standards can affect capacity appears in Anon [4]. They suggest that if time separation standards at the runway are slightly increased, departures will be possible between landings and capacity will significantly increase. While no analytical proof or data is provided, this concept agrees with that developed by Odoni. Oliver [2] also discusses departure capacity for runways with departures only.

Porter [23] develops an algorithm which allows the trajectory of incoming A/C to be optimized so minimum separation standards can be maintained and capacity correspondingly increased. This model assumes no wind or weather effects on the A/C, and therefore that the pilot can perform optimum movements.

Simpson [31] suggests a change in the time and distance separation criteria and determines the effect of this change. By using time separation standards at the gate instead of distance separation standards, the capacity can be significantly increased. The standard would depend on the velocity of each A/C so that





JACKSON'S APPROACH GEOMETR

Fig. 5.

time separation standards at the runway could be met.

Thus, most researchers have found that separation standards are the key to runway capacity. These standards are perhaps the greatest limiting factor with respect to any possible ATC solutions.

Delays

A/C delay is perhaps one of the problems easiest to understand of all those confront the ATC system. While the public may not understand capacities and separation standards, they readily comprehend what a delay is.

Again , Bowen and Pearcy [7] were the first to study this problem. They assumed random arrivals at a rate m and defined a utilization factor Υ where

$$\Upsilon = \frac{m}{C} \, .$$

They determine that the average delay W per A/C is given by

$$W = \frac{1}{2}\Upsilon.$$

While this is the average delay, the distribution of delays that they determine yields the fact that some A/C will be delayed until infinity. Pearcy later refined the above to

$$W = \frac{\frac{1}{2}\Upsilon^2}{1 - \Upsilon} \, .$$

This allows the average delay to approach infinity as the utilization approaches one. This result is more agreeable than their first.

Oliver [21] provides an extensive investigation of A/C delays. His discussion is in queuing theory jargon and in that sense he assumes Poisson or random arrivals at a rate λ and constant service times Δ .

For a single runway, he determines that the average number of A/C waiting in the queue to land, $\overline{N}_W$, is given by

$$\overline{N}_w = \frac{\lambda \Delta^2}{2(1 - \lambda\Delta)} \, .$$

Defining a utilization factor $\rho = \lambda\Delta$, he uses Erlang's formula for the probability that a delay is less than or equal to t (exclusive of runway occupancy time).

$$W(t) = (1 - p)e^{\lambda t} \sum_{j=0}^{k} \frac{(jp - \lambda t)^{j}}{j!} e^{-jp},$$

where $kp \leq \lambda t \leq (k + 1)\, p$.

For a large number of A/C, the average number of A/C delayed $\overline{N}d$ is given by

$$\overline{N}d = \frac{p}{1 - p}.$$

If a distribution of service times is used (as opposed to constant service times) and random arrivals are assumed, the average delay W is

$$W = \frac{\lambda b^{(2)}}{2(1 - \lambda b)},$$

where λ = average arrival rate,

b = average service rate,

$b^{(2)}$ = 2nd moment of service time distribution.

Oliver assumes an Erlang distribution of service,

$$b(t) = \frac{K\mu(K\mu t)^{K-1}}{(K - 1)!} e^{-K\mu t},$$

where $\frac{1}{\mu}$ = average service time,

$\frac{K}{\mu^2}$ = variance in service times,

$\frac{1}{\sqrt{K}}$ = coefficient of variance.

Using this he determines that

$$W = \frac{\lambda(K + 1)}{2\mu K(\mu - \lambda)}$$

where the freedom to choose K and μ allows one to model a wide variety of realistic service operations. If K = 1, service is exponential or random. If K is large, then service times are essentially constant.

Odoni [20] also uses a queuing theory approach to delays, but he modifies it to fit the problem better. His goal of accuracy yields very complex results so that he only solves his models for some specific cases.

Wisepart and Warskow [33] provide an analysis of a limited amount of data and reach the conclusion that the average delay to an A/C is directly dependent on the runway occupancy time that it requires.

Most of the approaches to delays are empirical or use classical queuing models. The assumptions needed to use standard queuing models have been investigated [6] and seem reasonable. Empirical results have as yet been somewhat limited owing to the time and expense of gathering data. Most studies conclude that delay is primarily dependent on the utilization factor. Also, the average delay does not give a full picture of the situation since many A/C will experience waiting times longer than the average. Thus, the probability that no delays will be greater than a certain length of time is a more informative statistic.

Priority Schemes

By changing the priority of the system to other than "first come-first serve" and "all landings first," the capacity of the airport and the delays to A/C can be significantly changed.

Pestalozzi [22] studied the effect of priority rules on delay and delay costs. He assumes random arrivals and service times as independent random variables from distributions specific to each priority class. The following rules are used:

1) Landings have priority over departures.

2) The first customer to enter service is the one with the highest priority in the waiting line.

3) The method attempts to minimize average delay for all A/C or average delay cost.

4) The A/C population is divided into classes with similar characteristics with respect to runway utilization time and delay costs .

The average waiting time $\overline{W}_j$ for the j^{th} priority class of K classes is given by

$$\overline{W}_j = \frac{1}{2}\lambda b^{(2)} \frac{1}{(1-\rho_{j-1})(1-\rho_j)},$$

where j = 1, 2, ..., K with class 1 having the highest proirity and

$\lambda_j = j^{th}$ arrival rate,

λ = total arrival rate = $\sum_{j=1}^{K} \lambda_j$,

b_j = mean service time for j - customers,

$b^{(2)}$ = 2nd moment of service time distribution for all customers,

$\rho_j = \sum_{i=1}^{j} \lambda_i b_i$, $\rho_o = 0$.

The total average delay for all A/C is given by

$$\overline{W} = \sum_{j=1}^{K} \frac{\lambda_j}{\lambda} \overline{W}_j .$$

Using the cost of delay C_j for j - customers, the average cost of delay is

$$\overline{C}_j = \overline{W}_j C_j .$$

The overall cost of delay is

$$\overline{C} = \sum_{j=1}^{K} \frac{\lambda_j}{\lambda} \overline{C}_j .$$

Pestalozzi found that $\overline{C}$ is minimized if the priority ranks are assigned to the classes in order of increasing ratio $\frac{b_j}{C_j}$:

$$\frac{b_1}{C_1} \leq \frac{b_2}{C_2} \leq \cdots\cdots \leq \frac{b_K}{C_K}$$

He concludes that the priority system did not effect average delay, but average costs were cut. However, he admits that quite uneven service is provided because many low priority A/C wait an extremely long time. He remarks that if landings are not given priority, the runway capacity is increased. It would seem that this would not be a minimum cost solution. Also, instead of considering average delay, using the probability of no delays longer than a certain period would certainly be applicable in this situation.

Oliver [21] examined several aspects of priority classing. He found that delay is only significantly affected when using a priority system if the service times of each class are materially different. He develops techniques for determining where the optimal points are to divide a population into classes considering landings and departures separately and as mixed operations. Because of the high cost of delay in the air, he found that landing must be given priority. He accomplishes this by grouping or platooning the arriving and departing A/C to minimize delay. Odoni [20] also considered this idea of platooning where lumps of arrivals are processed until a gap occurs and then a group of departures use the runway.

On the whole, studies of possible priority groupings have not found any systems which greatly improve the current approach. Platooning as discussed by Odoni [20] and Oliver [21] may be the exception.

Simulation

As previously mentioned, simulation has not yet been widely applied. Blumstein [8] did not obtain any numerical results, but his work showed the possibilities of simulation.

Simpson [31] developed what appears to be a sophisticated computer model to investigate different A/C approach and stack geometries. He did not produce any numerical results, but was able to complete testing of his program. He feels that the performance of the computer demonstrated its superior ability in making ATC decisions as compared to a human controller.

Jackson [18] has developed a simulation of arrivals. The numerical results depend on many factors,which he enumerates; these factors must be determined before a system is simulated.

Simulation is in the growing stage in ATC, but it appears that the ATC system is so complex that computer models will become popular.

Discussion

While there have not been many OR studies performed, the results are extremely valuable in gaining insight into causal relationships in ATC. Some of the underlying assumptions used in these studies should be discussed.

Arrivals into the system are assumed random. While A/C are supposedly on a schedule, when the density of A/C is high and natural errors in arrival times result, arrivals become random. This is limited to high density operating times, but these are the times when ATC problems are greatest and so the assumption of random arrivals does not limit application of OR's results.

Most investigations that consider the dynamics of the A/C assume no wind [23] or constant wind [31]. This assumption is limiting since varying wind situations often inhibit a pilot from making the exact maneuvers that the controller instructs him to perform. Further studies should perhaps consider some distributions of wind directions and velocities.

The distributions that are used for service times do not appear to have been verified to the extent that the arrival distribution has. The effect of various parameters such as weather and time of day might be included in such an investigation.

However, using all of these assumptions, several basic factors which influence ATC problems have been determined.

Separation standards and the error in maintaining them seem to be the crux of the problem. Minimizing these separations while maintaining safety can greatly increase runway capacity.

Also, populations of A/C which have widely varying characteristics can create a sluggish system. Priority classes can be created to smooth out the situation, but the uneven service that results is especially objectionable to the low priority A/C.

Different approach geometries can have effects on delays and capacity. These geometries often depend on the specific airport. Simulation is a convenient technique for study different approach patterns.

These are some of the problems that OR has defined. It now becomes the task of Design to change the system accordingly. The next chapter will discuss what has been accomplished.

V. DESIGN

Until recently very little equipment design was performed with ATC specifically in mind. Raben [27] lists some of the design projects carried out in the late fifties. Some companies have been involved with ATC throughout its years of development and have produced various types of equipment [11]. However, the "state-of-the-art" has advanced much more rapidly than ATC equipment and it is only in the past couple of years that technological innovation has been applied to ATC.

Design efforts include the areas of detection, communication, and display of information. Naturally, a great portion of the work is also focused on the interfaces between each of these areas.

ATC detection is accomplished using radar of World War II vintage. As previously discussed, its capabilities are limited, but higher accuracy equipment is available [31]. Detection between A/C can utilize this radar, but currently Collision Avoidance Systems (CAS) and Proximity Warning Indicaters (PWI) are being designed to aid in the vital problem of conflict detection and avoidance. Ebert [19] provides a thorough discussion of these systems. They were first proposed in 1955 and three years ago McDonnell Douglas Aircraft put such a system into use. They have yet to achieve wide acceptance because of the expense involved.

The established requirements for the CAS system are:

1) Detect all A/C without exception or false alarms.

2) Evaluate the nature and the degree of the threat or possible conflict posed by the detected A/C.

3) Decide if evasive maneuver is required.

4) Indicate the necessary evasive maneuver to the pilot in a manner that needs no interpretation.

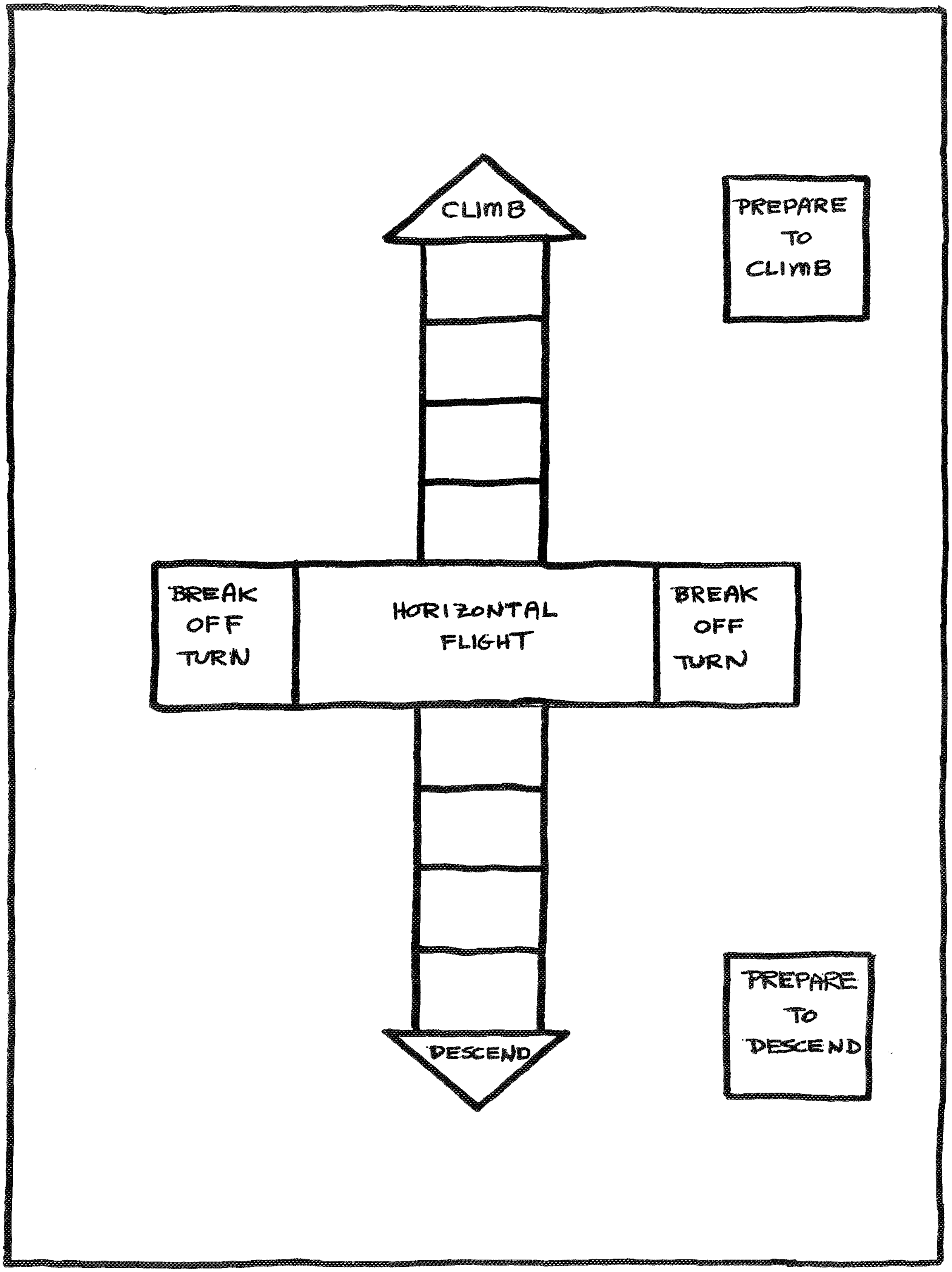
The criteria for judgements will be based on relative altitude, range, and range rate (velocity) of the conflicting A/C. A generalization of these criteria is the Tau factor where

$$\text{Tau} = \frac{\text{relative range}}{\text{relative range-rate}}$$

This is a good criteria above speeds of 216 knots, but below this a minimum separation of 1.5 miles is used. Therefore, the pilot receives a command for an evasive measure if one or more A/C find themselves at the same flight level and either the Tau factor reaches a predetermined value or the range between the A/C is below the minimum. The display system used for this CAS system is pictured in Figure 6. Lights on the display tell the pilot what evasive action should be taken. The range and range rate are determined by time differences based on high accuracy, calibrated standard clocks on board each A/C. Cesium or rubidium clocks are excellent though expensive. Thus quartz oscillators can be used, but must be frequently calibrated with the ground. This technique of collision avoidance is superior to the interrogate/respond principle via radio because the A/C need not individually communicate with each other.

The CAS is still fairly expensive with a quartz oscillator ($30-50,000) so a PWI is being designed to be less expensive, although it will have less capability. This system will simply inform the A/C of other A/C in the area and provide semi-accurate bearing, range, and altitude measurements. The basic technique used in the system will be the evaluation of the red component of a flashing Xenon lamp. A laser-employed technique has also been suggested for conflict detection along with several transponder methods.

Powell [24] describes a system developed by Decca Navigator Co. called Harco. It is an air navigation system that uses a computer and data links for communications between the air and ground. It is designed to work with the presently available beacon stations. Decca is not the only company considering



CAS DISPLAY

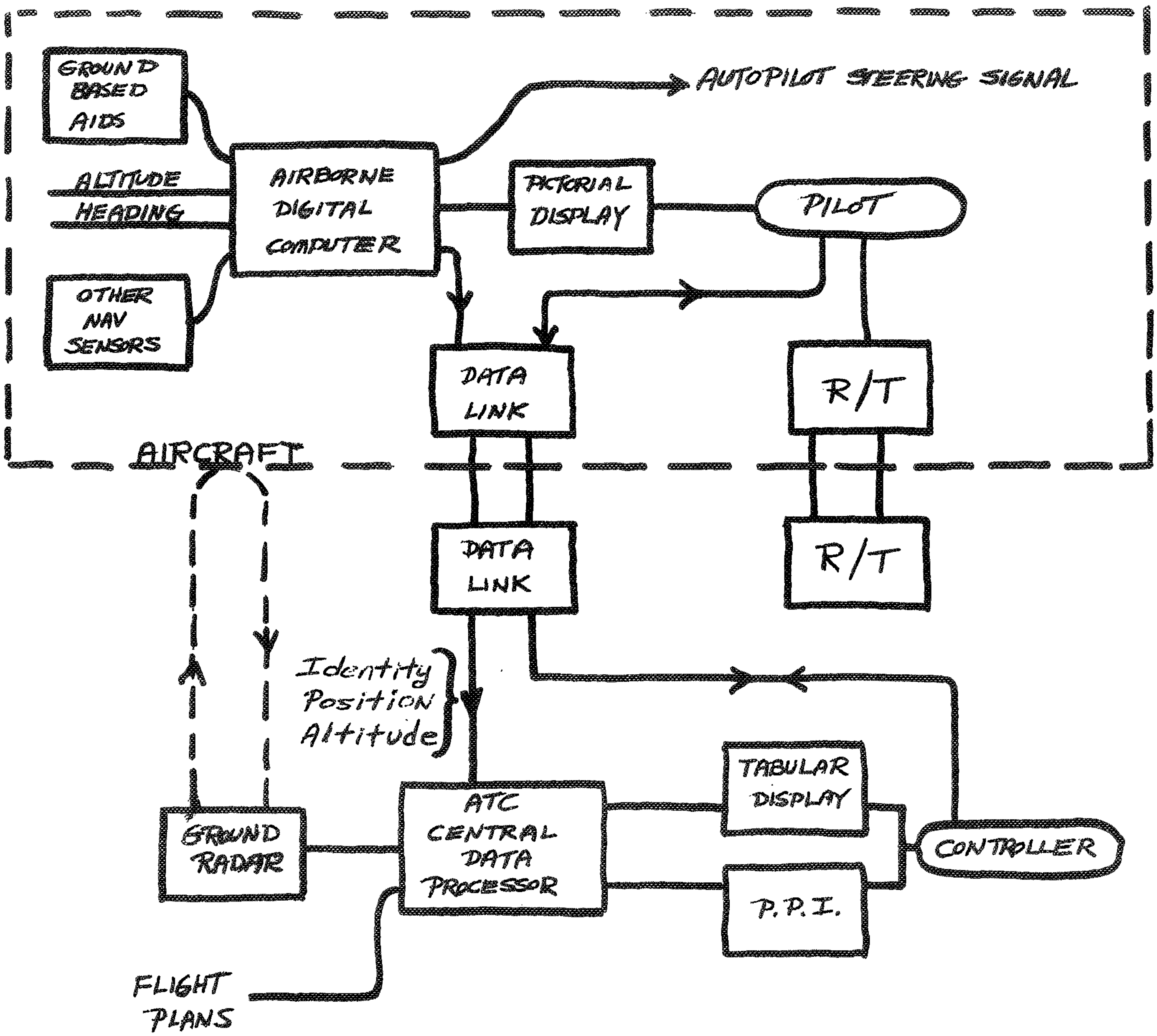
Fig. 6.

the use of data links for communications; this is currently a popular idea. Figure 7 illustrates an integrated ATC-HARCO system. A system called NAVSAT is being considered which relies on 2 or 3 satellites and also uses data links. This system is supposedly inexpensive and highly accurate [16]. Digital processing of radar information should allow more efficient processing of data. A system which employs this concept is now being suggested [15]. It utilizes smaller frequency bands for communications than the conventional, sometimes overloaded system. A completely automated system is stressed which of course requires high reliability. Figures 8 and 9 can be used to compare the conventional system and this proposed ATC system.

Displays are of great interest to both the pilot and controller. Decca Navigator has proposed a pictorial display for use by the pilot [25]. The display is basically a moving map or chart, as shown in Figure 10, with a stylus representing the A/C and the pilot viewing his A/C as moving relative to the map (he sees this either directly or as a projection). The map is driven by a computer which accepts range and bearing inputs. The path of the A/C is recorded as the pilot follows the display and he can follow traces already on the map. This is suggested as an ATC aid. If a projection-type pictorial display is used, films can be used instead of maps or charts.

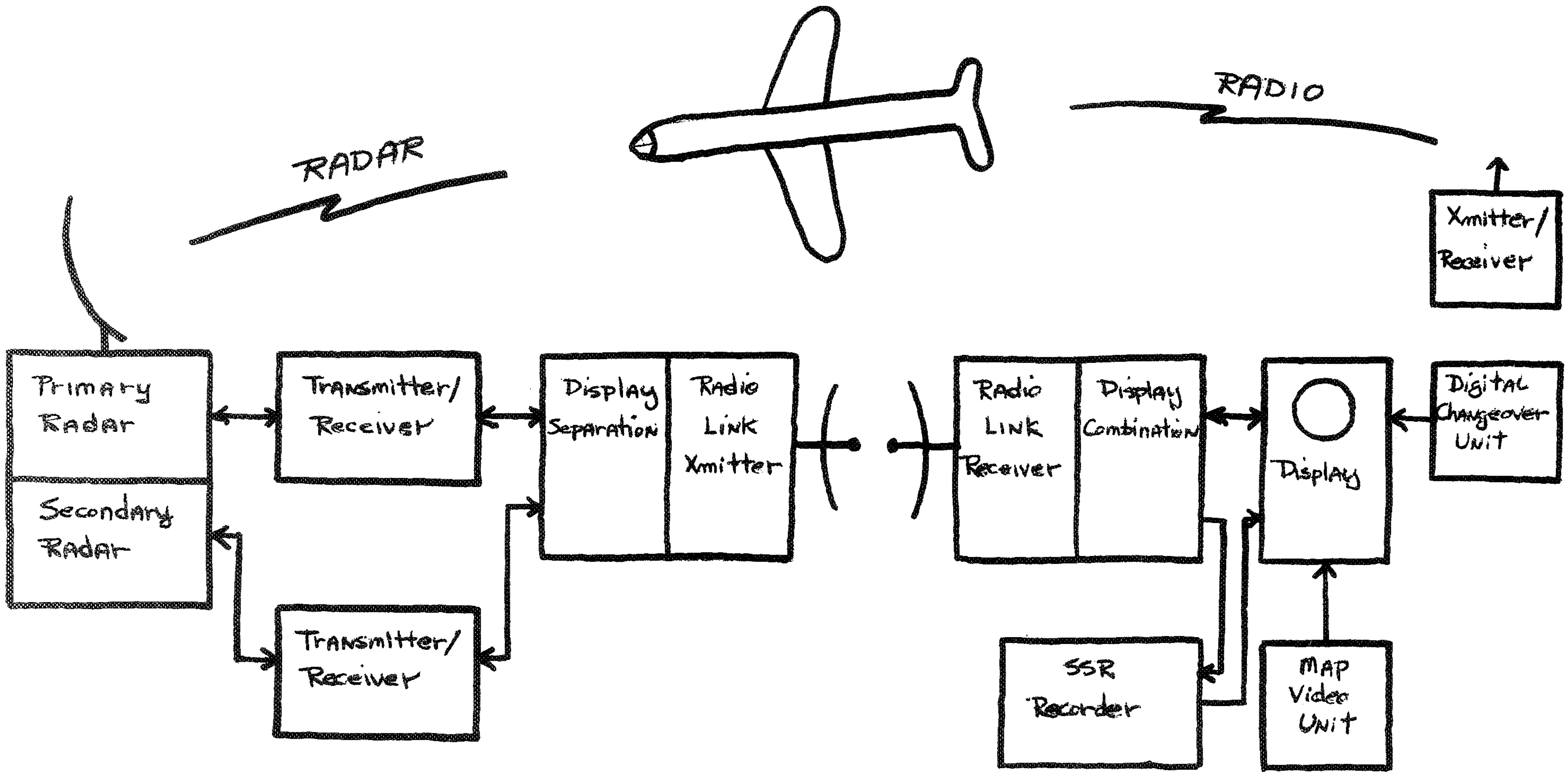
To aid the controller, alphanumeric displays are being designed which provide all pertinent information concerning each A/C on the radar screen beside the A/C blip, thus eliminating the necessity of the controller's manually writing down this information. This system utilizes a computer. Many of the problems with the system, such as radar sweep-time reduction, have been solved [13] but a basic difficulty still exists; that is, when traffic becomes very dense alphanumeric information overlaps and becomes unreadable.

Some government-supported design programs have been undertaken. The



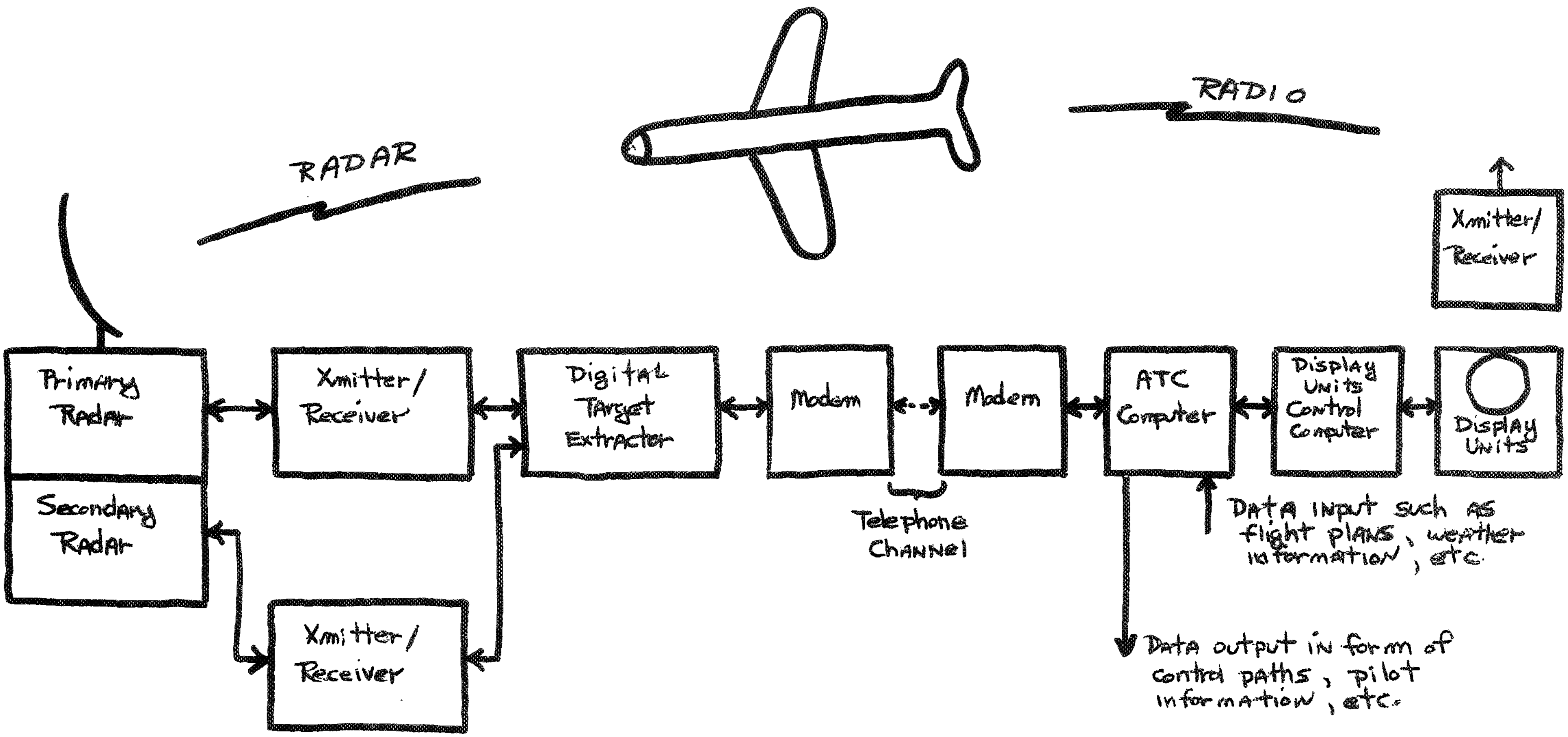
INTEGRATED ATC - HARCO SYSTEM

Fig. 7.



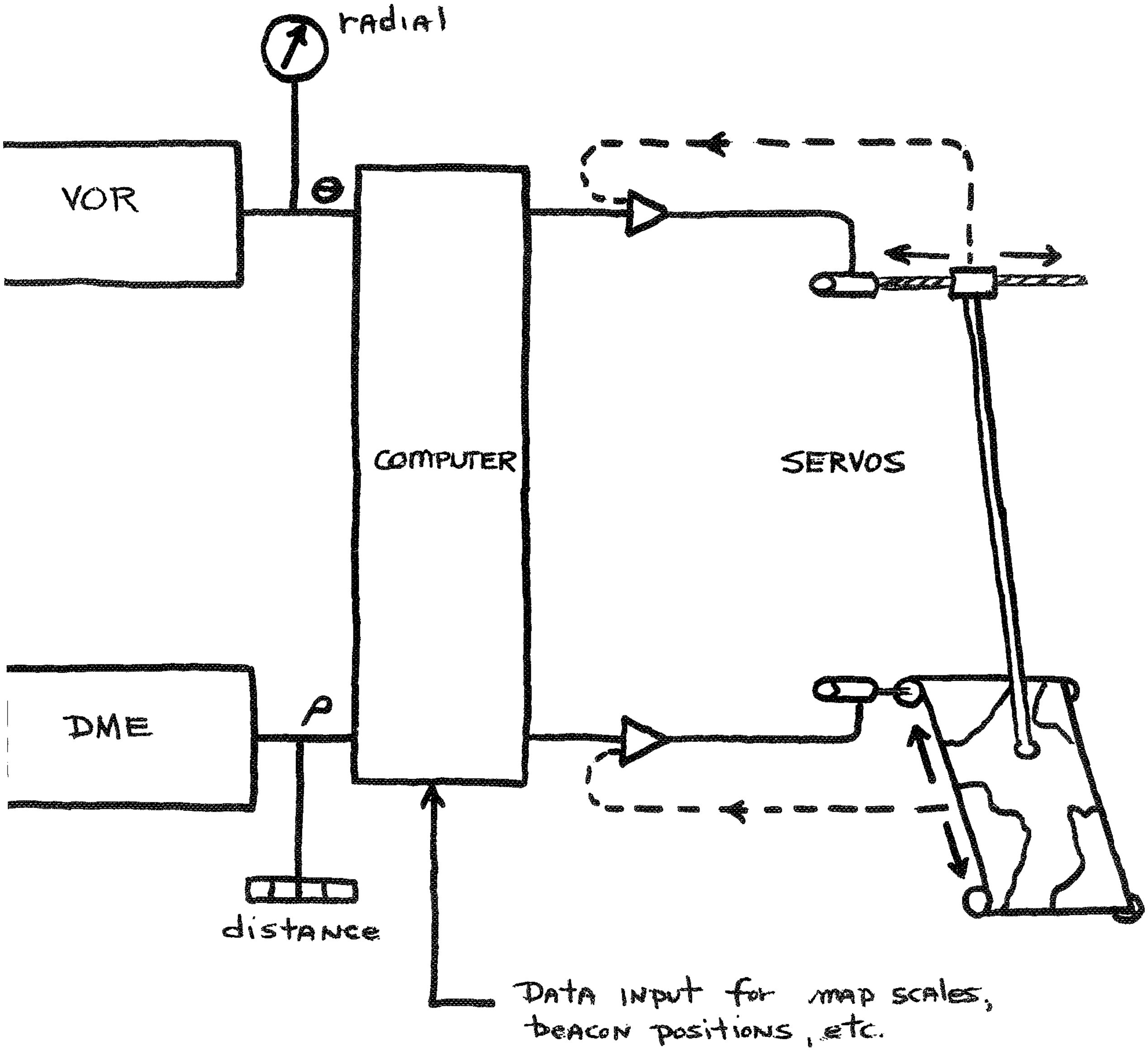
Conventional ATC System

Fig. 8.



Automatic ATC System

Fig. 9.



Basic Decca Pictorial Display

Fig. 10.

FAA is introducing a highly automated radar terminal system known as ARTS-III. This system puts a transponder in each A/C and uses alphanumeric techniques [3]. Partial automation is also being introduced into the enroute portion of the system under a program called Stage A of the National Airspace System (NAS). NAS Stage B will involve more sophisticated software for the Stage A computers. Systems for computer-aided approach spacing (CAAS) and speed-class sequencing (SCS), which arrange A/C according to performance characteristics, are being considered [4]. The FAA is evaluating these and other ideas at facilities such as its Experimental Center in Atlantic City (NAFEC). The as yet unpublished report of the Alexander Air Traffic Control Advisory Committee [32] will propose:

1) A modified beacon system using data link capabilities
2) Phased-array beacon antennae which will yield higher accuracy and data rates
3) Extention of NAS A and ARTS to include separation, conflict prediction and conflict resolution
4) A decrease in A/C and runway separations
5) A scanning beacon microwave ILS system

Many of the above systems utilize the concept of area navigation. This could be extremely helpful because it would eliminate the necessity for A/C to fly directly toward or away from a VOR on a radio beam. Area navigation allows the pilot to shift the position of a VOR to a new "phantom" VOR. In this way A/C can fly in parallel lines instead of single lines. The FAA has already established several area navigation routes [4].

There are many other pieces and types of equipment that are being designed. They are basically variations of those discussed here and are too numerous to mention. It is easy to see the trend toward automation, but it will not and cannot happen overnight [10]; some intermediate solutions are needed.

To insure that the air system can economically survive, some basic questions need to be answered.

A designer usually likes to redesign the system completely and throw out the old system. The ATC problem is of such magnitude that this may not be feasible. Thus many compromises will be made before any conclusions are reached, although any solution should answer these questions:

1) What is the purpose of the controller?
   a. Is he needed?
   b. What should his tasks be?

2. Can automation solve all the problems?

3. Should uniform service be provided to all types of A/C?

4. Will any proposed system be adaptable to unforeseen requirements in the future?

These are basically design questions. Management and OR have shown that here is where the problems exist and design must now decide what can be done to solve these problems.

Discussions of these questions will be left to a later chapter, since they are basic to general ATC problems rather than particular ones.

VI. SUMMARY

The preceding sections of this report have been aimed at gaining an understanding and familiarity of the ATC system and research that has been performed in an effort to solve the system's problems and improve its operation. The purpose of this section and the next is to derive some meaningful conclusions about what has been accomplished and what should be attempted.

Air traffic control has one basic purpose, which is to organize a random input to the system into an orderly flow in such a way that a safe and efficient operation will result. As previously discussed, management has indicated that some problems with the ATC system exist, OR has used available techniques to study and dtermine the possible causes of these problems, and Design has attempted to produce a system that minimizes the effects of these causes.

This indicated basic problem may be simply stated: The ATC control system as it currently exists is unable to service the volume of A/C that economy requires without these A/C experiencing costly delays that may be a detriment to a safe operation of the system.

Delays are caused when the system does not have the capacity to service A/C that it receives. Capacity can be defined as the maximum number of A/C that the system can service per unit time. The FAA defines capacity numerically in terms of delay. The delays that A/C experience are related to the utilization rate of the airport, or, in other words, how close to capacity the system is being operated. Hence, a discussion of delay or capacity necessarily includes both these parameters.

Before determining what are the basic causes of delay, it is best to define a measure of delay. Most sources use the average delay in their discussions. While this has meaning, the variance of the delay is also essential to any discussion. A system with an acceptable average delay may have a variance so large that an appreciable portion of the A/C entering will experience extremely long delays. One reference [33] attempted to assign some confidence limits to empirical data, but an analytical determination of an upper limit of delays is required, i.e, a delay limit such that there is a specified probability that an A/C will not experience a delay greater than this limit. Oliver [21] has considered this type of delay measurement, but most of the previous work of others concerns average delay. Thus, many important results will be summarized in the context of average delay and later extended to include delay variance.

A portion of the ATC system that is the cause of many bottlenecks is the glide path and runway. This is pictured in Figure 4. When A/C reach the gate they must be at least 3 miles apart and when they reach the threshold of the runway they must be separated by a time t_o, where t_o varies from .5 to 3 minutes from one airport to another due to local situations. If a fast A/C is following a slow one, the separation at the gate must be substantially larger than 3 miles if the t_o separation is not to be violated at the runway. Conversely, if a slow A/C follows a fast A/C, the separation at the gate will be 3 miles, but the separation at the runway will be substantially greater than t_o. Thus, in either situation airspace is wasted and delays are increased.

This could be solved using a sliding separation standard at the gate with respect to the relative velocities of the A/C [31], but this would complicate ATC procedures. As Blumstein points out, a shortening of the glide path would also help this situation. Blumstein and Odoni both indicated the affect of variance of the A/C velocity distribution on the glide path-runway combination. Odoni carried the analysis further by considering the error in spacing A/C coming through the gate. It was found to have a notable affect on capacity and delay.

Therefore, capacity of the system and delay of A/C due to the glide path and runway is primarily affected by:

1) The type and magnitude of separation standards

2) Relative velocities of the A/C

3) Positioning error at the gate

4) The length of the glide path

Separation standards reflect the accuracy of equipment used by the ATC system. Design has produced several ideas to increase this accuracy, but new equipment has not yet been installed because of several reasons. First (and most importantly), it takes several years to build and test prototypes, train controllers and pilots, and introduce major changes into the ATC system. Also, of the possible alternatives for equipment, a definite choice has not been made. Finally, system planners hope to solve ATC's problems for now and for the future and so are not willing to accept solutions that will not have lasting effect.

Separation standards are basically safety measures. Systems such as CAS and PWI are well on the way toward being utilized. This may eventually allow the reduction of separation standards since the controller would no longer be the only decision-maker responsible for conflict resolution.

The velocity distribution of A/C can be affected in several ways. All A/C can be required to fly at approximately the same speed, although with the great variety of types of A/C using an airport, this may not be possible. A priority system could be used where A/C with the shortest glide path-runway occupancy times were given highest priority and those with the longest times were given lowest priority. Intuitively such a system yields very uneven service and slower A/C would never get a chance to land [22]. This problem could be solved by only allowing certain types of A/C at specified airports, but this solution would somewhat limit the genral aviation pilot's freedom; still, it would help some of ATC's problems.

Positioning error at the gate is dependent on two factors: inaccuracy of the equipment and the ability and attitude of the controller. A controller's ability can be generally regarded as adequate, but his attitude tends to be cautious because he realizes the limits of his equipment and that A/C do not and/or cannot always follow his instructions. A/C often find that the geometry of the approach pattern to the gate has tremendous affect on the error; i.e., A/C are dynamically limited with respect to maneuvers that they can perform. However, these geometries cannot be arbitrarily changed because they are a function of such things as other approach patterns and noise abatement procedures and, also, the geometry of holding stacks limits the A/C from responding to the controller's instructions. Different patterns have been suggested [31]. Thus, decreasing positioning error depends on a better understanding of the effect of various geometries, better equipment and perhaps a redefined role for the controller.

The glide path is used to order and space A/C flow to the runway. The length of the path depends on what is considered necessary to perform this function, which again depends on equipment and the controller. An ILS system with a wider range could enable the use of several glide paths with one runway. A scanning beam microwave system appears to be a possible improvement over the current ILS system; such an improvement might reduce some of the limitations on approach geometry.

Delays also have causes outside the glide path-runway area. The need to fly directly at or away from a VOR limits airspace. Area navigation should substantially aid in solving this problem, and the NAS program is also directed at helping enroute A/C.

Departing A/C also experience substantial delays. Since landing A/C have priority, departures usually wait. This problem can be solved by using two or more independent runways so that departures have an exclusive runway. But since independent runways are subject to separation standards, land acquisition would become extremely expensive with this system so reducing runway separation standards has been extensively discussed in the literature [26]. Different procedures could be used such as grouping or platooning landings and departures, but it seems inevitable that landings will retain priority over departures.

Navigation aids for the pilot are being studied and evaluated so that some of the responsibility can be lifted from the controller. The alphanumeric system is one of the more popular of these.

Many have great hopes for "jumbo-jets" and the help they will give to improving the system, but the significance of this improvement remains to be seen. Right now larger A/C seem to be a doubtful panacea.

The primary (and many of the lesser) causes of ATC problems have been summarized. Where should technology's efforts be directed? The next chapter will discuss an approach and suggest answers to this question.

VII. CONCLUSIONS AND RECOMMENDATIONS

The purpose of most system studies is to draw conclusions about the present state of the system and to recommend what action is needed to meet future system requirements. This final chapter will present and discuss what can be concluded about the ATC system as it currently exists. With respect to recommendations, a framework will be presented whereby several possible directions for future research can be considered.

The following list presents the areas of ATC that need further research most and then each of these areas is discussed briefly:

1) Prediction of future ATC needs
2) Building of mathematical models to develop a better understanding of the system
    a) Update current models
    b) Produce new models for multiple runway operations
3) Determination of the needs for new airport construction
4) Design of standardized equipment with greater accuracy and increased information transmission rate
5) Determination of the appropriate role for the controller
6) Automation of appropriate system functions
7) Re-evaluation of airport operating rules
    a) Type of separation standards
    b) Magnitude of separation standards
    c) Type of service airport should offer
8) Determination of the responsibility of the pilot in ATC operations
9) Elimination of the many political barriers

It is necessary that future ATC needs be fairly accurately predicted because of the tremendous lag in changing the system . If it were suddenly realized in 1985 that the predictions were not reasonable, it would be 1995 or 2000 before changes could be made.

As chapter IV has shown, mathematical models are needed to determine causal relationships. Some model updating has already been performed, i.e., the updating of Blumstein's 1959 model by Odoni in 1969, but more is needed to better understand the simplified ATC system and also to develop a comprehension of the complexities of multiple runway operations.

Many of the present airports will be capacity-limited regardless of new equipment and procedures that are produced. New airports will have to be built but the scale of such construction should be analyzed. Trade-off criteria between new construction and rehabilitation will have to be determined.

Inaccuracies in present equipment is a big problem which will hopefully be given a high priority in ATC research funding. Standardization is necessary in that every A/C should have a standard method of identifying itself (this includes every A/C from single-passenger to jumbo-jet). Even present day radar contains more information than is currently received by ATC. Better processing techniques and equipment should allow much more information to be transmitted.

The controller can have many possible roles in the system. Instead of being a series element of the control link, a parallel role may be more beneficial. His job as it is currently defined (i.e., as performer of many routine and redundant tasks) should certainly be reevaluated, but he should not be eliminated from the system.

Automation can certainly rid the controller of many of his routine tasks, aid in information transmission, and solve many data processing problems. However, full automation of the ATC system may yield diminishing returns. It is important to determine what the computer's role is in ATC.

Operating rules can certainly be studied. Some have suggested changing the type of separation standards while others feel that only a magnitude change is needed. First-come-first-serve is not the most efficient way to run an airport because shorter average delays are possible using other priorities. Should every airport serve all types of A/C? Are priority rules possible? These questions can quickly become political issues.

Should the pilot be given more responsibility for guiding his A/C to the runway? Pilots would probably prefer this, but it may not solve any system problems.

Political problems are perhaps the hardest to solve. A mass education program to inform the public of problems in ATC may help, through public opinion, to provide solutions that benefit the most people.

These are the problems with ATC, but what are the solutions? Of what relative importance are each of the nine problem areas just discussed? There are many alternative ways to approach solving these problems. Each solution should be evaluated with a performance index of a type that will yield an accurate measure of the relative value of each alternative. Such a performance index (or cost-benefit ratio or decision-making model) should be able to answer such questions as, "Given a limited amount of support, would it be more beneficial to spend this money on developing new ATC models, building new airports, designing a new ATC system, or some combination of all of these"?

This discussion will in no way attempt to present a concise and complete decision-making model. It is important to realize that a discussion of the variables that need be included in a model can yield results that can be used very effectively to discuss the relative sensitivity of the system to various parameters. Such results can be helpful in narrowing down the choices. Naturally, a functional form for the model would be necessary before any final choices be made.

There are four basic areas that will be of concern when designing or updating the ATC system:

1) System procurement costs

2) System operating costs

3) Efficiency

4) Safety

System procurement costs C_p are fairly straightforward to determine although they are usually underestimated.

System operating costs C_o can be computed annually or discounted over the lifetime of the equipment.

Efficiency is related to the number of A/C that the system services per unit time N_A and the delays that the A/C experience or the probability P_D that an A/C experiences a delay greater than some reference D.

Safety can simply be related to the probability of a collision P_c.

N_A, D, P_D, and P_c are all interrelated. They have been described as functions of such variables as:

1) A/C velocity distributions

2) Positioning error distribution

3) Separation standards

4) Length of glide path

The separation standards and the length of the glide path are directly dependent on the velocity and error distributions. Assuming any of several standard distributions, these model variables can be characterized by

$$N_A,\ D,\ P_D,\ P_c = f(\overline{V},\ {}^2_v, \overline{X},\ {}^2_x),$$

where four different functions are likely and

$\overline{V}$ = mean of A/C velocity distribution

σ_v^2 = variance of A/C velocity distribution,

$\overline{X}$ = mean of positioning error distribution,

σ_v^2 = variance of positioning error distribution

Most of these variables can be determined using the methods presented in Chapter IV. However, no attempt will be made in this report to assign numerical values or a functional form to this model which is being discussed.

Thus, a basic decision-making model appears possible to aid in the discussion of some qualitative conclusions concerning the nature of future ATC research.

Discussion can now focus on the list of conclusions presented earlier in this chapter.

How accurately should future ATC needs be predicted? Considering the variables just presented, it becomes a simple question of cost versus the affect of unexpected A/C in the system. After a point, it is of more value to allow an error in predictions than to invest the time and money into gaining very accurate estimates. Since P_c will decrease and research costs increase with the accuracy of predictions, the trade-off would become straightforward though still very difficult.

Identical arguments can be used when discussing mathematical modelling, but on a larger scale the question is not strictly one of accuracy. The models aid in understanding and thereby decision models can be formed. Modelling can be overdone, but the researcher should have freedom to innovate.

New airports versus rennovation of existing ones is an interesting problem that eventually becomes a question involving the diminishing returns of increased investment. A decision-making model would ask the simple question "How much is increased capacity and/or efficiency worth"?

The need for new equipment is obvious. ATC desires a more accurate system, but how much accuracy is needed? As with new airports, this is a critical dollars and cents question. Engineers have been known to over-design. With limited funds such a practice can have detrimental affects on one part of the system without actually being of great benefit to the part of the system that it serves.

Although complete automation of systems is very popular, such a procedure is not always the most appropriate. Use of a computer to eliminate such tasks as handling flight strips and "handing-off" seem necessary; however, relegating the controller to a semi-active, parallel role in ATC does not appear to be the answer. Thinking in the framework of a decision-making model, it is easy to see that increased automation will increase system costs. Will automation increase the efficiency and safety of the system to such an extent that the value of the system will exceed that system based on controller decision-making? Efficiency and safety may not be improved greatly by automation since most design proposals include the controller as an element of the system that becomes activated in an emergency. It is hard to believe that a controller who spends the majority of his time as a passive observer will become an efficient active member of the system at a moment's notice. Thus, a system that relies on a controller only in emergency situations and ignores him during routine activity might not have a high value using the proposed modelling approach because costs will be high while efficiency and safety will not be substantially improved. The role of the controller may become that of a parallel element, but it appears that any new ATC system will need to combine the speed and accuracy of a computer with the flexibility of a human.

Since airport operating rules are not arbitrary constraints, they must be considered in relation to the limitations of the system. They can be studied to determine if they are reasonable, but such a study may not yield great returns; however, the affect of increased system accuracy on defining new separation standards may prove to be a study of greater worth. Not allowing smaller, general aviation A/C to use the airports where air carrier delays are high may violate several American practices, but this appears to be a necessary conclusion. Such a change would decrease the variance of velocity distribution significantly and thereby would directly affect the value model (which could easily become a political problem).

Political issues can be difficult to analyze. As previously mentioned, education of the public may increase interest in ATC's problems but society's enthusiasm based on too little knowledge can have adverse effects. The cost of a reasonable education program may be prohibitive -- a difficult problem to solve. A value model could be used for trade-offs but other subjective criteria will enter the analysis which were not discussed in this report.

The pilot has the basic responsibility for his A/C, but ATC usually "hand carries" him during IFR operations. While the pilot may prefer to have more control over his own A/C, the control should rest with the decision-maker that yields the highest value system. This has not been investigated, although it should be scrutinized in the future. Perhaps the pilot's role in ATC can be redefined to be more beneficial to the system. Many design organizations are pressing to produce equipment so that the pilot can take a greater role in ATC. This may not be the solution. Control of A/C should rest with the most effective system.

To answer any of the above questions, it becomes necessary to determine the affect of a solution on cost, efficiency, and safety. These have been characterized by C_P, C_o, N_A, D, P_D, and P_c. It is a far from trivial problem to find a functional relationship for these variables, but in themselves they present an interesting structure to any conclusions. Solutions should be discussed in the context of these variables. Such an approach insures that components of the system are considered not solely on their own merits but according to the value that they add to the system as a whole.

This report is necessarily of an open-ended nature; its results have been qualitative. Several basic problems still need to be considered. Since ATC is a public system, solutions to these problems can become very subjective and so trade-off criteria that accept subjective inputs are necessary. The way in which trade-offs are performed and the direction that future research takes is as important as the final system that is produced.

APPENDIX A. GLOSSARY

A/C -	aircraft
ATC -	air traffic control
ARTCC -	air route traffic control center
VOR and VORTAC -	VHF omni (very high frequency) omni range navigational beacons
TMA -	terminal area
ETA -	estimated time of arrival
VFR -	visual flight rules
IFR -	instrument landing system
OR -	operations research
CAS -	collision avoidance system
PWI -	proximity warning indicator
ARTS III-	automated radar terminal system
NAS -	national air space system
CAAS -	computer-aided approach spacing
SCS -	speed-class sequencing
NAFEC -	FAA Experimental Center, Atlantic City
DME -	distance measuring equipment
R/T -	radio receiver-transmitter
PPI -	radar screen
MODEM -	coding device for communications

APPENDIX B. ANNOTATED BIBLIOGRAPHY

1. Anon — "Computer Aids for Air Traffic Control," Engineering (U.K.) Vol. 191 (1969), April 7, p. 49. Discusses needs for automation in the ATC process. Mentions ideas by IBM utilizing computer to do routine work in a sophisticated manner. Very brief (1 page). No specifics mentioned.

2. Anon — "ATC Evaluation Unit at Work," Flight International, June 26, 1969. Discusses professional group involved with evaluating the total spectrum of ATC. Group is full-time, not just a temporary study group.

3. Anon — "The Tangled Mess in Aviation," Business Week, August 9, 1969. Discusses the need for the large scale modern management of the air system such as the one applied to the Apollo program. Describes the requirements to become an air traffic controller as well as the benefits and disadvantages of such a career. Presents some general suggestions for solving the problems. Presents the noise question with respect to airports.

4. Anon — "If You've Time to Spare, Go by Air," Engineering Opportunities, October, 1969. Discusses air traffic density predictions for the future. Indicates an ever increasing amount of IFR flights. Mentions U.S.'s lack of funding ATC research. Discusses new types of equipment that will be needed.

5. Ashton, W. F. — "The Impact of Automation on Air Traffic Control," proceedings on conference on Air Traffic Control Systems Engineering and Design, The Institution of Electrical Engineers, March, 1967. A very general discussion of the needs for automation in ATC. Stresses safety and reliability. Concrete suggestions are not included.

6. Bell, G.E. — "Operations Research into Air Traffic Control," The Journal of the Royal Aeronautics Society, Vol. 53 (1949). Discusses OR work in ATC done through 1949. Considers the accuracy of some of the assumptions popular at the time. Decides upon some "general" conclusions.

7. Bowen, E.G. & Pearcy, T. — "Delays in the Flow of Air Traffic," The Journal of the Royal Aeronautics Society, April, 1948. Demonstrates that delay is basically a function of how near the arrival rate is to the runway capacity. Concludes that airports should not be designed to be operated near capacity.

8. Blumstein, A. "A Monte Carlo Analysis of the Ground Controlled Approach System," <u>Operations Research</u>, June, 1957. Demonstrates the application of a simulation tool to ATC. Numerical results are admittedly unreliable, but approach proves interesting and could lead to a better model.

9. Blumstein, A. "The Landing Capacity of a Runway," <u>Operations Research</u>, Dec. 1959. Models capacity (i.e., A/C per unit time) of a runway. Considers capacity to be a function of the separation of A/C and their relative velocities. Uses no priority rules and assumes that runway is used only for landing.

10. Choules, C.W. & A.M. Patrick "Automation: The Quiet Revolution," <u>Flight International</u>, June 26, 1969. Presents auguments for automating ATC system, but as a phased change from the present system. Suggest some intermediate plans.

11. Cole, H.W. "Marconis' Contribution to ATC Development" <u>Flight International</u>, June 26, 1969. Discussion of one company's approaches to ATC problems through the years. Very general and equipment-oriented.

12. Davies, H. & V.A.M. Hunt "The Effect of Future Developments in Aeronautics on ATC," <u>AIAA</u> preprint 63-466, Oct. 1963. A general discussion of several important factors such as delay, weather and the effect of SST type A/C.

13. Dunn, W.J. & E.M. Santelle & A.J. Myura "Radar Video Sweep-time Reduction," <u>The Radio and Electronic Engineer</u>, Vol. 36 No. 1, July 1968. Describes techniques necessary for alphanumeric data to be economically written on a radar display. Basically consists of keeping the sweep-time long enough so that characters can be written at a speed that present technology can produce.

14. Ebert, D.H. "Development of Collision Avoidance Systems," Interavia, No.3/1969. System to warn pilot of other A/C in area. System tells pilot what maneuver to make to avoid conflict. Simpler system also proposed for smaller/inexpensive A/C.

15. Ebert, Dr. Ing. Heinz "Digital Processing of Radar Information in Air Traffic Control" Interavia, No.3/1969. Describes system to obtain more information from the radar signals. Naturally, also stresses system automation.

16. Engels, P.D. & L.M. Keane "NAVSAT-A Global Navigation System Utilizing Satellites," '68 NAECON, May,1968. A detailed abstract discussing capabilities of a navigation system utilizing 2 or 3 satellites in inclined synchronous orbits. Each satellite radiates a binary sequence code. Position locating within 0.1 nautical miles. Could be tied into ATC system via data link and ground station. User equipment costs less than $5,000.

17. Gilbert, G.A. Air Traffic Control, N.Y. Ziff-Davis, 1945. An interesting and amusing presentation of the history of ATC up until 1945. Discusses thoroughly the system as it stood in 1945. Illustrates the lack of change in the system since that period. The needs that the author indicates have not been fulfilled in the 25 years since the book was written.

18. Jackson, A.S. "A Computer Simulation Study of Five Automated Air Traffic Control Concepts," International Symposium on Man-Machine Systems. Transport Systems and Vehicle Control, Sept.1969. Simulation of an automated approach to landing A/C which uses as a measure of performance the variance of the schedule error at the gate. Investigates various approach patterns.

19. Kressner, W.K.H. "The 2707 Supersonic Transport," Proceedings of the I.E.E.E., Special Issue on Transportation, April, 1968. Very optimistic discussion of the role that the SST will play in eliminating traffic congestion. Also mentions needs for improvement in communications and navigation.

20. Odoni, A.R. An Analytical Investigation of Air Traffic in the Vicinity of Terminal Areas, Ph.D. Thesis, MIT, 1969. An extensive mathematical approach to several ATC problems. Changes of previously proposed models make results more general and realistic.

21. Oliver, R.M. "Delays in Terminal Air Traffic Control," Journal of Aircraft Vol.1, No. 3, May-June 1964, ppg. 134-141. A review of much of the work done to date in the area of air traffic control with respect to A/C being delayed during departure and arrival. A fair amount of mathematical theory is included. Several priority suggestions are considered, Includes substantial bibliography.

22. Pestalozzi, G. "Priority Rules for Runway Use," Operations Research, Vol. 12, No. 6, 1964. Considers various types of rules for landing and departing A/C. Divides A/C according to size and whether it is landing or departing. Determines the effect on delay and cost.

23. Porter, L.W. On Optimal Scheduling and Holding Strategy for the Air Traffic Control Problem, Electronic Systems Laboratory Report ESL-R-401, M.I.T., Sept. 1969. Through the use of optimal control theory, an algorithm is developed to predict optimum patterns for sequencing A/C into a regular flow and thus minimizing separations between A/C and increasing the capacity of an airport.

24. Powell, C. "HARCO-A Computer Based Air Navigation System," Aircraft Engineering, Feb., 1968. A system proposed for use in Europe which stresses automation with respect to interfaces between air and ground. Uses a pictorial display in the A/C.

25. Powell, C. "Pictorial Displays for Air Navigation," Interavia, NO.2, 1969. Display consists of a moving map or chart, coordinated by a computer, which pilot visually follows in flight.

26. Procedings of the 17th Technical Conference on Major Airport and Terminal Area Problems, Lucern, Oct., 9-14, 1967, Vols. I and II. This reference is extremely helpful and the many interesting articles are too numerous to annotate, but as specific articles are referred to in this report, the author's name will be included with this reference number.

27. Raben, M.W. A Survey of Operations and Systems Research Literature, Institute for Applied Experimental Psychology, Tufts University, 1960. Discusses research done in ATC and gives extensive bibliography. Presents some conclusions besides merely indicating references.

28. Schriever, B.A. & W.W. Seifert, eds. Air Transportation 1975 and Beyond; A Systems Approach, Canbridge, Mass., MIT Press, 1968. A very general discussion of the many problem areas in ATC. Stresses the need for better equipment. Discusses the equipment currently being developed.

29. Schriever B.A. "Can Systems Analysis Solve the Transportation Problem," Mechanical Engineering, July, 1969. System manager's approach to tackling transportation problems in general. Stresses the role of the public in design.

30. Shank, R.J. "Planned Evolution for ATC," AIAA preprint 63-467, Oct., 1963. Presents many statistics concerning the present ATC system. Indicates system's weaknesses and strengths. Discusses goals for evolution as the FAA envissions them.

31. Simpson, R.W. An Analytical Investigation of Air Traffic Operations in the Terminal Area, Ph.D. Thesis, MIT, 1964. Presents a very thorough discussion of the ATC as it currently exists. Uses analytical and simulation techniques to study approach patterns, holding stacks, glide paths, and other areas.

32. Taylor, J. Speech at ATC technical session. NEREM, Boston, Mass., Nov., 1969. A member of the Air Traffic Control Advisory Committee, General Taylor gave an informal report of the as yet unpublished conclusions of the committee. In general, it was decided to try to update present ATC system (as opposed to scraping it and starting over again). Noise is considered an important problem. Mentioned that separation standards may be lowered in the future and automation should be utilized where feasible.

33. Wisepart, I.S. & M.A. Warskow Statistical Analysis of Aircraft Delay, Airborne Instruments Laboratory Report 1400-6, July, 1965. A discussion of an analysis of several thousand pieces of data from several airports. The major conclusion is that air-carrier average delay is higher than the total average delay and that general aviation average delay is smaller. The difference arising from the different runway requirements of the two classes.