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AN ALGORITHM FOR TERMINAL AIR TRAFFIC CONTROL*

by

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ABSTRACT

An "area-navigation" method for automatic control of aircraft arriving in a random fashion from the en-route centers to the near terminal area is proposed. Control is exercised by a ground computer that sequences and schedules the aircraft. Altitude segregation is used to separate aircraft in velocity classes. Merging of all aircraft occurs near the outer marker. The merging region is designed so that no near misses will occur if the aircraft follow the assigned trajectories.

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1. INTRODUCTION

The rate of growth of the volume of air traffic operations has been, for the last decade, larger than anticipated. As a result the existing ATC system is often unable to effectively cope with the demand for landings and take-offs.

The ways that can improve air transportation efficiency and capacity are:

(1) Improve the ATC system presently available.

(2) Provide more runways at every airport.

(3) Build more airports.

The difficulties of implementing the latter two suggestions are very large due to the small availability of extra land to existing airports, and vigorous protests of political and environmental groups. However, research, e.g., [1] -[4], has shown that increased efficiency of the ATC system can delay the need to build more airports for at least two decades. It is to this problem that this paper is addressed.

The present ATC system, both en route and terminal, is manual. Experienced controllers, aided by radar, monitor the aircraft and guide them via voice commands, out of the airport's near terminal area (NTA), through the various sectors the national airspace is divided in, and finally to the runway of the destination airport. This system works efficiently when the airspace is not congested. However, when there are many aircraft demanding simultaneous service, it breaks down. The results have made national headlines in the form of long delays in take-offs and landings.

Automation is the educated answer to congestion. ARTS III, a semiautomated terminal ATC system, is at the developmental stage [5]. This system will automate many routine and time consuming functions of the controller, nevertheless, will keep the controller as the main decision element.

Complete automation with a computer as the main decision maker has been thought of in [3] as the ultimate ATC system. However, little research in this area has been carried out. Some contributions toward complete automation have been recently reported utilizing modern control theoretic concepts. The schemes of Porter [6], and Athans and Porter [7] employ the theory of optimal control of linear systems with quadratic criteria, to dictate precise aircraft trajectories along prespecified routes. The methods of Telson [8] and Erzberger and Lee [9] and Pecsvaradi [10] dictate minimum time trajectories to the outer marker for all aircraft. The main simplification of the above methods is that they assume that all aircraft have the same speed inside the NTA. In this report we present a related scheme for terminal air traffic control that lifts this assumption.

Any proposed "paper design" of a large scale system involves a host of assumptions and simplifications. Needless to say this is the approach taken in this paper. The assumptions and simplifications made were the result of attempting to preserve some sort of freedom of choice for the pilot, as long as safety was not compromised. Also, many of the assumptions can only be justified by considering the numerical values for certain key parameters; the ones selected were consistent with the current ATC system and current aircraft characteristics.

A full discussion of the interplay between assumptions, model specifications, design philosophy, mathematical development cannot be presented here; the interested reader can consult the S.M. thesis [12] of the first author. We shall only present an outline of the ideas involved so as to explain the major contribution of this paper, namely the digital computer ATC algorithm summarized in Figs. 18-20. Also, we shall explain the interplay between the adopted ATC philosophy and the design of the airspace in the near terminal area.

It should be stressed that this is an "open-loop" type deterministic design. It provides for a gross subdivision of the airspace and the determination of trajectory profiles as a function of the intanteneous demand. The stochastic aspects of the problem, e.g., errors in position and velocity, wind disturbances, pilot errors, etc., are not considered. These are more appropriate handled by an on-line stochastic feedback control system designed especially so that the statistical fluctuations of the underlying random and unpredictable quantities are taken into account.

However, state-of-the out limitations preclude the design of such a system right from the start. Hence, a deterministic ATC control concept of the type presented is this paper would serve as the one that determines on-line the nominal trajectories and speed profiles, while the stochastic feedback system would null deviations from the nominal quantities.

The structure of the paper is as follows. Section 2 discusses the assumptions, the ranges of certain key variables (e.g., speeds, deceleration constraints) and the general structure of the NTA airspace. In Section 3 we present the aircraft trajectory computations and the times required to accomplish certain trajectories and delay maneuvers. In Section 4 we discuss the determination of geometrical constants, e.g., altitude levels, length of the various NTA regions etc. Section 5 summarizes the overall system algorithm, the sequence of events that take place, and the key calculations that must be executed by the digital computer. The paper concludes with a discussion of the results.

2. THE PROPOSED ATC SYSTEM

The problem that is tackled is the following. Given random arrivals of aircraft to the boundary of the NTA find a way to guide the pilots to the outer marker (OM).

(1) Safely

(2) Efficiently (Faster aircraft have priority over slower ones).

(3) Decision making is carried out mainly by a control tower based computer.

The method of approach used here is,

(1) Define geometry in the NTA airspace such that

  (a) Aircraft trajectories are simple enough to fly, and for computer on-line implementation.

  (b) Safe separation between merging aircraft is ensured.

(2) Choose trajectories and types of delay maneuvers of the aircraft in the NTA.

(3) Devise algorithms for sequencing, scheduling and delay assignment.

(4) Base design on a worst case approach.

A. Assumptions

1. The identify of each aircraft is known.
2. The true position and velocity of each aircraft is known.
3. Every aircraft has a minimum turn radius (not the same for all aircraft).
4. Only jets are considered.
5. The landing speed of any landing aircraft is in the range [100, 150] knots (see Appendix A).
6. Only one runway is considered.
7. No other airport's airspace interferes with the NTA at hand.
8. Aircraft enter the NTA with speeds in the range [200, 300] knots.
9. Aircraft inside the NTA must be longitudinally separated by at least d_{min}. For numerical evaluations here d_{min} = 2.5 n.miles.
10. When an aircraft descends or turns, the groundspeed is kept constant.
11. The maximum permissible descent rate is λ. Here λ = 1000 ft/min.
12. The maximum permissible deceleration is B. Here B = 1 knot/sec.
13. At any instant of time at most one of three tasks, descending, turning or decelerating will be executed.
14. Wind speed is zero. No variation of speed occurs with changes in altitude and temperature (i.e., groundspeed = airspeed).

B. The Geometry

The NTA will be divided in three main regions description of which is shown in Figs. 1 and 2. Automatic control will start as soon as an aircraft enters the buffer zone.

While the aircraft is in the buffer zone (BZ), the ground computer sequences it, schedules it, and assigns to it a delay, if necessary. The middle region called the outer merging space (OMS) will be the delaying area, while the inner most region called inner merging space (IMS) will be the critical zone where aircraft descend toward the OM and decelerate to the landing speed.

While in the BZ and OMS the aircraft will be constrained to fly on a discrete number of altitude levels. On each altitude level traffic of only one speed will be allowed; for noise (and other) considerations higher levels will carry traffic of higher speeds. At each altitude level the OMS intersects the IMS in a circular boundary, whose radius projected on the x, y plane does not have to be the same for all levels (see Fig. 2).

The problem of merging aircraft of diverse landing speeds in the IMS will be solved by the following convention. No matter from what altitude level an aircraft enters the IMS, and no matter what its landing speed is, it will have to traverse the IMS in a time interval T_o, which is the same for all aircraft.

Traffic will enter the NTA from fixed points distributed along the NTA boundaries for each altitude level. These will be called traffic source points. The distance, along the NTA circular boundary, between traffic source points will be chosen so that aircraft centering from two adjacent points will not interfere during their flight through the BZ and OMS. Beyond the NTA, air routes are fixed. Inside the NTA, however, the aircraft will perform trajectories dictated by a computer.

The delaying procedure will be different than the conventional stacking. Aircraft will perform delay maneuvers on the same altitude level they enter the NTA. Delays will be performed in region called delay slots and illustrated in Fig. 3. Each delay slot will be large enough to accomodate safely the maximum delay maneuver necessary.

The choice of the magnitudes of the various geometrical constants will be discussed in the sequel.

C. The Control Process

The functional description of the control algorithm is illustrated in Fig. 4. The blocks indicate the functions that are performed by the computer while the aircraft is in the NTA. The last checkpoint is the point where the aircraft enters the IMS — which is on the circular IMS boundary but is different for every aircraft. If the aircraft has arrived too early or too late at the IMS boundary a correction is possible, in the form of a new descent and deceleration profile in the IMS. Automatic control stops at this point.

3. AIRCRAFT TRAJECTORIES

Before we discuss the specification of the system geometry it is essential that we understand the trajectories that aircraft will follow inside the NTA.

A. Trajectories in the BZ and the OMS

It seems reasonable to design the system so that if no other traffic interferes with an aircraft, this should reach the IMS boundary in the shortest possible time. In the BZ and OMS regions the flight is on a plane and with constant speed. The problem which is illustrated in Figs. 7 and 8 thus becomes.

Given the state equations for one aircraft.

$$\dot{x}(t) = v \cos\phi(t) \tag{1}$$

$$\dot{y}(t) = v \sin\phi(t) \tag{2}$$

$$\dot{\phi}(t) = \frac{g[\tan\theta(t)]}{v} \triangleq \frac{u(t)}{v} \tag{3}$$

with initial conditions

$$[x(0), y(0), \phi(0)] = [x_o, y_o, \phi_o] (x_o^2 + y_o^2 = R_N^2) \tag{4}$$

final conditions

$$x^2(T) + y^2(T) = L^2 \tag{5}$$

$$\tan\phi(T) = y(T)/x(T) \tag{6}$$

Find the control $u_{[0,\,T]}$ such that $|u(t)| \le A$ and such that the cost functional

$$J = \int_0^T dt \tag{7}$$

is minimized.

The maximum value of the control is determined by the maximum allowable bank angle $\theta(t)$ which currently is 30^o. Thus

$$A = g\tan\frac{\pi}{6} = g/\ 3 \tag{8}$$

where g is the acceleration of gravity.

The solution to the above problem was found by application of the minimum principle of Pontryagin [11]. A simplifying assumption was that the difference R_N-L is larger than 2R where R is the minimum turn radius, and L is the IMS radius. This assumption holds in the proposed system because we are dealing mainly with jets. The problem becomes much more complicated if the assumption does not hold, as the case might be with STOL traffic, and can only be solved numerically.

The detailed solution can be found in [11]. Here we only present the final answers.

(1) If the aircraft's bearing (azimuth) with respect to the OM at time t = 0 is zero, then the optimal control law is $u^o = 0$. The aircraft flies in a straight line until it reaches the IMS boundary in time

$$J = T_{min} = \frac{R_N - L}{v} \tag{9}$$

(2) If the aircraft, at time t = 0, has a counterclockwise bearing with respect to the OM, then the optimal control law is $u^o = [-A, 0]$. The aircraft turns "hard right" for time t_s given by:

$$t_s = \frac{v}{A}\left[\phi_o - \tan^{-1}\left(\frac{y_o - \frac{v^2}{A}\cos\phi_o}{x_o + \frac{v^2}{A}\sin\phi_o}\right) - \sin^{-1}\left(\frac{\frac{v^2}{A}}{\left[(y_o - \frac{v^2}{A}\cos\phi_o)^2 + (x_o + \frac{v^2}{A}\sin\phi_o)^2\right]^{1/2}}\right)\right] \tag{10}$$

Then it continues on a straight line until it reaches the IMS boundary. The value of the minimum time is:

$$T_{min} = \frac{[x^{o^2}(t_s) + y^{o^2}(t_s)]^{1/2} - L}{v} \tag{11}$$

where:

$$x^o(t) \triangleq x_o + \frac{v^2}{A}\sin\phi_o - \frac{v^2}{A}\sin(\phi_o - \frac{A}{v}t) \tag{12}$$

$$y^o(t) \triangleq y_o - \frac{v^2}{A}\cos\phi_o + \frac{v^2}{A}\cos(\phi_o - \frac{A}{v}t) \tag{13}$$

(3) If the aircraft at time t = 0 has a clockwise bearing with respect to the OM, then the optimal control law is $u^o = [A, 0]$. The aircraft turns "hard left" for time t_s' given by:

$$t_s' = \frac{v}{A}\left[-\phi_o + \tan^{-1}\left(\frac{y_o + \frac{v^2}{A}\cos\phi_o}{x_o - \frac{v^2}{A}\sin\phi_o}\right) - \sin^{-1}\left(\frac{\frac{v^2}{A}}{[(y_o + \frac{v^2}{A}\cos\phi_o)^2 + (x_o - \frac{v^2}{A}\sin\phi_o)^2]^{1/2}}\right)\right] \tag{14}$$

Then it continues on a straight line until it reaches the boundary of the IMS. The value of the minimum time is:

$$T_{min} = \frac{[x^{o^2}(t_s') + y^{o^2}(t_s')]^{1/2} - L}{v} \tag{15}$$

where:

$$x^o(t) \triangleq x_o - \frac{v^2}{A}\sin\phi_o + \frac{v^2}{A}\sin(\phi_o + \frac{A}{v}t) \tag{16}$$

$$y^o(t) \triangleq y_o + \frac{v^2}{A}\cos\phi_o - \frac{v^2}{A}\cos(\phi_o + \frac{A}{v}t) \tag{17}$$

B. Delay Maneuvers

The delay maneuvers adopted are with minor variations the same as the ones described in [6] - [8]. We state them here for completeness.

Let $D = \frac{2\pi R}{v}$ be the time required by the aircraft to complete a full circle. Let t_D be the time by which the aircraft must be delayed, then:

(1) If $t_D < D$, the delay is affected by an oscillation or θ maneuver (see Fig. 7). The magnitude of θ is calculated by

$$t_D = \frac{4R}{v}(\theta - \sin\theta).$$

(2) If $t_D = D$, then the maneuver is a full circle of radius R (see Fig. 8a).

(3) If $D < t_D \leq 2D$, the maneuver is a fly-around one (see Fig. 8b). For this maneuver

$$\ell = S + 2R = \frac{(t_D - D)v}{2} + 2R \qquad (18)$$

The maximum ℓ occurs when $t_D = 2D$

$$\ell_{max} = \frac{Dv}{2} + 2R = (\pi + 2)R \qquad (19)$$

(4) If $2D < t_D \leq 3D$, the maneuver will be a circle followed by a fly-around one as described in (3).

(5) If $3D < t_D$ then $t_D = k \cdot 2D + t_1$ $(k = 1, 2, \ldots)$ where $D < t_1 \leq 3D$. The delay maneuver is then k fly-around maneuvers of the "maximum racetrack" type, described in (2) followed by a maneuver as described in part (4).

Notice that none of the delay maneuvers on a particular altitude level requires length more than ℓ_{max}. The delay maneuvers will be initiated only when the aircraft is flying on the straight portion of its minimum time trajectory.

C. Trajectories Inside the IMS

While inside the IMS each aircraft must accomplish the following two objectives in time T_o.

(1) Decelerate from its entrance speed to the NTA v to its desired landing speed v_L.

(2) Descend from its altitude level in the OMS to the level of the OM.

Each aircraft enters the IMS with heading toward the OM. We shall assume for simplicity that the flight continues along this heading, until the OM. Ideally the aircraft should reach the OM with heading along the x-axis, i.e., toward the runway. For the distances involved (to be found shortly) the error incurred by assuming the above heading is small, but the analysis greatly simplified.

Let the IMS radius be L(v) for the particular altitude level that carries speed v (From now on we shall denote by IMS radius, the radius of the circular projection on the (x, y) plane of the IMS boundary, e.g., A-OM in Fig. 2). The velocity profile in the IMS will be of the type shown in Fig. 9, i.e., only one deceleration at the maximum permissible rate.

During the remaining time $T_o - (v - v_L)/B$ the aircraft must descend to the OM. Given that $T_o - (v - v_L)/B > (H_v/\lambda)$, where H_v is the elevation above the OM of the altitude level at hand, and λ is the maximum descent rate, there is an infinite range of possible descent profiles. We shall not specify a precise descent profile (although we could). Instead we shall communicate to the pilot the latest time he can start descending, so that if he descends from then on at the maximum rate he will arrive at the OM in time T_o. This time, $t_{descent}$, is trivially found as

$$t_{descent} = T_o - \frac{v - v_L}{B} - \frac{Hv}{\lambda} \tag{20}$$

Thus a typical trajectory of an approaching aircraft would look as in Fig. 10.

4. GEOMETRY SPECIFICATION

The geometrical constants that have to be specified to define the geometry are:

(1) T_o = Common time available to all aircraft at all altitude levels, to cross the IMS

(2) $L(v)$ = Radius of the circular projection to the (x, y) plane of the IMS boundary at the altitude level H_v

(3) H_v = Altitude, above the level of the OM, of the altitude level carrying speed v

(4) Length of a Delay Slot

(5) Length of OMS at each altitude level

(6) Length of Buffer Zone

(7) Distance between Traffic Source Points

(8) Radius of the NTA, the same for all altitude levels.

We shall try to determine the minimum allowable magnitudes for these quantities, because we want to keep the NTA region as small as possible so as to avoid simultaneous control of too many aircraft.

A. Choice of T_o

T_o is common for all aircraft. For each pair of entering and landing speeds (v, v_L) it must be true that

$$T_o \geq \frac{Hv}{\lambda} + \frac{v - v_L}{B} = t_o(v, v_L) \tag{21}$$

Since higher altitude levels carry higher speed traffic the maximum value of $t_o(v, v_L)$ for $v \epsilon [V_1, V_2]$ and $v_L \epsilon [V_{L1}, V_{L2}]$ knots, where V_1, V_2, V_{L1}, V_{L2} = 200, 300, 100, 150 knots respectively, occurs at $v = V_2, v_L = V_{L1}$

Thus if

$$T_o \geq \frac{H_{V_2}}{\lambda} + \frac{V_2 - V_{L1}}{B} = t^* \tag{22}$$

then we are assured that no matter from what altitude level an aircraft is entering the IMS, and no matter what its landing speed is, it <u>can</u> accomplish the descent and deceleration objectives.

It will be seen that the upper limit H_{V_2} will be left to be specified by the designer. For $H_{V_2} = 6000$ ft t^* is about 10 minutes.

B. Choice of L(v)

Instead of providing lengthy motivation (can see [12] for this), we present the result and then explain it.

Proposition: Suppose there is only one altitude level, carrying traffic at speed v. Let T_o be fixed (e.g., $= t^*$). Then if

$$L(v) \geq T_o v - \frac{(v - V_{L1})^2}{2B} = L^*(v) \tag{23}$$

there is no chance for a near miss in the IMS, between aircraft entering the IMS from this particular altitude level H_v.

Proof: Since all aircraft must traverse the IMS in time T_o, they must enter the IMS separated in time by their scheduled temporal separation τ over the OM. For mixed landing speeds traffic the minimum τ is 1 minute (see [2] for a detailed discussion).

The range of speed profiles in the IMS, dictated by $L^*(v)$, is shown in Fig. 11. It is noticeable that the deceleration is delayed very close to the end of the interval T_o for all choices of v_L. Consider now two cases of two successive aircraft entering the IMS within one minute of each other.

(1) First aircraft has lower landing speed than the second, i.e., $v_{\ell 1} < v_{\ell 2}$. Their speed profiles are shown in Fig. 12. Neglecting the fact that the aircraft might have entered the IMS from different points in the circular boundary, we consider their longitudinal separation as if they entered from the same point (clearly this is the worst case). Their initial separation is ABCD. Their smallest separation occurs over the OM and is (ABCD) - (EFGHJ), which is a desirable situation.

(2) First aircraft has higher landing speed than the second, i.e., $v_{\ell 1} > v_{\ell 2}$. The respective speed profiles are shown in Fig. 13. Again the minimum longitudinal separation occurs over the OM.

Thus for all possible cases the minimum longitudinal separation in the IMS between successive aircraft occurs over the OM. Had we chosen L(v) smaller than $L^*(v)$ the minimum would occur at same point inside the IMS. This minimum, however could be much smaller than d_{min} (see Fig. 14).

For the speed ranges considered and $T_o = 10$ min. typical values of $L^*(v)$ are from 32 to 45 nm.

C. Choice of H_v

The rule by which the minimum altitude separation between successive levels should be chosen by the designer is

(1) Choose the speed v_o of the highest level and H_{v_o}, the altitude of this level

(2) Choose v_1, the speed of traffic flying on the level immediately below H_{v_o}

(3) Choose the IMS radii for the two levels by Eq. 23 (i.e., $L(v_o) = L^*(v_o)$)

(4) Consider the "worst" situation, i.e., an aircraft entering the IMS from the top level followed closely ($\approx$ 1 min) by an aircraft entering the IMS from the level below. Assume the aircraft are on the same vertical plane.

(5) Find d(0), the longitudinal separation at the time the second aircraft enters.

(6) If $d(0) \geq d_{min} = 2.5$ n. miles then choose

$$H_{v_o} - H_{v_1} = \Delta H_1 = \text{minimum FAA vertical separation standard } (\sim 1000 \text{ ft}) \tag{24}$$

(7) If $d(0) < d_{min}$ then set

$$\Delta H_1 = \lambda(t_s + t_{sf}) \tag{25}$$

where

$$t_{sf} = \frac{d_{min} - d(0)}{v_o - v_1} \qquad (26)$$

and t_s = minimum allowable temporal runway separation (~ 1 min).

The above rule ensures that there is no interference in the IMS between traffic of two altitude levels. Typical descent profiles are illustrated in Fig. 15.

D. Length of a Delay Slot

We will choose the length of a delay slot L_{DS}, so as to accomodate with safety margin the largest possible delay maneuver.

$$L_{DS} = \ell_{max} + d_{min} = (\pi+2)R(v) + d_{min} \qquad (27)$$

It is true that the length of a delay slot is different for different altitude levels. Typically $L_{DS} \sim 10$ nm.

E. OMS Length

The length of the OMS now can be chosen for each altitude level, as an integral number of delay slots. Thus

$$L_{OMS}(v) = n(v)\, L_{DS}(v) \qquad (28)$$

The number n(v) will typically be the same for all altitude levels.

F. Buffer Zone Length and NTA Radius

For the top level the smallest BZ length is chosen so that all aircraft will enter the OMS while they are flying on the straight portion of their minimum time trajectory. The limiting case is shown in Fig. 16. In this case

$$L^*_{BZ}(v) = (AD) = R + (BD) = R + (B0) - (D0) = R + (B0) - (C0)$$

so

$$L^*_{BZ}(v) = R + [R^2 + (L_{OMS} + L_v)^2]^{1/2} - L_{OMS} - L_v \qquad (29)$$

The minimum NTA radius now is completely specified via

$$R_N = L^*(v_o) + n(v_o)L_{DS}(v_o) + L_{BZ}(v_o) \tag{30}$$

The BZ length for the lower levels is specified by

$$L_{BZ}(v_k) = R_N - L^*(v_k) - n(v_k)L_{DS}(v_k) \geq L^*_{BZ}(v_k) \tag{31}$$

Typically, for 2 delay slots, we find that for v = 230 knots, $R_N = 55.4$ nm with $L^*_{BZ} = 1.4$ nm, for v = 270 knots, $R_N = 65.1$ nm, $L^*_{BZ} = 2.1$ nm, values which are reasonable.

G. Distance Between Traffic Source Points

Referring to Fig. 17, we would like to choose the minimum distance between two traffic source points so that in the "worst" situation illustrated in Fig. 17, the distance GH is safe i.e.,

$$GH \geq 3.4R + d_{min} \tag{32}$$

where 3.4 R refers to the maximum oscillation maneuver (see Fig. 7b).

The equations applicable then are:

$$(AB) = 2R_N \sin(\phi+\omega) \tag{33}$$

$$\sin\phi = \frac{R}{R_N - R} \tag{34}$$

$$\sin\omega = \frac{(GH)}{2L} = \frac{3.4R + d_{min}}{2L} \tag{35}$$

A typical value for $R_N = 70$ nm, v = 250 knots, $d_{min} = 2.5$ nm, L = 39 nm is (AB) ≈ 17 nm.

We can see now the delay capabilities of the proposed system. At each level there can be at most $\left[\frac{2\pi R_N}{\text{arc}\,(AB)}\right]^\dagger$ traffic source points. For $R_N \sim 70$ nm, we can have about 25 source points at each level.

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† [ ] denotes the largest integer function.

If the OMS length is 2 delay slots, then each level can delay simultaneously 50 aircraft.

5. THE SYSTEM ALGORITHM

Now we are ready to describe the automatic nature of the system. Figure 18 indicates the functions that are to be performed by the pilot and the computer during the landing phase.

As soon as the pilot enters the NTA be radioes to ground, aircraft identification, position, heading, time of entrance, speed v (commensurate with altitude level), and desired landing speed v_L.

The first task of the computer is to calculate the minimum time trajectory and hence the expected time of arrival (ETA) of the aircraft. This is done by calling the subroutine ETA-MTT, which essentially does the calculations described in the section on aircraft trajectories in the BZ and OMS.

The next task is to sequence and schedule the aircraft. This is done by calling the subroutine SEQ-SCHED (see Fig. 19). This subroutine considers the ETA's of all the aircraft that are still in the BZ. It compares the ETA of the newly arrived aircraft to the rest of the ETA's. The rule that is adopted for landing order is that the only time a later arriving aircraft will supercede an earlier one, is when the former by so doing does not oblige the latter to delay. Specifically only if

$$ETA(m) \leq ETA(m-k) - \Delta t(m, m-k) \tag{36}$$

will aircraft m be scheduled to land before m-k. Here $\Delta t(m, m-k)$ is the minimum allowable temporal separation over the OM between the two aircraft (typically 1 min).

Next the algorith assigns a delay slot to the aircraft where a delay maneuver will be performed if necessary. This is done by calling the delay assignment subroutine DAA (see Fig. 20). This subroutine first calls on DELAY-TYPE to calculate the type of maneuver to be performed, via the rules previously established. Then it scans all the slots for the particular source point of the new aircraft and sees which ones are "filled up" and which ones are not. It then assigns a slot and dictates to the pilot the exact time T(Q) where he should leave the straight flight and start performing the maneuvers. The block labeled "Aircraft ID(Q) should not enter OMS" is entered when all the slots are already occupied. The resolution of this dead end conflict, lies in appropriate metering so that e.g., not move than 4-5 aircraft per hour enter the NTA from a particular source point.

Finally the algorithm calls on the IMS-NOMinal trajectory subroutine which simply calculates the time the pilot should start decelerating (TDECEL), and the latest time the pilot can start descending (TDESCENT).

If there is an error in arrival time the IMS-NOM subroutine is called again to update TDESCENT and TDECEL. Flow charts for the less important subroutines can be found in [12].

J. CONCLUSIONS

We saw that it is possible, by appropriate definition of the airspace geometry in the NTA, to design a deterministic terminal control system. The system proposed here is an open loop automatic control system that dictates, for each aircraft, nominal trajectories in the NTA.

The main advantage of such a system is that it frees the controller from routine decision making. He can now act as an ultimate decision maker, correcting for errors that might occur, and taking charge in case of an emergency. In other words the controller would be the element in the feedback loop of the closed loop control system.

This type of a system offers possibilities for solutions to the problem of automatic control with multiple runways, and overlapping airspaces. The idea would be to assign some altitude levels to traffic landing to one runway (or airport), and other levels to traffic utilizing a different runway (or airport).

Scheduling take-offs is not a problem because as soon as there is a demand for a take-off the system algorithm could schedule it in a "gap" between two scheduled landings. The details of this procedure have been considered in [12].

Routing of take-offs through the NTA is another problem that should be considered. This one could be tackled by changing some traffic source points to traffic "exit" points, thus opening corridors for departing aircraft. It should be noted that the subset of the NTA assigned to takeoff trajectories can be incorporated as a state variable constraint in the minimum time problem described in Section 2, so that the aircraft reaches the boundary of the IMS in minimum time without entering any forbidden airspace. Regions of severe torbulence that should be avoided can be handled in an analogous manner. Since the basic computations to be carried out are simple, frequent updating (as weather conditions change, landing and takeoff demands vary) is possible. Additional research and simulation studies are necessary to examine whether or not rapid updating is feasible to correct for stochastic errors that will arise.

APPENDIX A*

Approach Airspeed in Knots

Jet Type	Operating Empty Weight	60% Load Factor	Maximum Loading Weight
737-100	100 Knots	130 Knots	138 Knots
737-200	103 "	125 "	133 "
DC-9-30	105 "	125 "	128 "
DC-9-40	106 "	125 "	128 "
727-100	95 "	122 "	130 "
727-200	102 "	122 "	133 "
707-120	118 "	142 "	146 "
707-120B	115 "	135 "	140 "
720	102 "	123 "	128 "
707-320	117 "	140 "	143 "
707-320B	103 "	122 "	127 "
DC-8-61	118 "	137 "	143 "
DC-8-62	108 "	135 "	140 "
DC-8-63	115 "	137 "	141 "
DC-10-10	112 "	133 "	137 "
DC-10-20	117 "	135 "	140 "
747	115 "	140 "	144 "

* we would like to thank Prof. A. Odoni of M.I.T. for this table.

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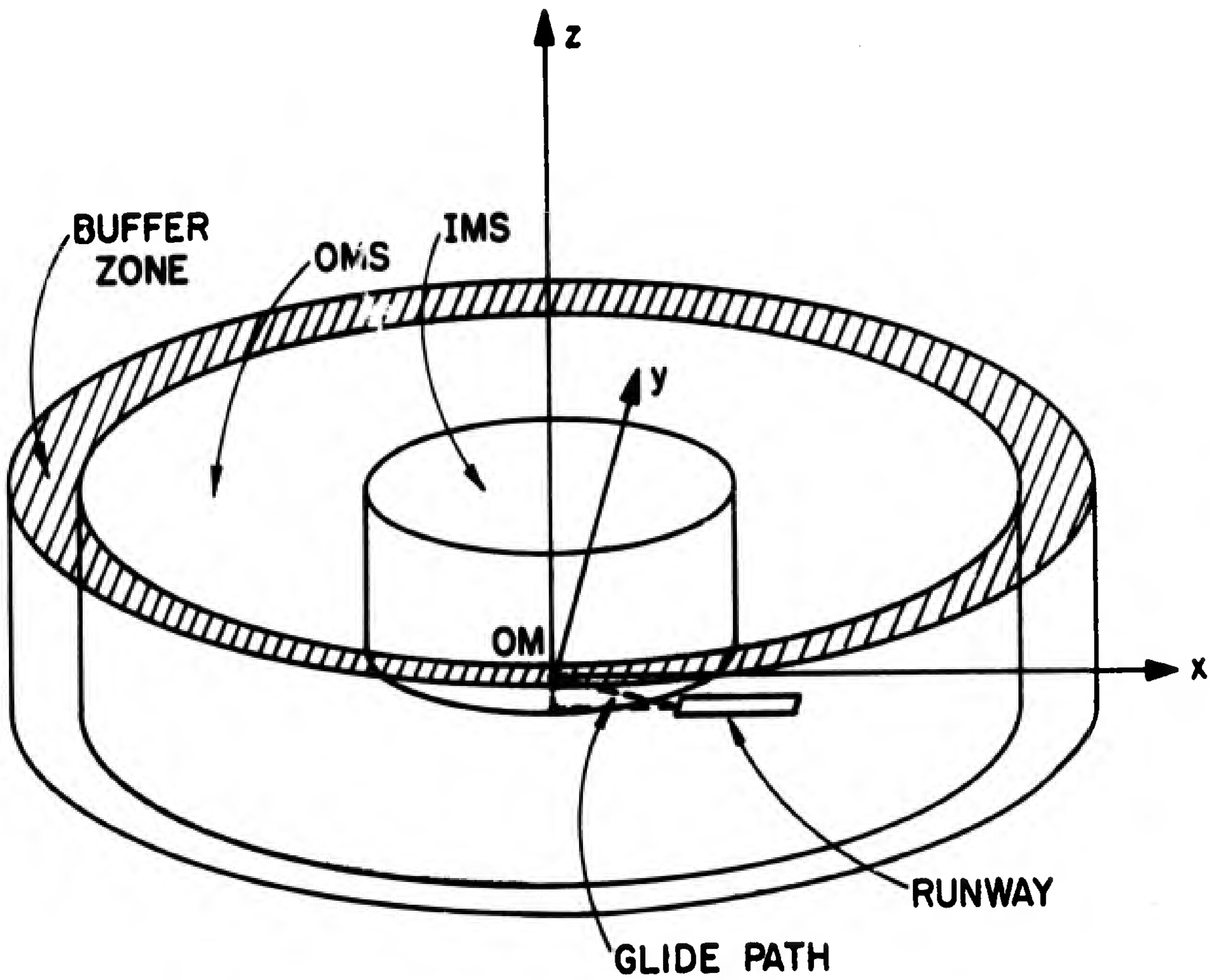

Fig. 1 "Rough" Description of Airspace Segregation Inside NTA

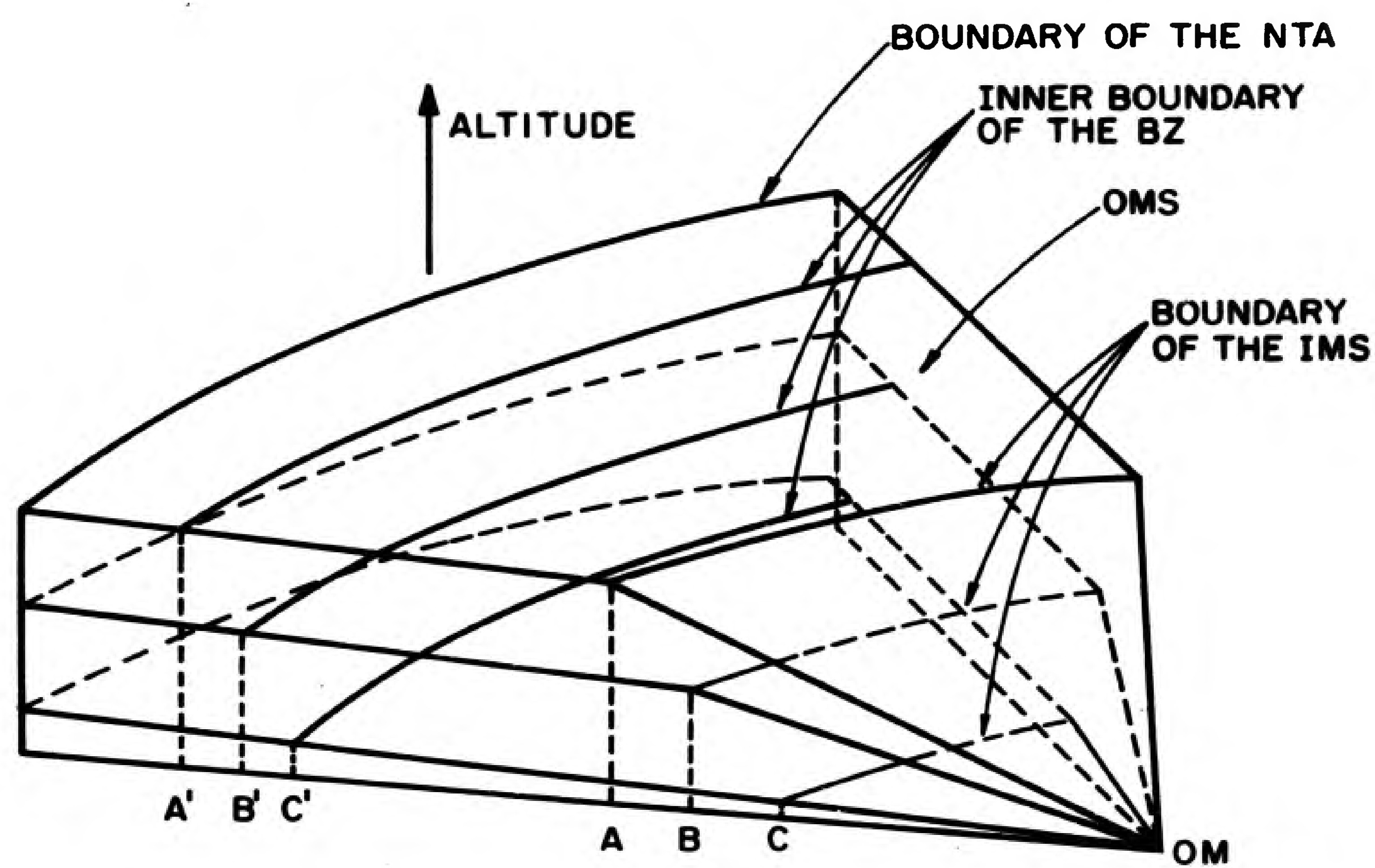

Fig. 2 Segregation of the BZ and OMS in Altitude Levels

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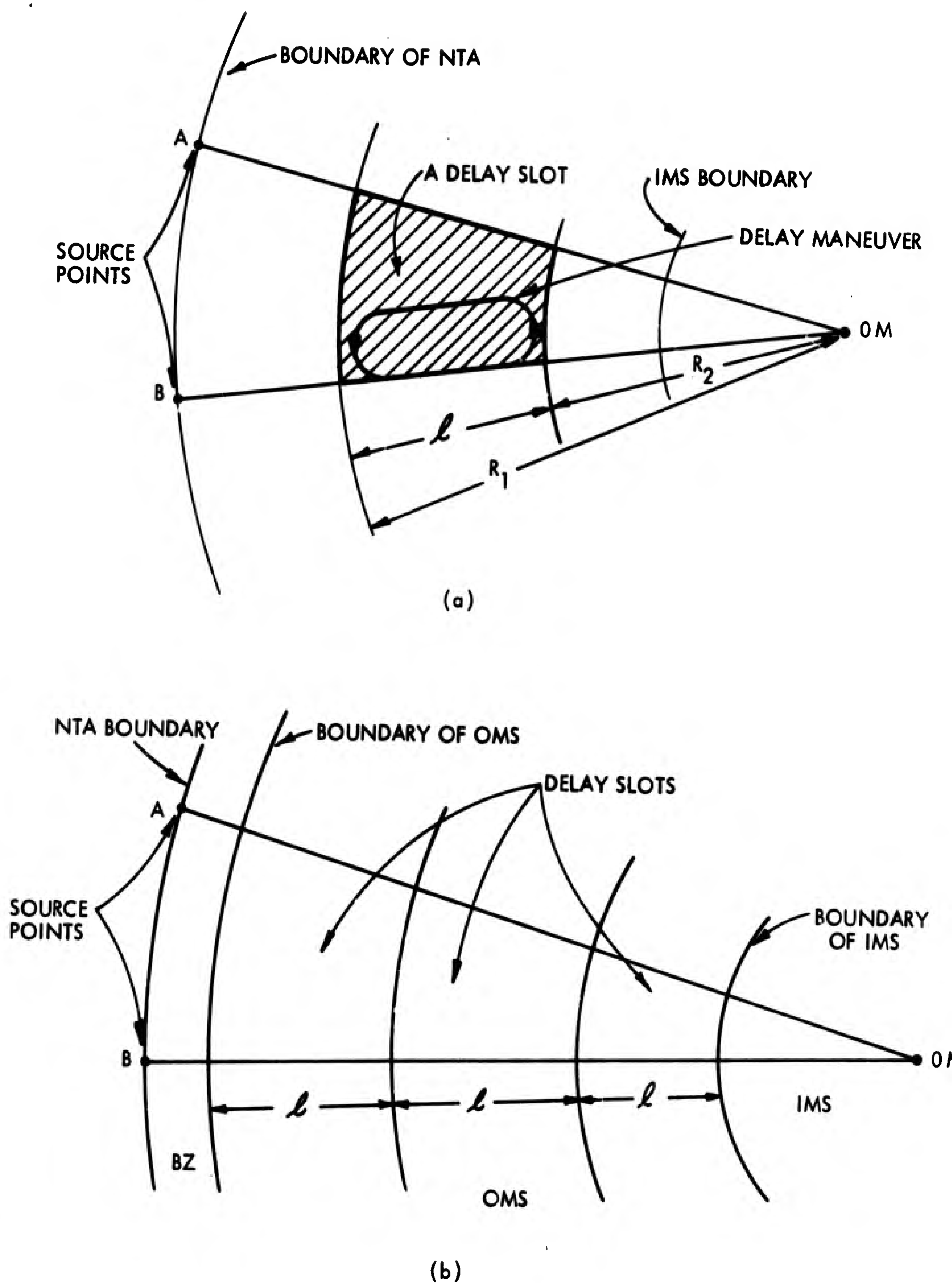


Fig. 3 Illustration of Delay Slots

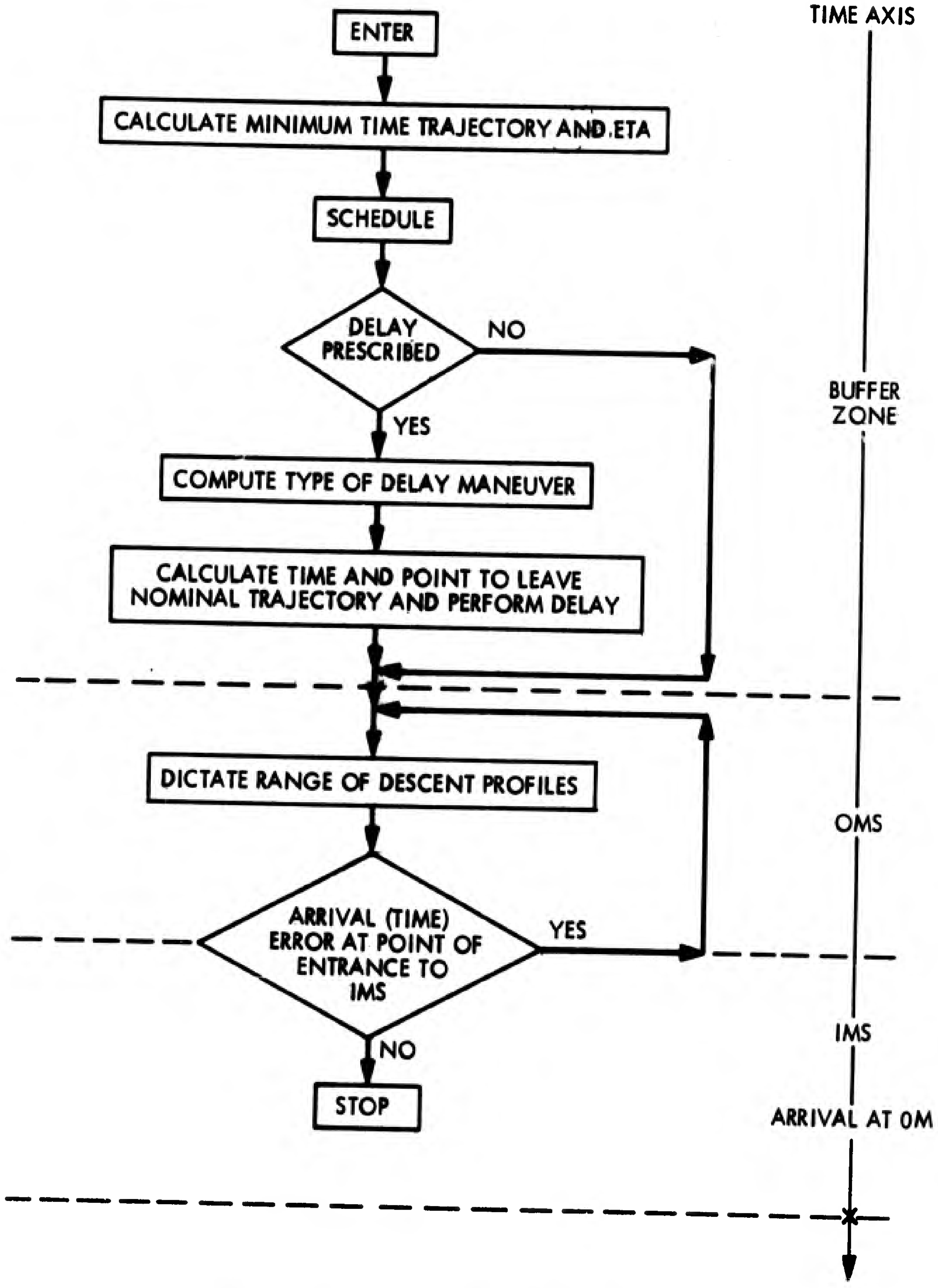


Fig. 4 The Function of the ATC Algorithm

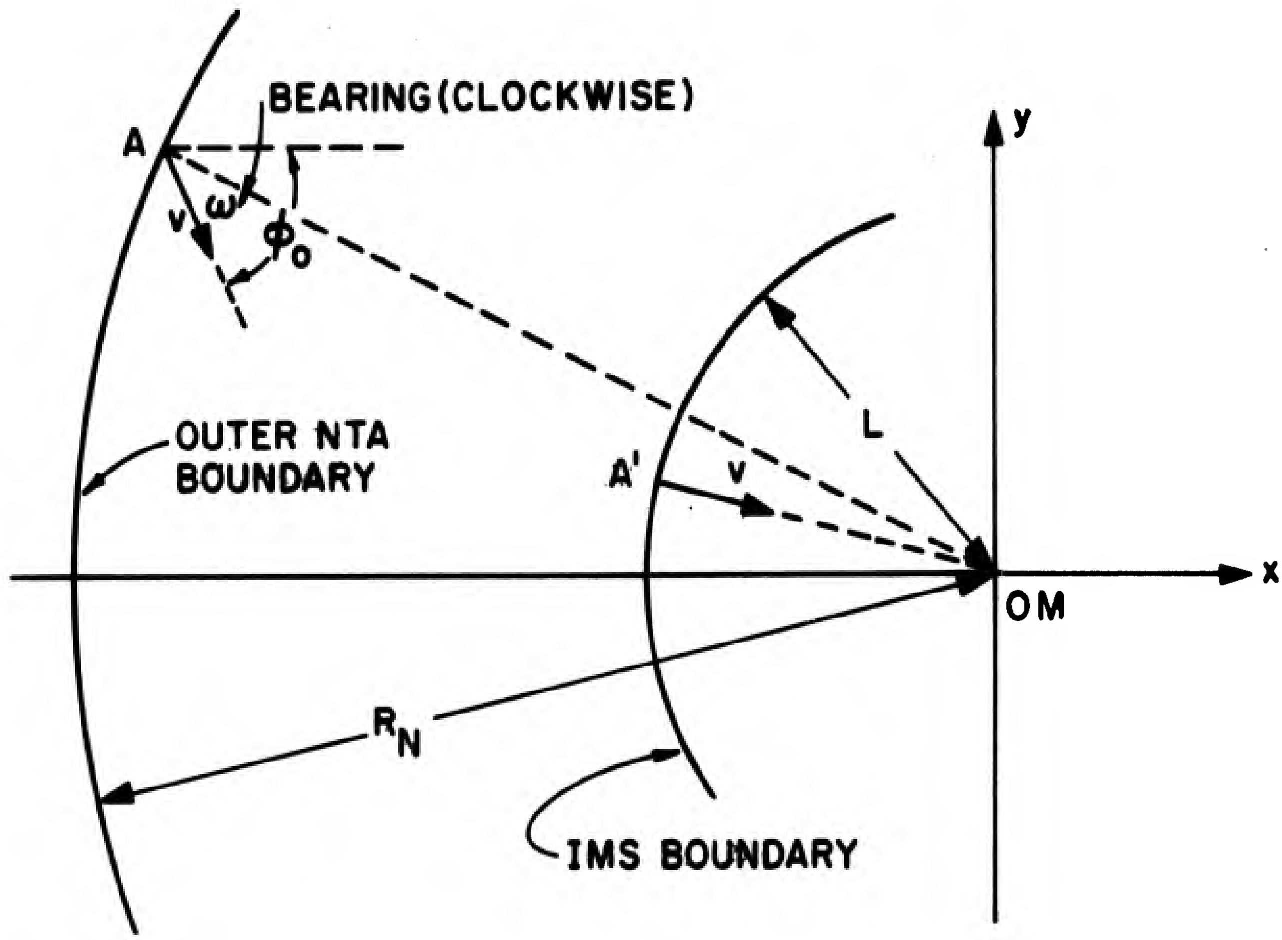


Fig. 5 Illustration of the Minimum Time Problem

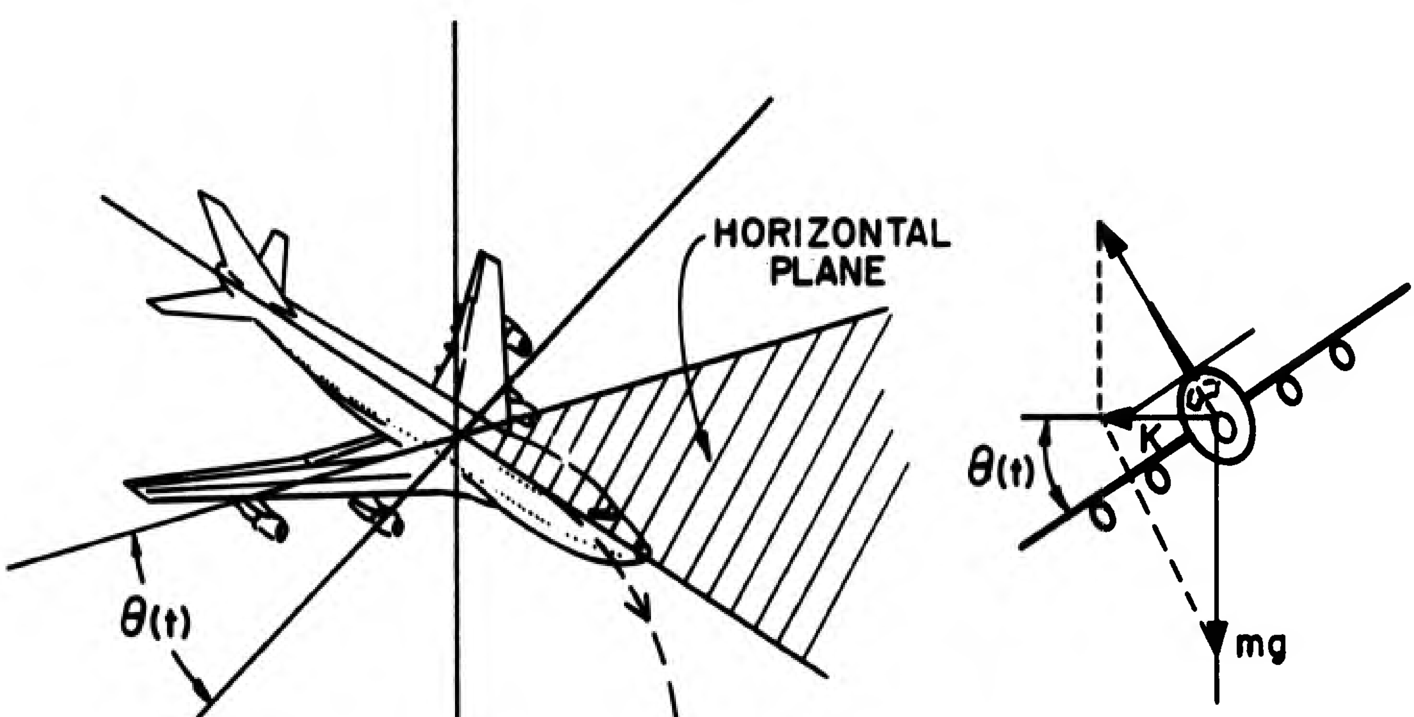
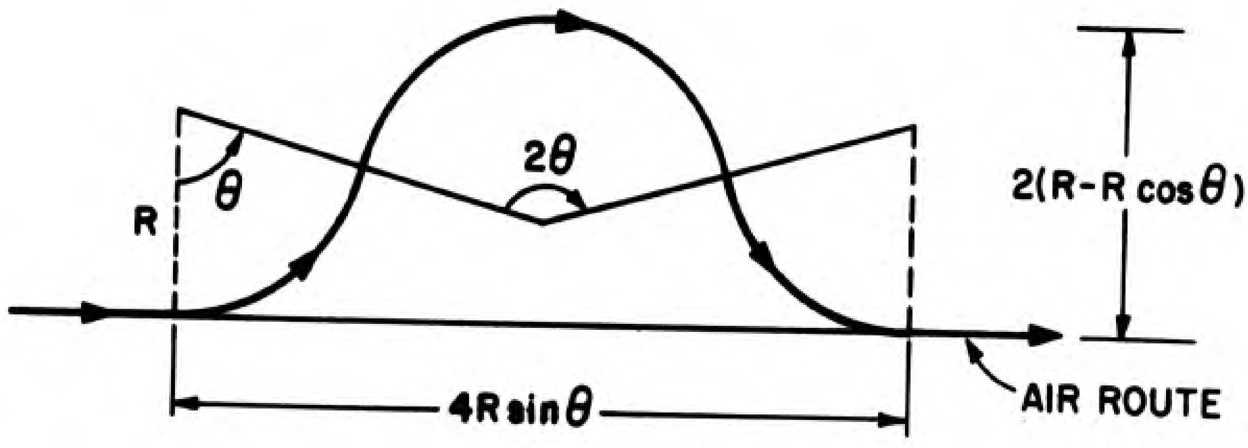
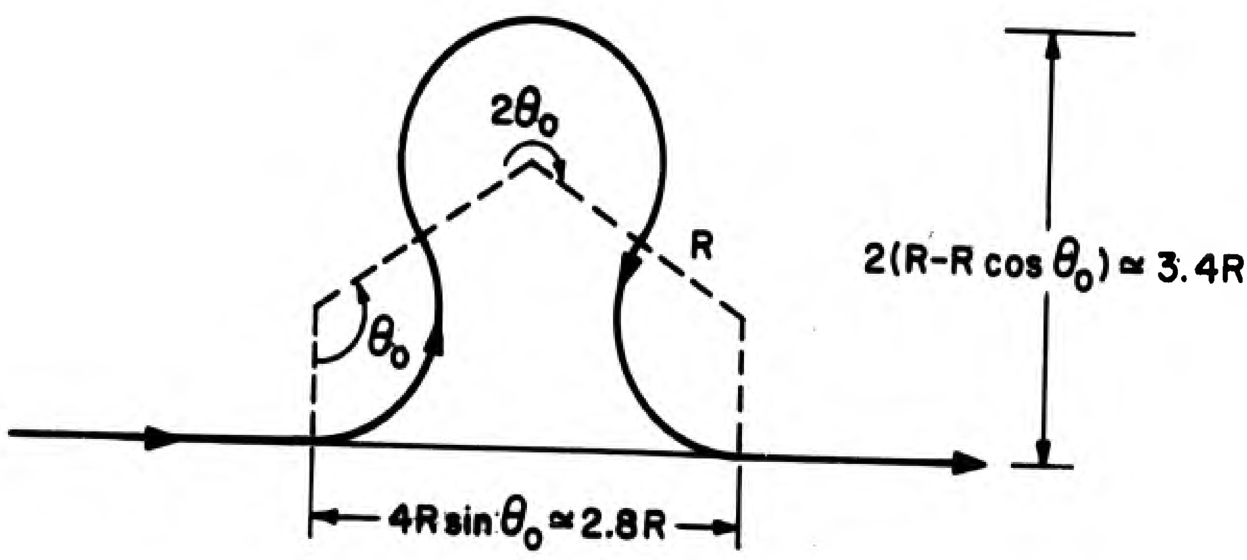


Fig. 6 Aircraft Turn

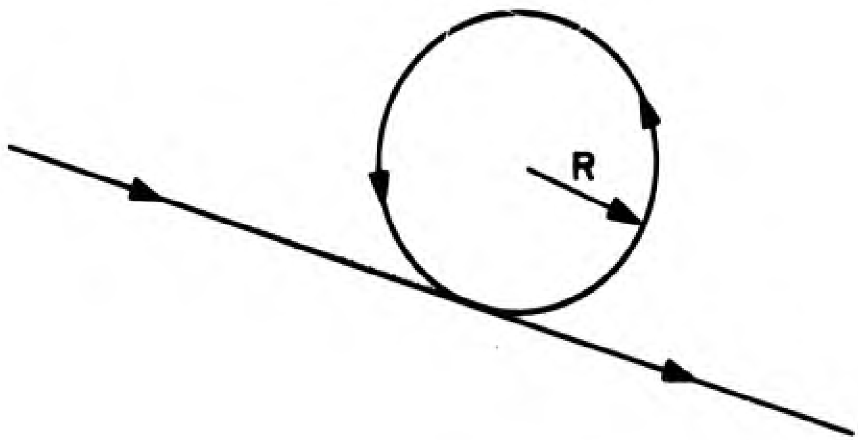


(a) The Oscillation (or θ Delay) Maneuver

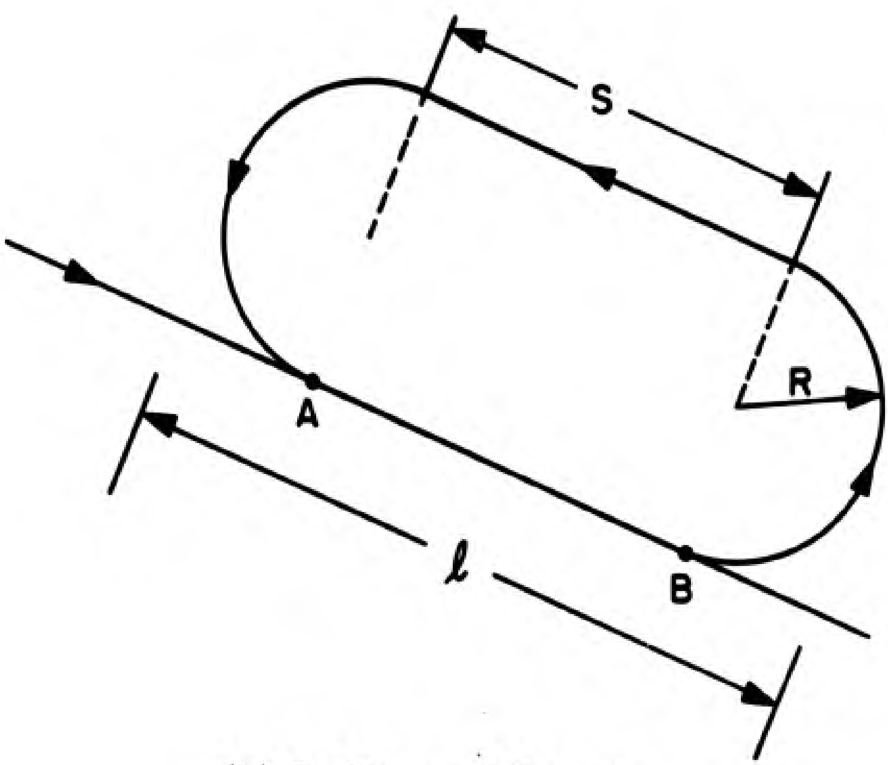


(b) Maximum Oscillation Maneuver

Fig. 7 θ Delay Maneuvers



(a) The Circle Maneuver



(b) The Fly-around Maneuver

Fig. 8

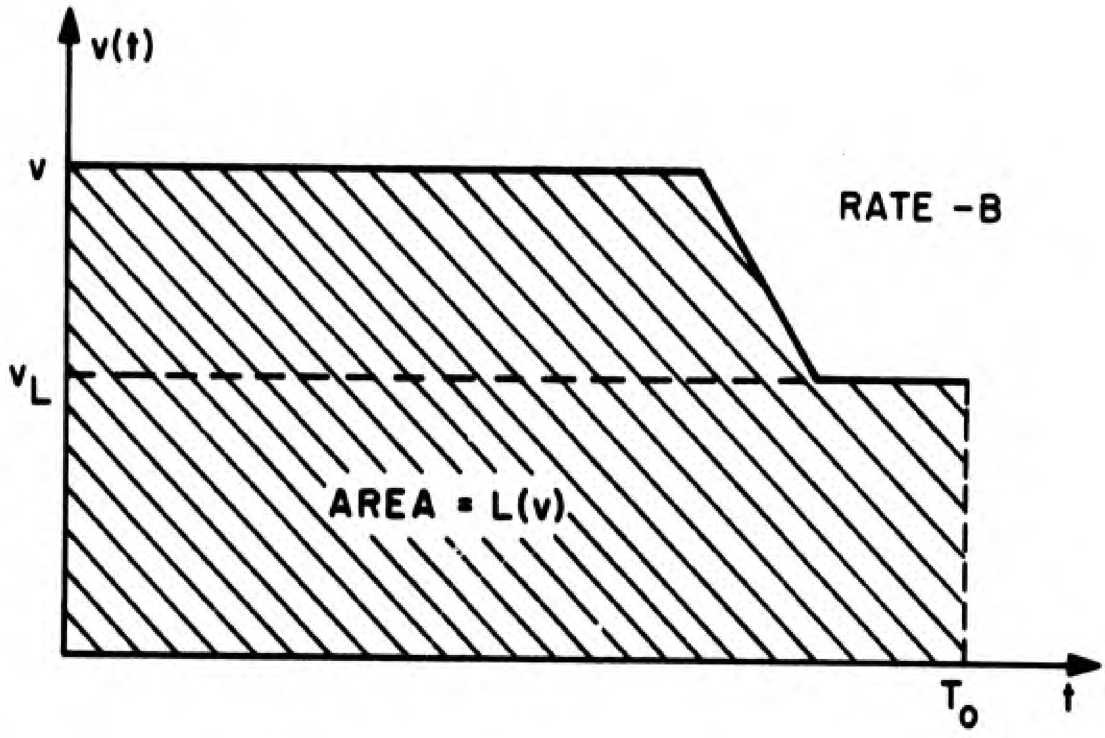


Fig. 9 Velocity Profile of an Aircraft in the IMS

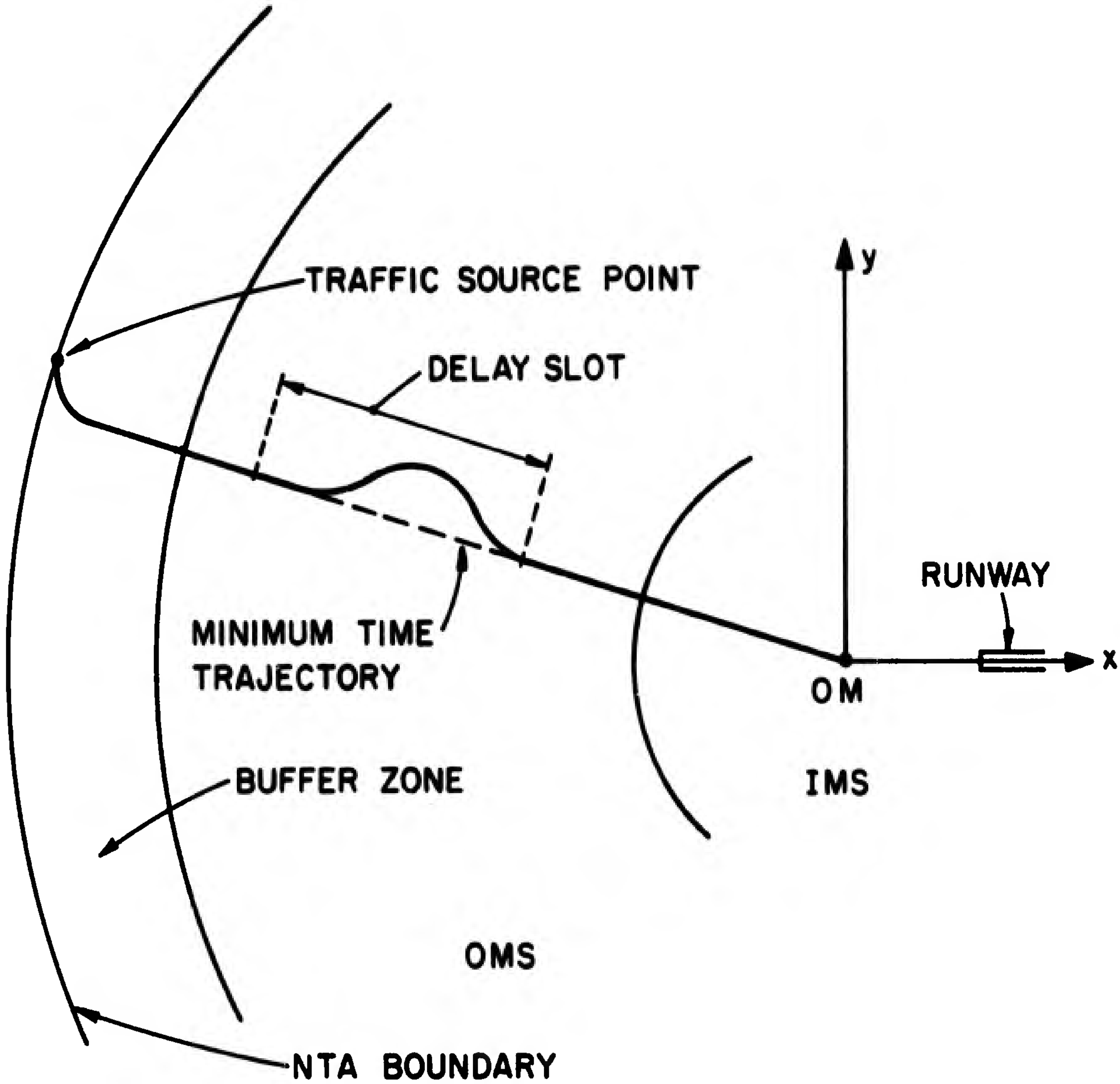


Fig. 10 Typical Aircraft Trajectory Adopted (Planar View)

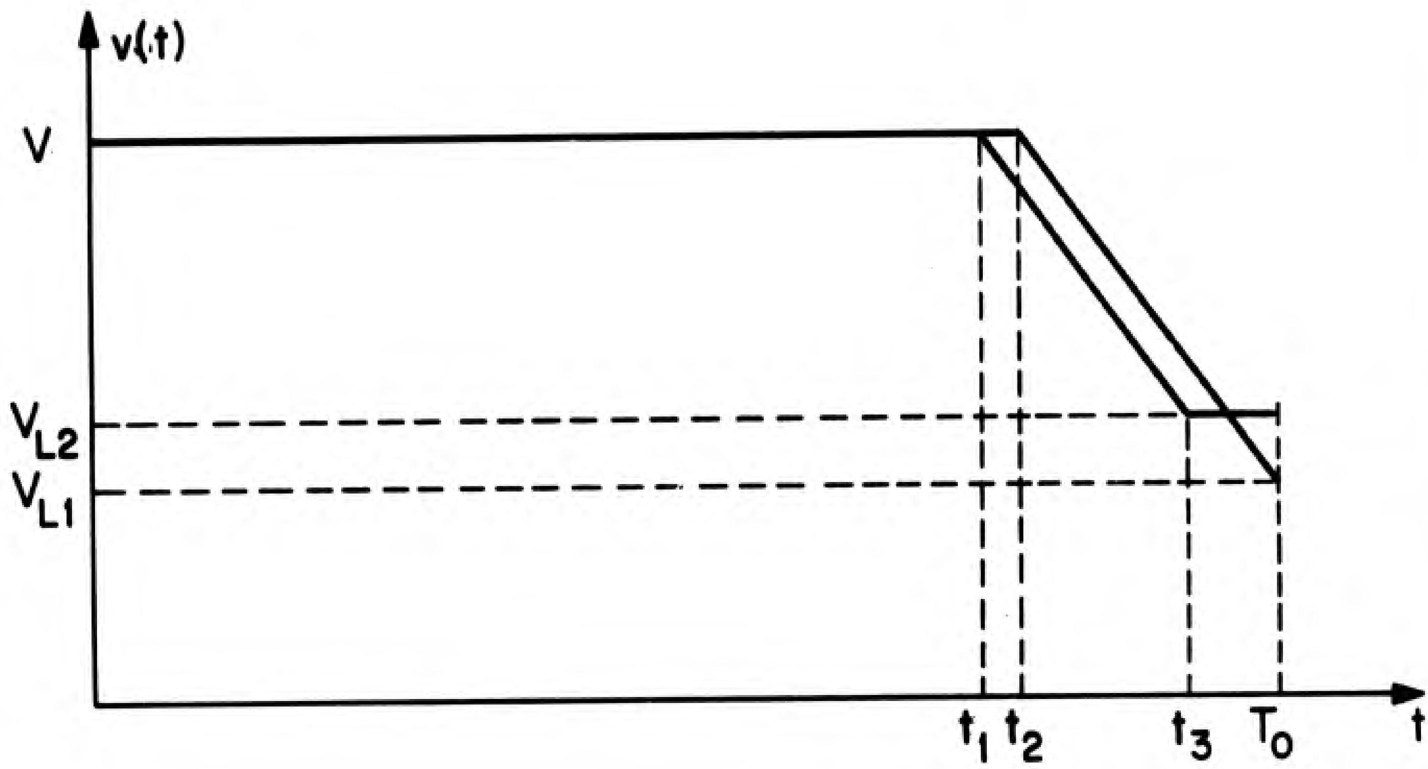


Fig.11 Range of Speed Profiles in the IMS for Aircraft of Level H_v

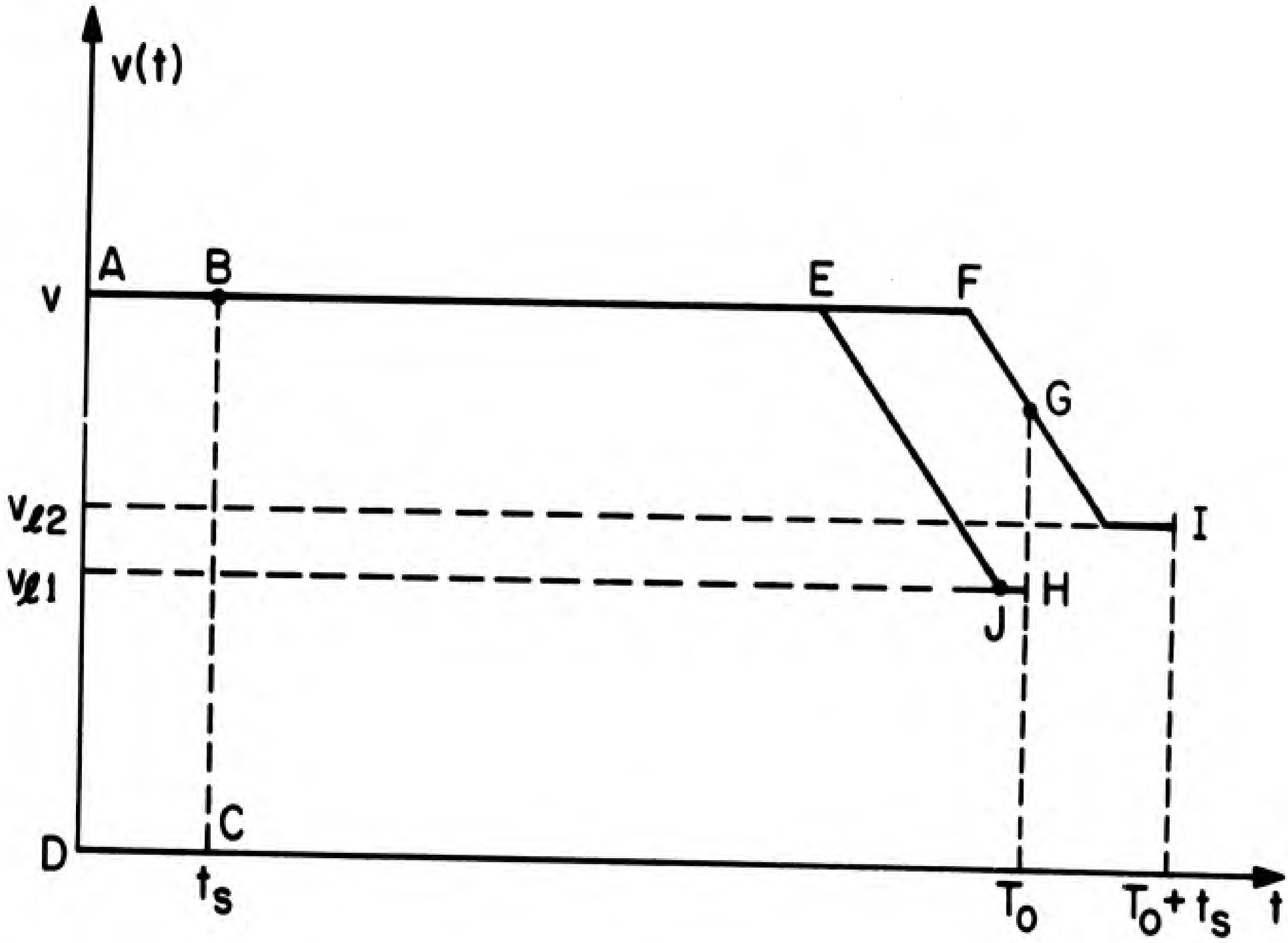


Fig. 12

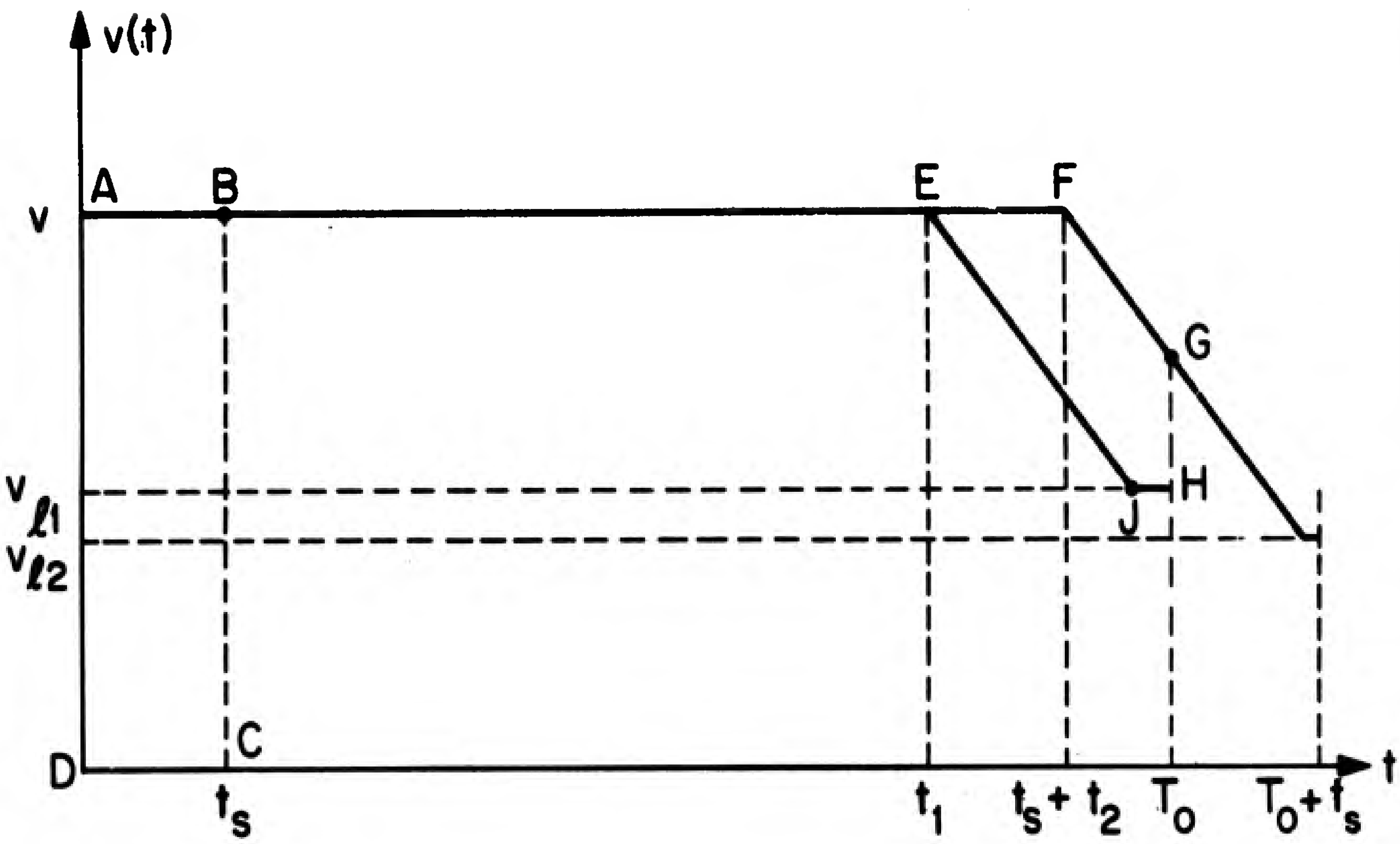


Fig. 13

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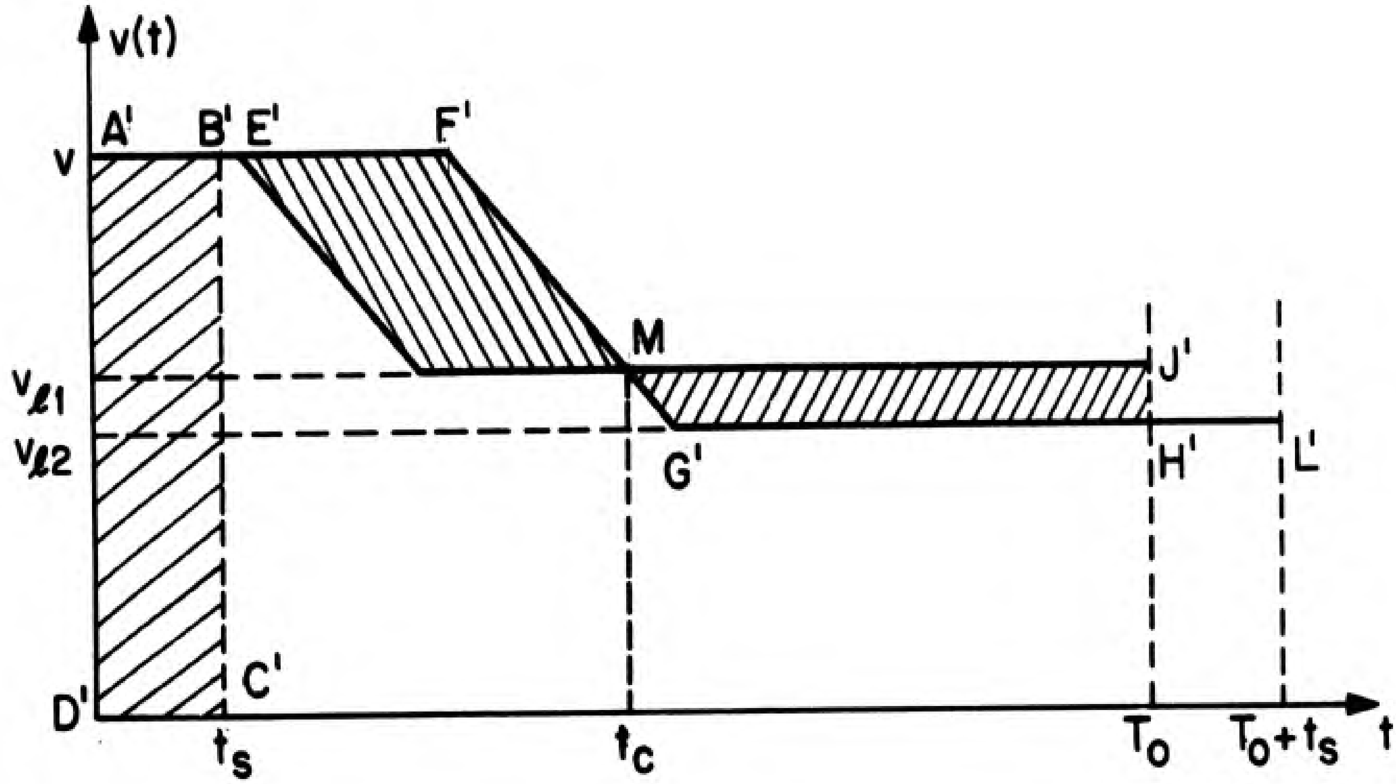

Fig. 14 Conflict in the IMS Arising from "Bad" Choice of L(v)

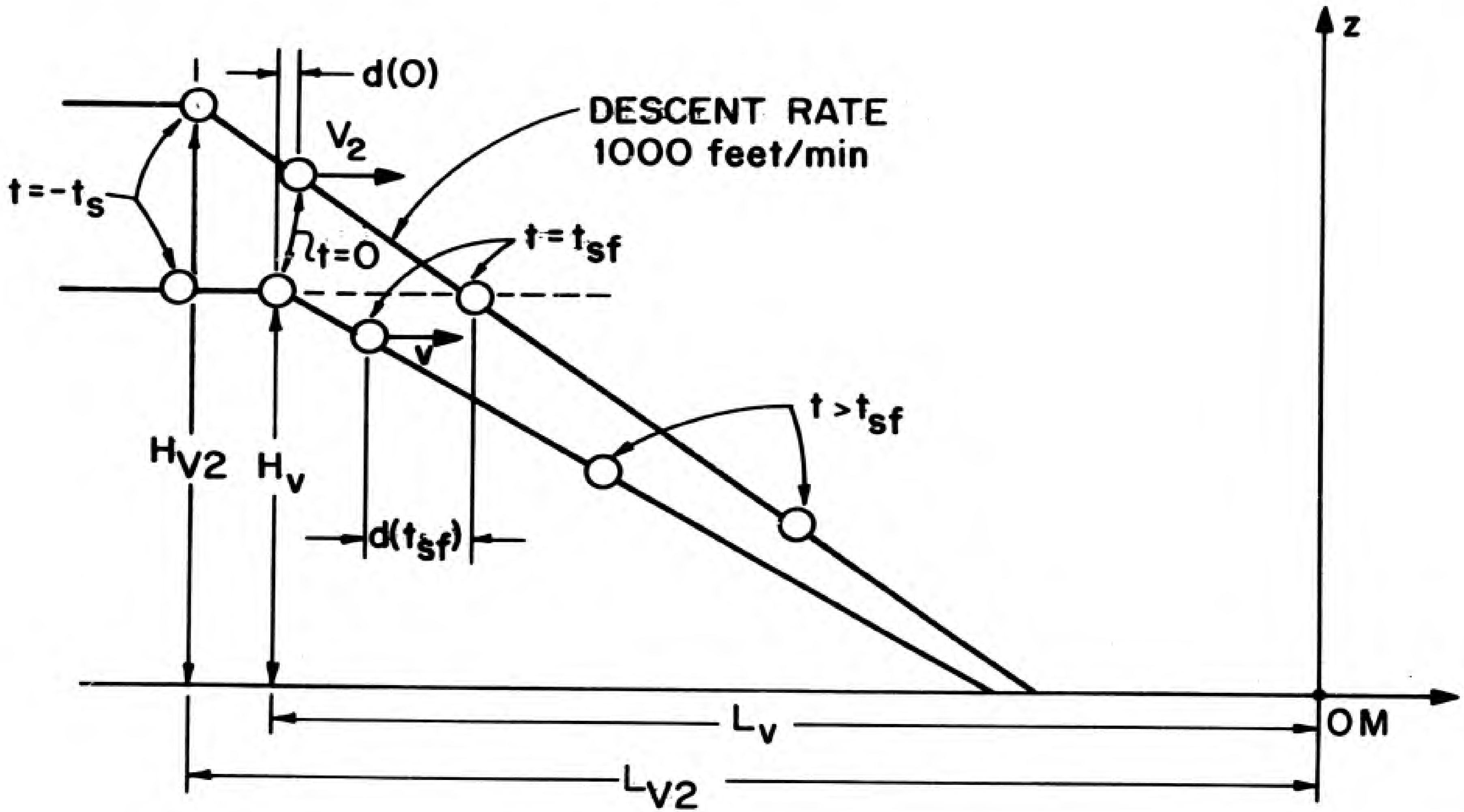

Fig. 15 Progress of Successive Aircraft Entering IMS from Adjacent Altitude Levels

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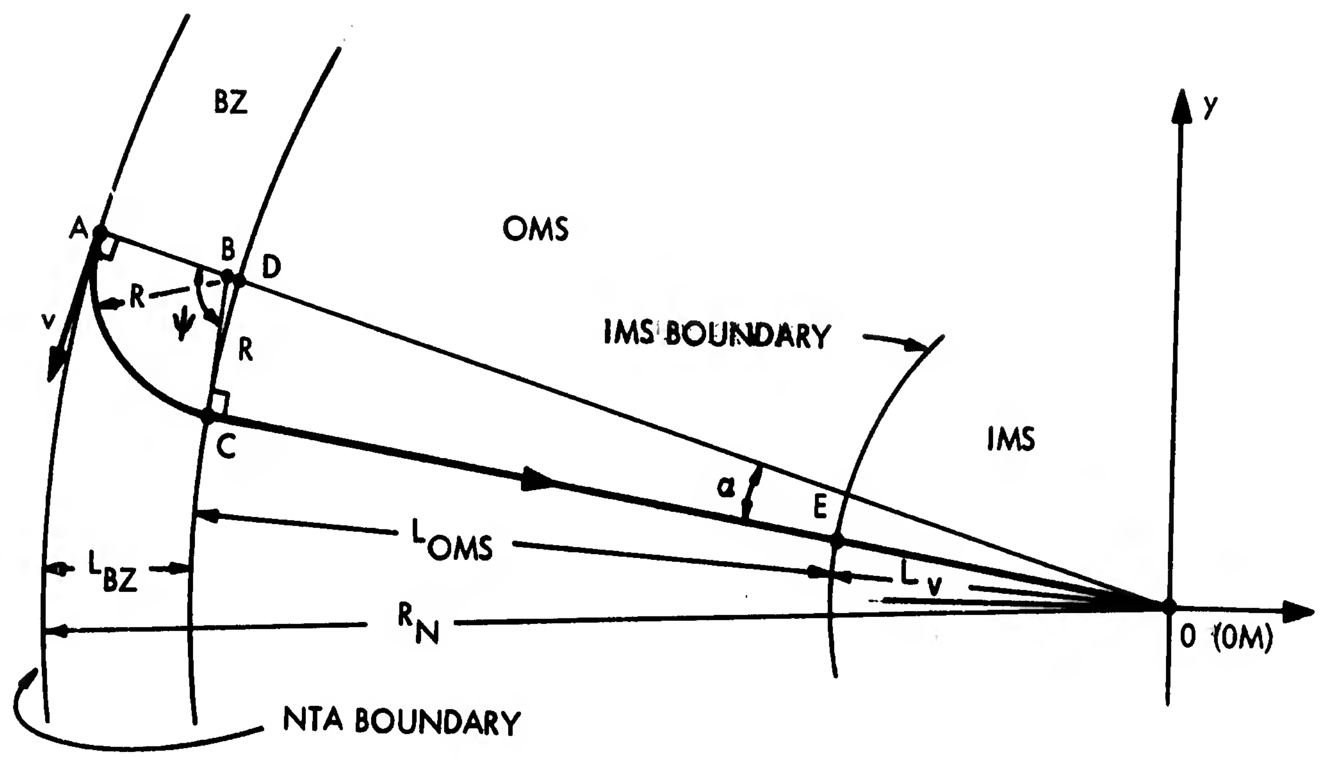

Fig. 16 Buffer Zone for an Altitude Level

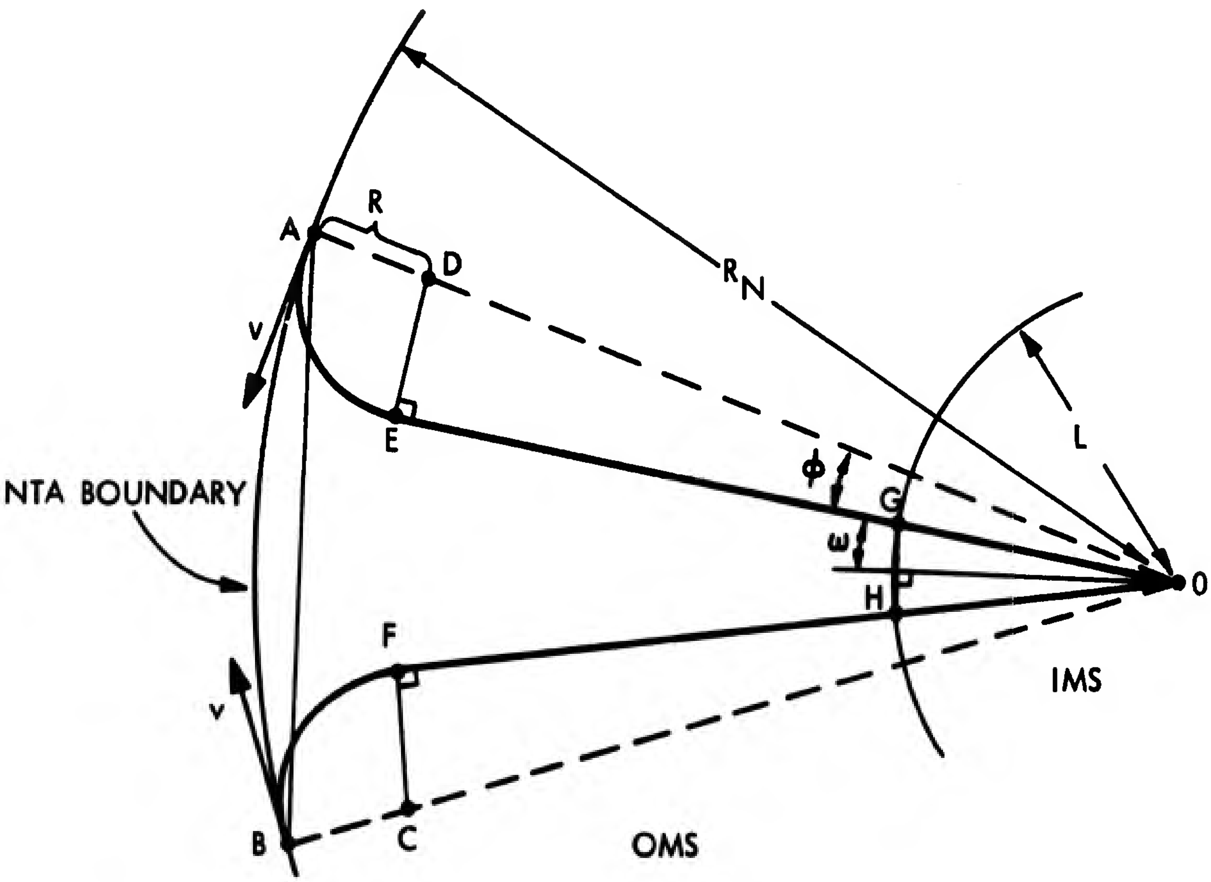

Fig. 17 Geometry for Choice of Source Points

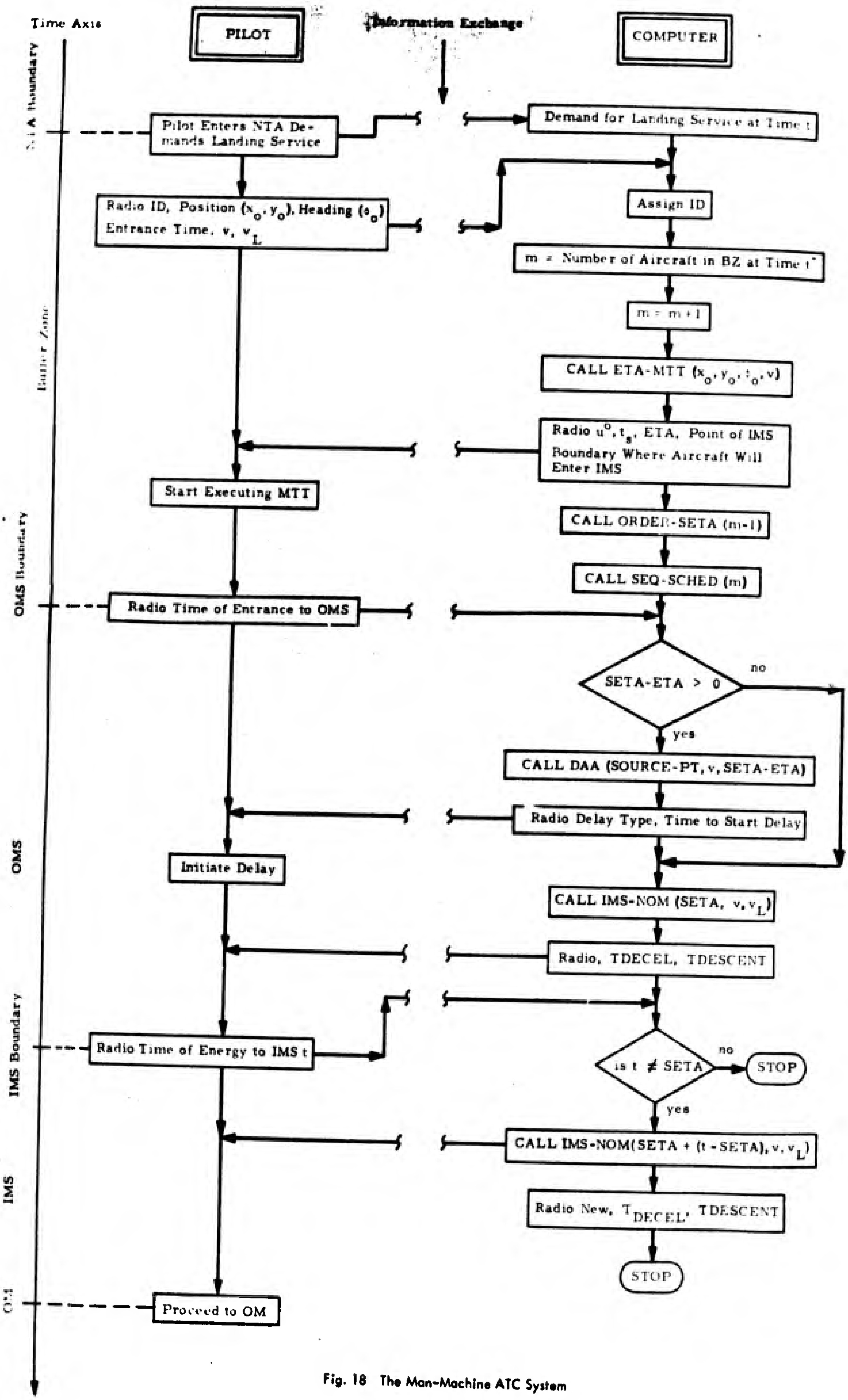

Fig. 18 The Man-Machine ATC System

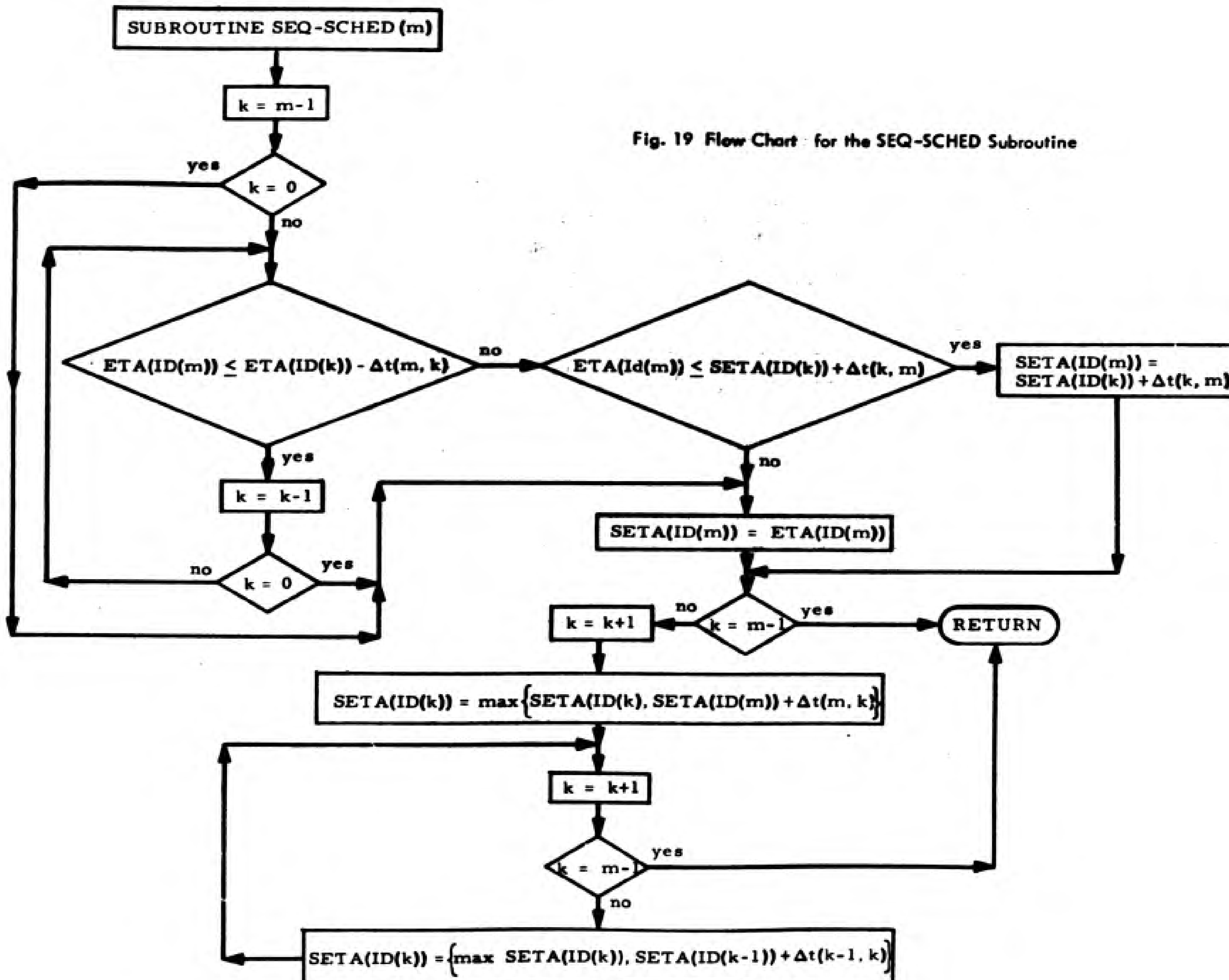

Fig. 19 Flow Chart for the SEQ-SCHED Subroutine

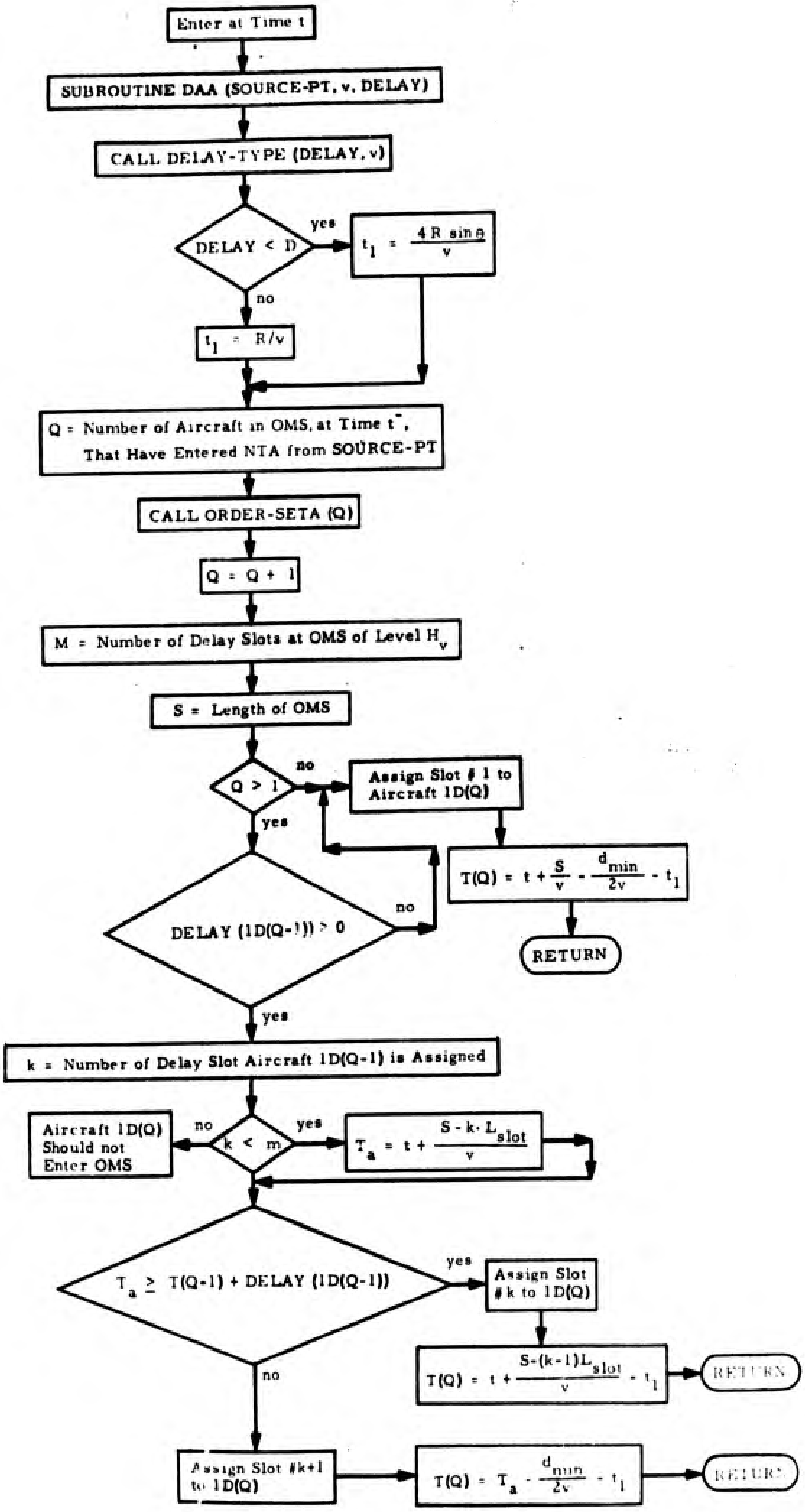

Fig.20 Flow Chart for the Subroutine DAA