CoA Note E and C No. 2

THE COLLEGE OF AERONAUTICS
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PROPOSALS FOR A BASIC THEORY OF AIR TRAFFIC CONTROL

by

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July, 1964

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DEPARTMENT OF ELECTRICAL AND CONTROL ENGINEERING

Proposals for A Basic Theory of Air Traffic Control

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SUMMARY

This note serves as an introduction to the work on Air Traffic Control currently being carried out at The College of Aeronautics.

The basic principles of Air Traffic Control are examined and a mathematical basis for an analysis of the current and future ATC complex is discussed. The theory is based upon feedback control concepts using intermittent data. Examples showing the application to en-route airway and parallel track flying are given. These demonstrate the effect of positional data up-dating rate upon separation minima for both subsonic and supersonic aircraft. Application to both fixed route (Airway Control) and free-route (Area Control) are currently being considered. A full report is to be published at a later date.

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Background

Some 15 years ago the author was associated with the study of digital computers at a time when the development of large electronic computers was in its infancy. The great interest then was primarily in the engineering and programming aspects although thought was being given to possible applications for the machines.

Since the author had been associated with aviation for many years it was natural that he should consider possible applications in this field. The use of computers for scientific and basic design studies in aeronautics was obvious and acceptable, but if one propounded the idea that the computer could take over, in the foreseeable future, the duties of an Air Traffic Controller, then one was subjected to considerable scepticism; at that time the idea of a computer even assisting in the clerical work of producing flight progress strips was considered radical.

This situation has altered in recent years; to-day one sees the introduction - albeit on a small scale - of electronic digital computers into the everyday workings of air traffic control organizations for clerical purposes. So perhaps a proposal for using computers to achieve more sophisticated Air Traffic Control will now be better received.

Introduction

At a time when one was restrained to using the earths surface for travel, one was prepared to accept the fact that insurmountable difficulties could face one along the direct path, and that the destination was eventually to be reached by a devious route. It was extremely rare for one to be able to proceed directly to one's destination. When the first powered aircraft flew in 1903 it pointed to a future where a traveller could proceed directly to his destination. For many years this ideal was achievable, but then air travel became more popular and more stringent safety precautions were of necessity introduced. From these early days has developed our present-day system of airways which at the time of their inception still provided a direct route, but with the longer routes of to-day do not generally provide a straight line direct path between point of departure and destination. Thus the promise of air travel has not been completely fulfilled.

As an example of a modern airways flight it can be seen from fig. 1 that an IFR flight from London to Oslo is constrained to fly by the way of Airway Red 1 and Airway Amber 7. The only part of the direct route between London and Oslo to be utilized is from London to Brookman's Park - really insignificant in practice - and from Kristiansand to Oslo. The rest of the flight path hugs the North Sea coast following roughly an arc of a circle. The need for frequent reporting points in airways flying dictates a need for radio beacons, and these are more readily located on land. In the example given, the restriction due to the need for many reporting points is clearly apparent.

The airway is a relic of a time when an aircraft needed only to use a heading indication and stop-watch to proceed from beacon to beacon, the stop-watch being necessary to estimate the time at the next reporting point so that the ATC authority could ensure adequate time separation.

With the improvements in airborne navigational equipment and ground surveillance systems now being used by ATC one could say that modern progress is being used only to improve an antiquated system of control. The time has come to re-examine the requirements of Air Traffic Control in the light of modern scientific achievement.

Fundamental Principles of Air Traffic Control

In most fields of industrial engineering are to be found automatic control processes designed to ensure a smooth and continuous flow between input and output. For their success these processes depend upon continuous or intermittent sampling at stages along the production line and the resultant analysis being fed back so as to control some parameter of the process. Feedback control is now an established theory amenable to mathematical analysis. The author can see no objection to taking the subject of ATC and treating it exactly the same as any other feedback control system since, after all, it is a continuous process which for its success depends upon the feedback of positional information to the controlling authority.

In fig. 2 is seen a schematic diagram of the Air Traffic Control loop. In effect this consists of two closed loops which are self-contained in the aircraft and one closed loop relating the aircraft to the ground controlling authority. The controlling authority for the aircraft loops is the pilot or autopilot as appropriate. In one loop the aircraft movement is indicated by the flight instruments showing heading, airspeed, altitude, etc. and in the other loop it is indicated by the airborne navigation system giving position and possibly, track made good, heading etc. The ground ATC authority receives appropriate data obtained from both flight instruments and navigation system by way of the air-ground data link. This data is used in conjunction with that contained in the filed flight plan to seek possible conflicts, and any control instructions deemed necessary are then passed to the pilot by way of the ground-air data link. It can be seen that this main control loop has major built-in time delays in both data transmission and conflict search; to-day the data link is VHF radiotelephone and the conflict search is by a human control officer using his flight progress board with its flight progress strips. In the future the process will be accelerated by using automatic data transmission and computer control. It should be appreciated that the ATC loop relies on intermittent sampled data for its operation, and that the rate of updating information will be an important parameter.

Mathematical considerations

As with any other form of control, the first essential is to set up a generalised mathematical model of the ATC concept using symbols to represent the parameters. Particular situations can then be assessed for optimum conditions by allocating numerical values to the appropriate symbols.

Examples of the types of quantities to be put into the basic symbolic equation are as follows:

a) The accuracy of the navigational fix.

b) The permitted deviation from a predetermined position.

c) The response time of the ATC system.

d) The aircraft dynamic response characteristics.

e) The surveillance data rate for up-dating of positional information.

f) The velocity errors of the aircraft.

g) Pilotage and aircraft instrument errors.

The permitted deviation from a pre-determined position is a basic quantity which is largely instrumental in determining whether a control instruction is required; it could be considered to be the limits of variation permitted on the cleared flight path without ground control intervention. The response time of the ATC system includes the elapsed time due to the air to ground data link, decision time on the ground by either a human controller or computer, and delay on the ground to air data link. The surveillance data rate for up-dating of positional information is the rate at which the controlling authority receives positional data on aircraft and it is a measure of the maximum age of positional information. The velocity errors of the aircraft include both course and speed errors in three-dimensional airspace; local meteorological conditions will, of course, be included under this heading.

In deciding when to exercise control, the time of decision is a function of the position error, the time due to elapse before the next up-dating of information, and the response time of the control circuit including the aircraft dynamics.

Having determined the mathematical model a systems engineer will optimise his system. In this case, the author suggests there are three fundamental questions to be considered.

a) Is there an optimum relationship between the accuracy of fix and required up-dating rate?

b) Is there an optimum relationship between (a) and the aircraft manoeuvrability?

c) Is there an optimum relationship between navigational accuracy and safety separation standards?

In addition, if the answer to (a) and (c) is YES, then there will exist a composite optimum between navigational accuracy, date rate, and separation standards.

In performing the required mathematical analysis one may on occasion have to give a decision on the relative importance of some of the parameters. When this occurs, the author suggests that of first importance should be the data rate, second navigational accuracy, and third aircraft manoeuvrability. His contention is that nowadays aircraft manoeuvrability must be considered in the control problem since, with the advent of the supersonic transport, we have cases where an acceptable rate of turn yields turning circles of some 60 miles diameter.

The Application of the Mathematical Model

With a mathematical model based on the parameters outlined in the previous section one can test the sensitivity of the closed loop response of the ATC system by variation of one or more of the parameters. For instance, the separation standard can be assessed for conditions involving varying numbers of aircraft of either the same or different flight characteristics. Alternatively, having specified a given separation standard one can decide the permissable traffic density for a given navigational accuracy.

If a free-route (Area Control) system is envisaged where a computer is to be used to assess conflict situations the mathematical model is necessary to provide a measure of the permissable time elapse between successive conflict searches, and to indicate when situations arise which may call for an increase in the up-dating rate of positional information relating to any particular pair of aircraft.

This concept leads to the idea of setting up a mathematical control formula applicable to a given area, and then using it to determine the minimum rate of information flow necessary at any time to maintain a safe flow of air traffic through the area. The air-ground communication channel can then be operated more efficiently; the controlling authority will not be inundated with redundant information, and the ground-air channel will only be used when a control instruction is necessary for reasons of safety. The philosophy of ATC ought to be that all aircraft should be encouraged to find their own way to their destination, the controlling authority solely looking after the safety aspects.

Although one would like to think that the reason for ATC is to get an aircraft safely and expeditiously on its way, in actual fact the basic requirement for ATC is the safety factor, and this is the only criterion on which to evolve an ATC system. The optimisation of this system should then provide one with the most expeditious traffic rate possible in any given circumstance.

However, of more immediate practical interest is the application of the control formula to the present fixed route (Airways Control) system. Here it can assess the degree of efficiency of a particular airway under specified navigational accuracies and aircraft types. In the fixed route, as against the free route system, one is restricted to parallel track flying and this simplfies the mathematics involved in deciding when to exercise control. By reference to the schematic diagram (fig. 3) one can appreciate how the time of decision to apply control is a function of the position error in the navigational fix, the time due to elapse before the next up-dating, and the response time of the aircraft. The control formula for the airways case can be readily used to calculate minimum separation standards both along track and across track for given conditions of traffic density, navigation equipment, and aircraft characteristics. Of great concern is the relationship between positional information up-dating rate and the minimum separation standard for a given collision risk.

Progress to Date

The initial work on the theory has been mainly confined to investigation of the effect of the up-dating rate of navigational information. In order to test the basic theory under reasonably straightforward conditions before proceeding to general applications, the en-route phase of a long trans-ocean flight has been subjected to analysis.

Here, we have the aircraft themselves performing the navigational task and their measured positions being transmitted to the ground controller. The mathematical models both for parallel track flying and for time separation of aircraft on the same track have been set up and analysed for both subsonic and supersonic aircraft. Full details of the work will be published later but an indication as to the type of result can be gained from figs. 4, 5, 6 and 7 which represent results for aircraft speeds of 450 KTS and 1250 KTS, and an A.T.C. system response time of 6 minutes. Figs. 4 and 5 show the influence of up-dating period upon the minimum lateral separation for parallel track flying. It will be noted that in the supersonic case (fig. 5) an improved navigational system accuracy is assumed. The effect of a shorter (3 minute) ATC response time is shown for the supersonic case. Figs. 6 and 7 show the influence of up-dating period upon the minimum time separation for similar aircraft flying the same track, the effect of a 3 minute response time is again shown for the supersonic case. Curves of the 1 in 3160 risk when height separation is practised are also shown.

A full analysis and discussion of the results will appear in a later publication.

Work has also been started on collision prediction and the evaluation of the latest possible time of decision to exercise control so as to achieve safe avoidance. In this work, as well as in the parallel track investigation, the use of the Ferranti Pegasus Computer at the College of Aeronautics was of great value, in most cases considered the assembly of the necessary data on a large scale could not have been achieved without the use of this computer.

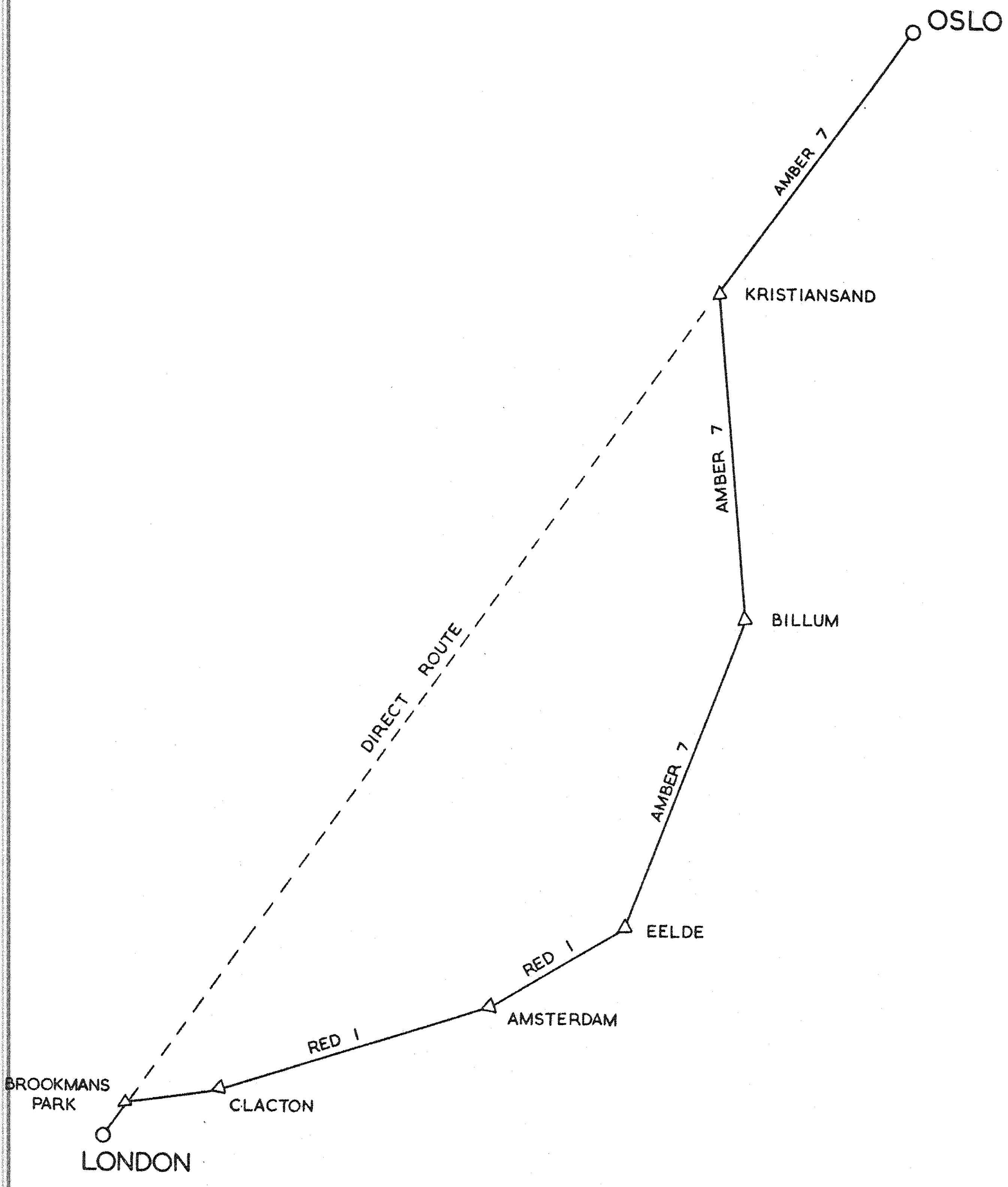

FIG. 1. LONDON TO OSLO VIA AIRWAYS

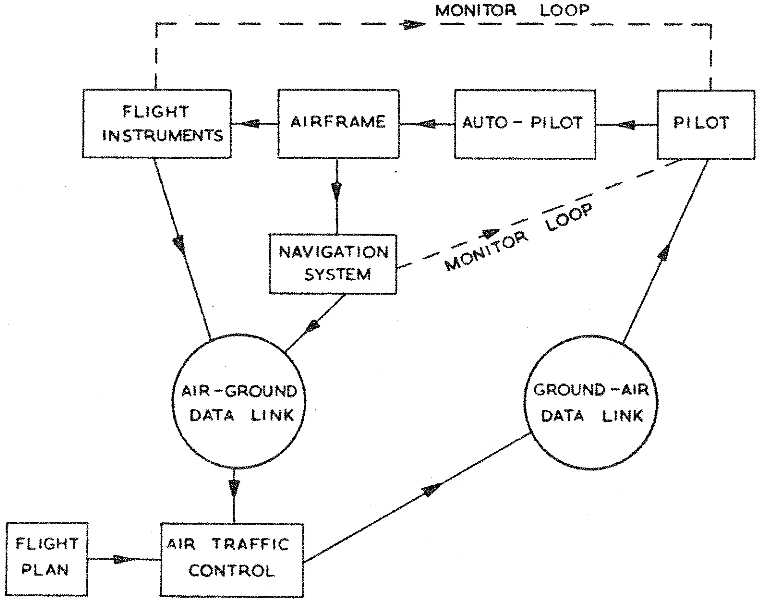

FIG. 2 THE CONTROL LOOP

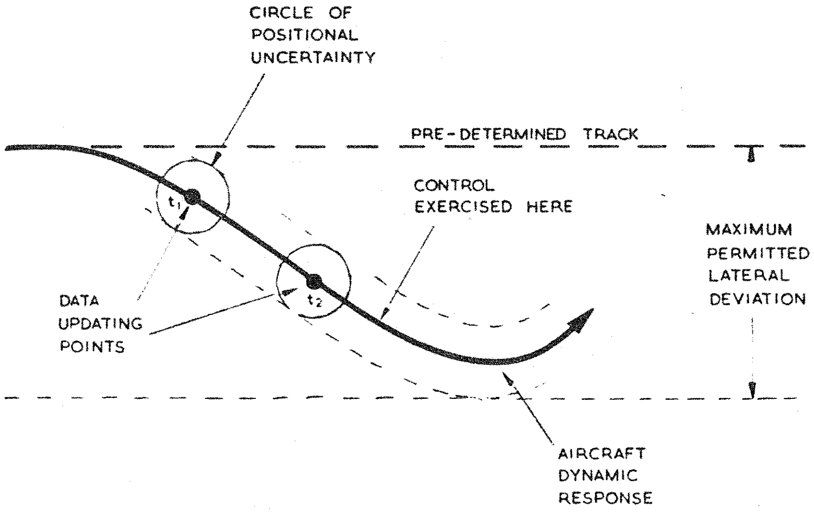

FIG. 3 LATERAL SEPARATION DIAGRAM

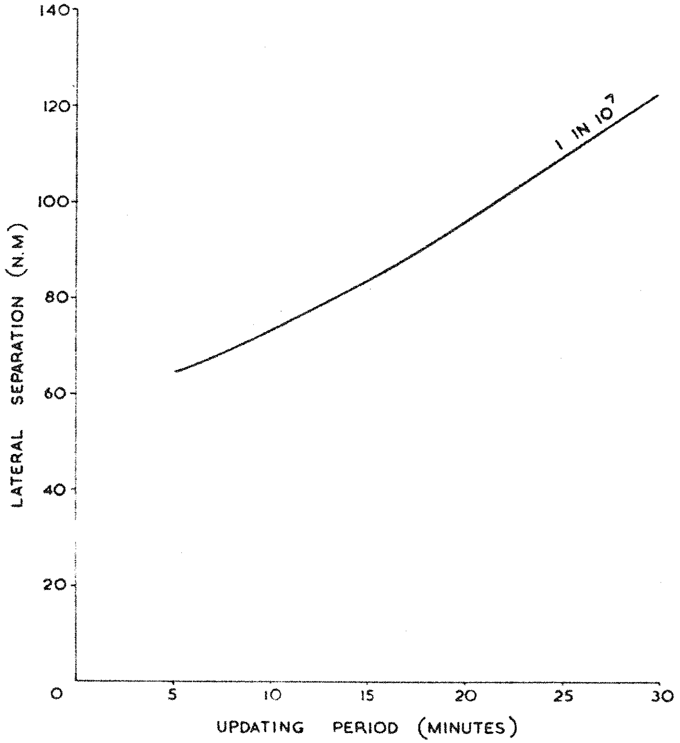

FIG. 4 MINIMUM LATERAL SEPARATION WITH PARALLEL TRACK FLYING FOR A 1 IN 10^7 RISK. (AIRCRAFT SPEED 450 KTS, TOTAL SYSTEM RESPONSE TIME 6 MINS, FIXING ERROR STANDARD DEVIATION 5·3 N M)

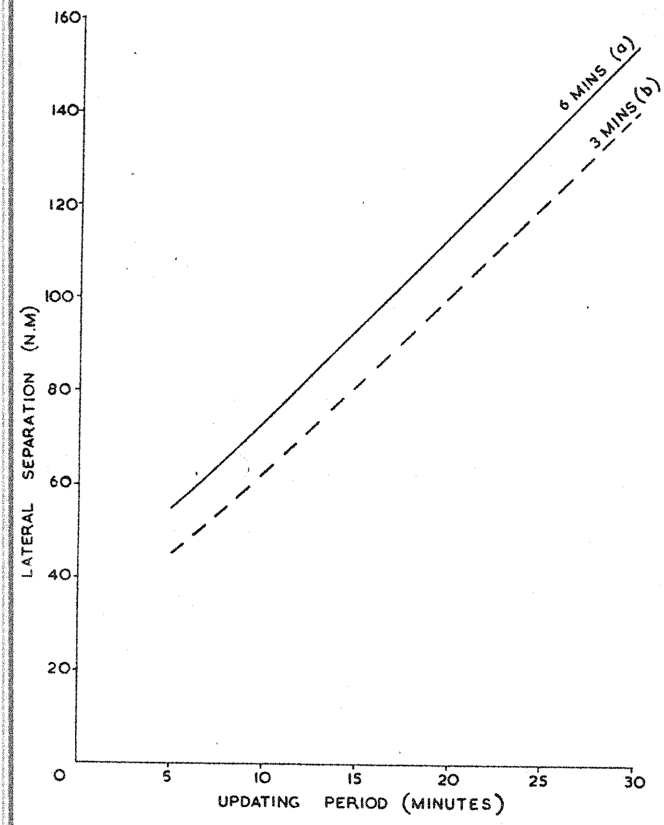

FIG. 5 MINIMUM LATERAL SEPARATION WITH PARALLEL TRACK FLYING FOR A 1 IN 10^7 RISK. (AIRCRAFT SPEED 1250 KTS, TOTAL SYSTEM RESPONSE TIME (a) 6 MINS, (b) 3 MINS, STANDARD DEVIATIONS 1) FIXING ERROR 3 N.M 2) HEADING ERROR 1 DEGREE)

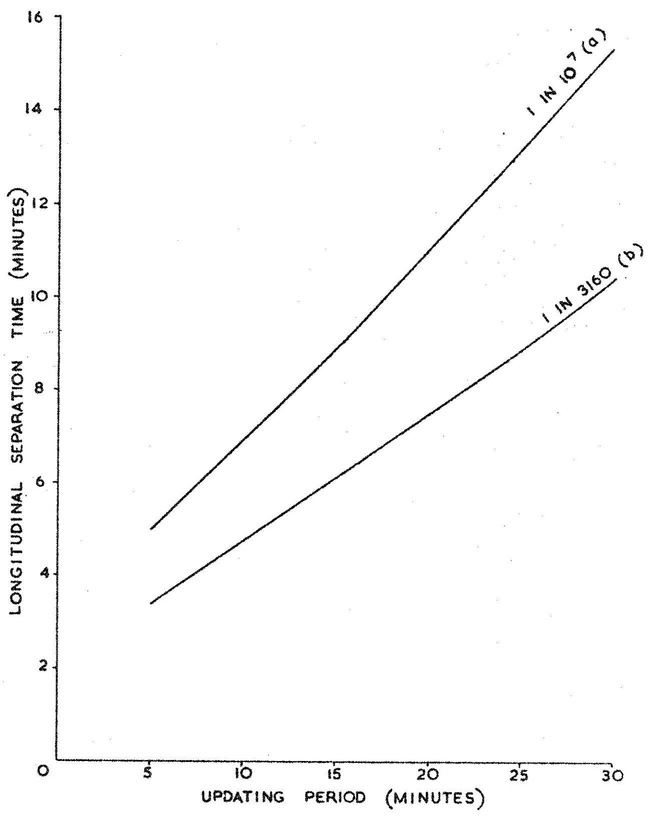

FIG. 6 MINIMUM LONGITUDINAL SEPARATION TIME FOR AIRCRAFT FLYING THE SAME TRACK (AIRCRAFT SPEED 450 KTS, STANDARD DEVIATIONS 1) SPEED 0·025 PER UNIT 2) FIXING ERROR 5·3 N.M, TOTAL SYSTEM RESPONSE TIME 6 MINS, LEVEL OF RISK (a) 1 IN 10^7 (b) 1 IN 3160)

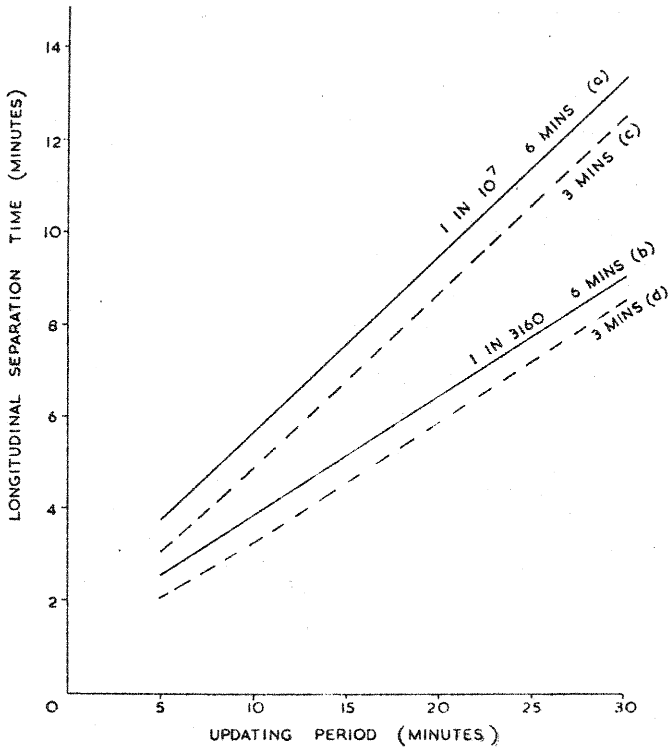

FIG. 7 MINIMUM LONGITUDINAL SEPARATION TIME FOR AIRCRAFT FLYING THE SAME TRACK. (AIRCRAFT SPEED 1250 KTS, TOTAL SYSTEM RESPONSE TIMES 3 MINS AND 6 MINS, LEVEL OF RISK 1 IN 10^7 AND 1 IN 3160, STANDARD DEVIATIONS 1) SPEED 0·025 PER UNIT 2) FIXING ERROR 3 N.M)