A MODEL CONCEPT OF AIR-GROUND COMMUNICATIONS IN TERMINAL APPROACH CONTROL
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A Model Concept of Air-Ground Communications
in Terminal Approach Control

by

Noriyasu TOFUJI*

Abstract

This report contains the results of a model concept development for computer simulation of
the air-ground communications in the terminal approach control. The purpose of this model concept
is to relate the message generation of the air-ground communications with the aircraft movement and
utilize statistics of a single communication transaction and message element, so that the statistical
behaviour of communications will be examined for approach control in different terminal areas and
for different traffic volume.

In the model concept, the aircraft movement is modeled so as to follow the flight profile which
is defined in terms of the arrival route, the altitude, and the speed. The arrival route consists of the
linear and curved portion, and it is assumed that aircraft fly along the linear portion by adjusting the
heading, and in the curved portion, they maintain a constant indicated airspeed, a constant bank
angle, and a constant altitude. With regard to the wind effects, a wind pattern which varies with the
altitude is used.

The communications are to be generated based upon a message generation mechanism, and an
arrival time estimation method based upon the simplified altitude and speed profiles is introduced
for the heading instruction, the altitude instruction, and the speed adjustment instruction. The time
required to complete a message element will be approximated with the gamma distribution as will
those of the communication transaction and transmission.

This model concept still includes some unresolved areas, e.g., a selection of the gamma distribu-
tion's parameters for the message element. In the next stage, further studies and refinement will
be worked out.

* Evaluation Division
1. INTRODUCTION

In today's Air Traffic Control (ATC) environment, the air-ground communication system is essential to maintain safety and efficiency of air traffic. It serves as a link between the controller and the pilot, and is being operated by means of voice communications on VHF/UHF radio frequency channels. Aircraft flying under the services of the ATC system communicate with the ATC facilities using this communication system. An increase in air traffic, therefore, is accompanied with heavy communication congestions. Matter of fact, the air traffic increase in the early 70's in Japan caused heavy communication congestions in high-density airspaces and terminal areas. The statistical analysis of eight hours of communication data gathered at the Tokyo and Osaka International Airport (TIA and OIA) in 1974 found that the channel utilization of approach control reached nearly 80 percent in very busy hours.\(^1\) It also found that the number of communication transactions per aircraft and the occurrence rate of message elements varied depending upon the hourly traffic, arrival routes, and control procedures, i.e., holding, vectoring, and their mixture. The channel utilization in this analysis was defined by the sum of the communication transaction time in a certain time interval. Busch\(^2\) and Dunlay Jr.\(^3\) used the channel utilization to derive the controller's communication workload. Hunter et al.\(^4\) conducted an extensive statistical analysis of busy two hours of communication data of 101 sectors in the New York Air Route Traffic Control Center (ARTCC) in 1974, and developed and validated a simulation (GPSS-V) model for New York ATC communications based upon the analytical results.\(^5,6\) It was observed that, by comparing the results of Reference 1 with those of Reference 4, statistics relating to a single communication transaction and message element were similar to each other.

The purpose of the model concept for computer simulation described in this report is to relate the message generation of the air-ground communications with the aircraft movement under the services of approach control and utilize statistics of a single communication transaction and message element, so that the statistical behaviour of communications will be examined for approach control in different terminal areas and for different traffic volume. Then, it will be possible to evaluate the capacity of the air-ground communications and obtain a basic data for the future communication system design. The reasons of selecting approach control are that it is the most complicated and busiest portions of the ATC system, and it is a potential candidate for a future introduction of the data link.

This report first describes a basic approach, that is, a scope of the model concept and how the factors which affect the air-ground communications are treated. Second, a modeling of approach control including the flight profile and the aircraft movement is given so as to cover approach control in different terminal areas. Then, statistics of the air-ground communications are reviewed referring to the results of the statistical analyses mentioned above, and a message generation mechanism is considered in relation to the aircraft movement. Finally, a computer simulation aspect is briefly described.

2. BASIC APPROACH

A typical configuration of the present ATC system is depicted in Figure 1. It shows a cross-section in view of the flight progress, and consists of three control positions of Control Tower, two control positions of Instrument Flight Rules (IFR) Room, and two control sectors of Area Control Center (ACC)*. These control positions and sectors are linked with aircraft by means of surveillance and communications.

With regard to the air-ground communication system, two frequencies (primary and secondary) are usually assigned to each control position or sector. An aircraft enters the air-ground communica-

\* The term, "ARTCC", is used in the U.S.
tion system when she calls for starting engines at her departing airport, and then she is under the services of the air-ground communication system until reaching a ramp of her destination airport. The controllers on the ground always watch for conflicts and provide for efficient flow giving her appropriate instructions and information, if necessary. There are various kinds of instructions and information for these communications, and most of them are issued in terms of the phraseology adopted by the International Civil Aviation Organization (ICAO). This would result in statistics of a single communication transaction and message element being similar without regard for differences in the types of the terminal area.

Approach control position hatched in Figure 1 serves arriving aircraft between enroute transition and local control, i.e., the descent phase before landing. The first communication for an initial contact with approach control will consist of pilot initiated progress reports (altitude, speed, route to fly, ATIS* confirmation, etc.) and the controller’s reply (initial instruction for next progress, e.g., descent and speed adjustment, and altimeter setting value). The last communication with approach control will include the information for transfer (hand-off) to local control, e.g., frequency change and hand-off point. Also ATC clearance for final approach and landing should be given prior to or in the last communication.

1. ATC FACILITY ← Control Tower ← IFR Room ← ACC
   (Entrance)

2. Sector or Position
   (Exit) ← Clearance Delivery ← (Taxi) ← Ground Control ← (Take-off) ← Local Control ← (Landing)
   → (Taxi) → (Approach Control (Descent)) ← Departure Control → (Climb) ← Enroute Transition (Climb & Cruise) ← (Descent & Cruise) → (Cruise) → Enroute

3. Surveillance ← Flight Progress Strip ← VHF/UHF Air-Ground Communications ← RDP/FDP**

4. Communication
   Legend:
   Flight Progress
   Flight Phase

**FIGURE 1** ATC system configuration

These three communications are considered as very minimum requirements. On the other hand, in-between communications will be issued depending upon traffic volume, arrival route configurations, and control procedures, etc.

In addition, the model concept is based upon the air-ground communications in the Automated Radar Terminal System (ARTS)**. III operational environment, and is to be applied to a computer simulation of the air-ground communications due to arriving air-carrier aircraft operations for one hour in a large hub terminal area. The ARTS-III can provide the controller with the following: 1) aircraft (target) symbol, 2) alphanumeric aircraft identification, 3) Mode-C reported altitude, and 4) calculated ground speed, etc., in every four seconds. In these air situations, the factors which affect the air-ground communications will be chosen as shown below:

* Automatic Terminal Information Service.
** The Radar Data Processing (RDP) and Flight Data Processing (FDP) system are similar to NAS-A (National Airspace System – enroute Stage A) in the U.S.
*** The ARTS-III is in operation at the Tokyo and Osaka International Airport in Japan and at 63 airports in the U.S.
1) Traffic : Traffic volume, mixture, and flow.
2) Static system : Flight profile and airspace.
3) Aircraft : Aircraft movement in horizontal and vertical plane, plus speed.
4) Environment : Weather (particularly winds).
5) Ground Surveillance : Surveillance radar and processing system (ARTS-III).
6) Message control : Separation criteria and message generation mechanism (part of the ATC procedures).
7) Communication Link : Voice link (time required to complete message exchanges).

Figure 2 illustrates the relationships between these factors. It also shows how they are treated in the model concept. That is,

a) To a given input (Factor 1, traffic), Factors 2) to 6) will act on and produce a set of communication data composed of communication times and messages.

b) To the output obtained above, Factor 7) will act on and produce channel utilization data.

FIGURE 2 Relationships between factors in the model concept
3. MODELING OF APPROACH CONTROL

This section is divided into three subjects, Traffic Elements and Control Procedures, Flight Profile, and Flight Progress, which are related to the traffic data generation and the aircraft movement in the descent phase before landing.

3.1 Traffic Elements and Control Procedures

The terminal ATC system handles several traffic elements, for example, arriving and departing aircraft in view of the flight phase, air-carrier and non air-carrier aircraft in view of the aircraft category, etc. Among them, the model concept, as mentioned in 2, is directed to simulate the air-ground communications due to arriving air-carrier operations for one hour. Therefore, traffic elements and their interactions are considered first.

3.1.1 Arriving and Departing Aircraft

As shown in Figure 1, arriving and departing aircraft are served by different control positions when flying under the services of IFR Room, and they communicate with the controllers using different frequencies. Arrival and departure routes are designed so as to alleviate unnecessary control tasks of maintaining the separation between arriving and departing aircraft. But they are not totally independent to each other. The following will be considered as major interactions of departing aircraft with arriving aircraft:

1) Runway use condition.
2) Traffic information.

The runway use condition will be an indirect interaction, since it will primarily affect the arriving aircraft acceptance rate. According to the FAA Advisory Circular, the single runway configuration has a 42 (aircraft) runway operation capacity, and two intersecting runway configuration has a 42 to 60 (aircraft) runway operation capacity. Here, the runway operation capacity means the IFR practical hourly capacity. In the former, both arriving and departing aircraft share one runway, and in the latter, it is very likely that they use two runways separately or one of two depending upon wind conditions. This means that in both cases, the number of runways in use is one for arriving aircraft. Most of Japanese major airports are in this class, and the major airports in the U.S., except for those where the parallel runway operation is made simultaneously for arriving air-carrier aircraft, will also use one runway for arriving air-carrier aircraft in a specific wind condition and if the aircraft operation is limited to that for one hour. Therefore, the following are first assumed as a basis of the model concept development:

a) One runway is used for arriving air-carrier aircraft.
   b) Maximum rate of arriving air-carrier aircraft is 30 for one hour.

Traffic information will affect the air-ground communications more directly. Where arrival and departure routes are closely located, though not violating the separation criteria, and when an arriving and departing aircraft fly there at about same time, traffic information may become necessary to give a proper warning or information to one or both aircraft. This is made by the air-ground communications, e.g., “Your traffic is a departure on heading 290 . . . .”. This interaction is discussed further in the latter section (4.3.4).

3.1.2 Air-carrier and Non Air-carrier

Further consideration of traffic elements concerns air-carriers and non air-carriers, i.e., air-taxi and general aviation. It is understandable that air-carriers are high performance jet aircraft categorized in the weight class of Heavy or Large, and non air-carriers are small jet aircraft and light airplane. The difference in performance of these aircraft results in their flights being separated in the terminal
area, except for the area close to the final approach course. In this area, when necessary, traffic
information, e.g., "Traffic behind/ahead . . . .", is issued to arriving aircraft. It is sometimes fol-
lowed by the speed adjustment instruction for spacing between two successive arriving aircraft, e.g.,
"If feasible, reduce your speed to 160 knots . . . .". Flights of non-air-carriers in this area will increase
this kind of traffic information for air-carriers. But this interaction would be negligible*.

### 3.1.3 Aircraft Type

Two weight classes, Heavy and Large, mentioned in 3.1.2 are shown in Table 1. They are re-
ferred to in the FAA Manual on ATC(8). For simplification sake, two aircraft types, Aircraft-Heavy
and Aircraft-Large, are used in the model concept. This is necessary to apply the separation criteria
due to wake turbulence of the heavy aircraft. Presently, the criteria shown in Table 2 are used in ap-
proach control for two successive arriving aircraft flying at the same altitude or within 1,000 ft.

<table>
<thead>
<tr>
<th>TABLE 1 Aircraft weight class(8)</th>
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<tr>
<td>Heavy</td>
</tr>
<tr>
<td>Large</td>
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</table>

<table>
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<tr>
<th>TABLE 2 Separation criteria for arriving aircraft(8)</th>
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<tbody>
<tr>
<td>(Radar control)*</td>
</tr>
<tr>
<td>Leading Aircraft</td>
</tr>
<tr>
<td>Heavy</td>
</tr>
<tr>
<td>Heavy</td>
</tr>
<tr>
<td>Large</td>
</tr>
<tr>
<td>Large</td>
</tr>
</tbody>
</table>

* This table is only for combinations of Heavy and Large.

### 3.1.4 Traffic Flow and Control

Figure 3 illustrates an ATC terminal arrival scheme using two pairs of the enroute transition
sector, the approach control position, and the entry fix. The terminal area has an outer area served
by enroute transition, and has entry fixes near the boundary.

![FIGURE 3 ATC terminal arrival scheme](image)

* VFR (Visual Flight Rules) aircraft operations in major Japanese airports are less than 4 percent of total
aircraft operations, and most of them are non-air-carrier aircraft.
It will be reasonable to consider that the aircraft which have departed from different airports will arrive at the outer area based upon the Poisson (random) arrival without regard for the specific route or sector. After that, if there is no additional control for spacing and scheduling by means of speed adjustment, altitude separation, and enroute holding, they will further enter the terminal area in the same fashion. But actually, some of them will have to have such control. Therefore, in the model concept, it is assumed that approach control handles a modified or previously controlled aircraft series.*

In Figure 3, approach control is divided into two control positions. This is called the sector division, and is made depending upon the terminal area size and traffic volume. In this situation, each control position will have its own air-ground communication frequencies, i.e., primary and secondary. Typical examples are a simple area division and a division along the flight progress, for example, North and South, and approach and feeder. In the former, the aircraft from the north are served by North Approach Control until reaching the jurisdiction of local control, and those from the south by South Approach Control in the same way. In the latter, they first communicate with approach control, then with feeder control. The latter case requires additional communications for hand-off. Therefore, it will be necessary to prepare one or two control positions, in order to examine the effects of these sector divisions relating to the channel utilization and communication queue problems.

3.2 FLIGHT PROFILE

The flight profile is to specify a static structure of the flight path in terms of the arrival route, the altitude, and the speed, and it relates closely to the message generation of the air-ground communications. This section describes a modeling of the flight profile, and its related communication aspects, initial contact and transfer.

3.2.1 Arrival Route Configurations

Figure 4 shows a simplified arrival route configuration which has two entry fixes, one exit (i.e., one runway in use for arriving aircraft), two holding points, and an alternative route for each entry fix. It is based upon the arrival route configuration actually used in the terminal area of TIA before the opening of New TIA**. On the other hand, the arrival route configuration used in the terminal area of Boston International Airport, which was chosen as a sample of the airport in the U.S., shows different features from Figure 4. That is, as shown in Figure 5, holding is used when traffic becomes congested, but its minimum altitude is 14,000 ft, which is outside of the terminal area, and vectoring is used before aircraft get on the final approach course, if necessary, so that there is no alternative route for each entry fix. It is a simpler configuration, but it will need more precise control of the aircraft schedule, because it has less margin space. In view of fuel saving which is a trend in the present aircraft operation and the ATC system, it will be more efficient. It this section, these two types of the arrival route configuration, i.e., one includes holding points and the other does not, are considered.

* This arrival scheme is discussed further relating to arrival time series in the latter section (3.2.5).
** The communication data analyzed in Reference 1 were gathered in this situation. According to the NOTAM of Japan (Nr. 192, 1977), the arrival route configuration of TIA has had a considerable change because of the opening of New TIA. Appendix 1 shows an arrival route configuration presently used at TIA.
FIGURE 4  Simplified arrival route configuration of TIA (Before the opening of New TIA)

FIGURE 5  Arrival route configuration of Boston International Airport (Runway 04R)
(1) **Modeling of Arrival Route**

As shown in Figures 4 and 5, the arrival route has one or more angled portions where aircraft have to turn, then consequently deviate somewhat from the route. Some of the Standard Terminal Arrival Route (STAR) charts specify the arrival route including the curved portion for turning*. Therefore, it will be more realistic to consider it in modeling the arrival route.

Figure 6 depicts part of two arrival routes named #1 and #2 for explanation. Arrival Route #2 merges Arrival Route #1 in the left upper side of the figure.

![Diagram of Arrival Routes](image)

**FIGURE 6** Modeling of arrival route

In the model concept, several points are used to define an arrival route, and the range and the azimuth from a ground fixed point, i.e., a radar site, are specified for each point together with the altitude and the speed, which are discussed in 3.2.2 and 3.2.3. \( P_{i-1}, P_i, \text{ and } P_{i+1} \) in Figure 6 are part of them. \( P_{i-1} \) is an example of the point where a linear portion of an arrival route merges with another arrival route, which is named the merging point for convenience sake, and \( P_i \) is an example of the point where the extensions of two linear portions intersect. For a very long linear portion, an intermediate point is also used*. In addition, \( P_{i-1}P_i \) is named the route segment in the model concept for distinguishing it from the linear portion.

3.2.2 Altitude Profile

Figure 7 illustrates an altitude profile when aircraft fly along the arrival routes shown in Figure 4. It has a holding stack shown in broken line, which means temporary control. On the other hand, an altitude profile without holding is shown in solid line. Figure 8 illustrates an altitude profile for the arrival routes shown in Figure 5 in the same way. As can be seen in Figure 7, aircraft enter the terminal area at different altitude levels, then they repeat descent and short level flight several times and enter the jurisdiction of local control. The difference in an entering altitude primarily results from that in aircraft performance, e.g., B747 vs. YS11. In Figure 8, aircraft enter the terminal area at

* Refer to Appendix 1.
a single altitude level. This situation is observed in the Boston terminal area particularly for air-
carrier arriving aircraft, and indicates that traffic flow is well arranged before the entry fix.

![Altitude profile (Case A)](image)

**FIGURE 7 Altitude profile (Case A)**

![Altitude profile (Case B)](image)

**FIGURE 8 Altitude profile (Case B)**

The number of descent and level flight phases will be determined by the route time to fly from
the entry fix to the runway, and traffic volume. For example, in the Boston terminal area, the airc-
craft from the west proceeding to Runway 04R (the primary runway for arriving air-carrier aircraft)
will have four descent phases, $140 - 100 - 60 - 40 - 30$ ($\times$ 100 ft), which correspond with the
altitude instructions issued by the controller. Aircraft, on receipt of the altitude instruction, will
start descending with an appropriate descent rate, and after reaching the assigned altitude, will
maintain that altitude until receiving the next altitude instruction.

1. **Modeling of Altitude Profile**

   For modeling the altitude profile like Figures 7 and 8, the basic altitude $H_i$ is specified at
   $P_i$ ($i = 1, 2, \ldots, n$), and it is assumed that aircraft are in a level flight when passing $P_i$ or its nearest
   point in case of turning. But when traffic becomes congested and two or more aircraft fly closely
   in trail or when two or more aircraft from different arrival routes pass near the merging point closely
   in time, it may be difficult to assign $H_i$ to the following aircraft, since the leading aircraft may be
   still flying at $H_i$. 
In this situation, these aircraft may cause a threat of conflict. Therefore, as one of the resolution methods, it will be necessary to assign an alternative altitude to the following aircraft. To permit this assignment, a variable range is also given to $H_i$. This variable range is named the altitude gate $\Delta H_i$ in the model concept. It will be, for example, from 1,000 ft below to 1,000 ft above $H_i$ for merging points, and will be broader in range for holding points*. $\Delta H_i$ is also used, particularly at the entry fix, to cover the difference in an entering altitude (see Figure 7). Figure 9 depicts a modeling of the altitude profile for one arrival route.

\[ \text{FIGURE 9} \quad \text{Modeling of altitude profile (Referred to Figure 7)} \]

Finally, the term, altitude, is represented by the pressure altitude, which is decoded on-board and is sent to the ground radar processing system (ARTS-III).

### 3.2.3 Speed Profile

With regard to the term, speed, there are several definitions, e.g., Indicated Air Speed (IAS), Calibrated Air Speed (CAS), True Air Speed (TAS), Ground Speed (GS), Mach Number (M), etc. In the ATC environment, the controllers watch for the aircraft movement in the radar display (ARTS/Data Entry and Display Subsystem, DEDS), that is, GS, and if necessary, initiate the speed adjustment instruction in terms of IAS. On the other hand, the pilots maintain the aircraft speed or follow the speed adjustment instruction issued by the controllers watching the speed (IAS) indicator in the cockpit. GS depends upon TAS and winds, so that the conversion from IAS to TAS is first required.

#### (1) IAS-TAS Conversion

Since Mach number is defined as the ratio of TAS to the speed of sound in the surrounding air\(^9\)

\[
\text{TAS} = M \cdot a
\]  

where

\[ M = \text{Mach Number}, \text{ and} \]

\[ a = \text{speed of sound}. \]

The speed of sound is given by\(^10\)

\[
a = \sqrt{\frac{\gamma}{\rho_0}} \frac{v}{\rho_0} \frac{v}{\sqrt{v}} \]  

\[
\text{* Refer to Appendix 1.}
\]
where
\( \gamma \) = specific heat ratio of air = 1.4 (exactly),
\( \rho_0 \) = air-density at sea level,
\( p_0 \) = pressure at sea level,
\( v_0 \) = temperature at sea level, and
\( v \) = temperature at altitude concerned.

Mach number is further expressed in terms of the pressure ratio, the density ratio, and CAS, then TAS is given by\(^{11} \)

\[
TAS = \frac{1479}{\sqrt{\sigma}} \sqrt{\mu \left\{ \left( \frac{1 + 0.2(CAS/661.5)^2}{\mu} \right)^{3.5} - 1 \right\}^{1/3.5}} - 1 \quad (3)
\]

where
\[
\mu = \frac{p}{p_0} = \frac{\text{pressure at altitude concerned}}{\text{pressure at sea level}},
\]
\[
\sigma = \frac{\rho}{\rho_0} = \frac{\text{density at altitude concerned}}{\text{density at sea level}}, \text{ and}
\]
\[
\frac{\mu}{\sigma} = \frac{v}{v_0} = \frac{\text{temperature at altitude concerned}}{\text{temperature at sea level}}.
\]

Figure 10 shows the relationship between TAS and CAS in Eq. 3.

![Figure 10](image)

**FIGURE 10** Relationship between TAS and CAS

Therefore, it is possible to obtain TAS from CAS, if a set of \( \mu \) and \( \sigma \) is known*.  
* ICAO Standard Atmospheric Data or actually observed data can be used.
With regard to the conversion from IAS to CAS, it is assumed that, since IAS and CAS are within a few knots of each other, the difference between them is negligible. This means that Eq. 3 with IAS in place of CAS is used.

(2) Modeling of Speed Profile

The speed profile is considered as a series of speed changes (reduction) and the constant speed. For modeling of the speed profile, the basic speed $S_{aj}$ in terms of IAS is specified at $P_i$ ($i = 1, 2, \ldots, n$) like the basic altitude. Also a variable range, which is named the speed gate $\Delta S_{aj}$ in the model concept, is given to $S_{aj}$. $\Delta S_{aj}$ is used for issuing the speed adjustment instruction, which is discussed in the latter section (4.3). The speed change rate from $S_{aj}$ to $S_{aj+1}$, i.e., between two successive points, is set to be constant. Figure 11 depicts a modeling of the speed profile for one arrival route.

![Diagram of speed profile model](image)

**FIGURE 11** Modeling of speed profile

3.2.4 Remarks on Flight Profile

As the results of the previous discussions, $P_i$ is defined with a set of parameters as shown below:

$$P_i = (R_i, \Theta_i, H_i, \Delta H_i, S_{aj}, \Delta S_{ai}) \quad (4)$$

where

- $R_i$ = range,
- $\Theta_i$ = azimuth,
- $H_i$ = basic altitude,
- $\Delta H_i$ = altitude gate,
- $S_{aj}$ = basic speed (IAS), and
- $\Delta S_{ai}$ = speed gate (IAS).

3.2.5 Initial Contact and Transfer vs. Flight Profile

Further consideration of the flight profile concerns where the first and last communication are made. With regard to initial contact, it will be reasonable to consider that it is made by or for aircraft before the entry fix. The point of initial contact varies depending upon the controller's and pilot's judgement, but it will be a slight variation. Therefore, it is set uniformly for all aircraft in the model concept, e.g., 10 n.m. from the entry fix. Then, the arrival time scheme mentioned in 3.1.4 is applied at this point.

Let $T_a$ and $T_{aij}$ be a set of arrival time series generated using the Poisson arrival method and its element respectively. That is,

$$T_a = \{T_{a11}, T_{a12}, T_{a21}, \ldots, T_{aij}, \ldots\} \quad (5)$$
where the subscript $ij$ means the $j$-th arrival of the $i$-th entry. The percentage of the aircraft which pass each entry fix is used for the entry fix assignment. Also the percentage of Aircraft-Heavy and Aircraft-Large is used for the aircraft type assignment. Then, the subset $T_{ai}$ regarding the $i$-th entry fix is

$$T_{ai} = \{T_{ai1}, T_{ai2}, \ldots, T_{aij}, \ldots\}.$$  \hspace{1cm} (6)

Using Eq. 6, it is possible to check the difference between $T_{aij}$ and $T_{aij+1}$ to see if there are two aircraft spaced less than the minimum separation about to enter the terminal area through the $i$-th entry fix. If there are any, the following aircraft is delayed so as to assure the minimum separation, and if this is not feasible because of the aircraft flying after the following aircraft, the leading aircraft is asked to maintain a high speed.* The time corresponding with the minimum separation $\tau_a$ is 60 seconds, if an average aircraft speed of 300 knots (GS) in this area, i.e., before the entry fix, and 5 n.m. as the minimum separation are assumed. Figure 12 illustrates an arrival time series and how it is modified.

![Arrival time series](image)

**FIGURE 12** Arrival time series

With regard to the last communication for transfer to local control, it is also assumed that it is made at a fixed distance, e.g., 10 n.m. from the runway end. In some terminal areas, it corresponds with the exit of the arrival route. In addition, at this point, the separation between successive arriving aircraft should be maintained, i.e., 3, 4, or 5 n.m. (see Table 2). If an aircraft speed of 150 knots (GS) is assumed at this point, the time separation becomes 1.2, 1.6, or 2 minutes.

### 3.3 FLIGHT PROGRESS

This section describes a modeling of the wind pattern and a control method of the aircraft movement.

#### 3.3.1 Wind Pattern

Winds are one of the most influential elements, since they directly affect GS. They vary greatly with the time, the altitude, and the place. Therefore, these elements are discussed to determine an appropriate wind pattern for the model concept.

(1) Winds vs. Altitude

Table 3 shows how two wind parameters, i.e., the wind speed and the wind direction, vary with the altitude. It is part of the wind data cited in Reference 12. Although it is an example of a specific place and time, it can be said consequently that aircraft have to receive different wind effects at different altitudes when changing their altitude. In the model concept, the wind variation with the altitude is used as a basic wind pattern, and the wind speed and direction data actually observed will be used. In Table 3, $H_{wi}$ is the $i$-th observation point in terms of the altitude, and $Sw_i$ and $Aw_i$ are the wind speed and the wind direction at $H_{wi}$. The wind speed and the wind direction at an altitude between $H_{wi}$ and $H_{wi+1}$ are interpolated.

* This method would be conservative in case of Figure 7, since it does not regard the difference in an entering altitude.
TABLE 3  Wind data (Example)\(^{12}\)\(^*\)

<table>
<thead>
<tr>
<th>Altitude (H_{W_i}) (x 1000 ft)</th>
<th>Wind Speed (S_{W_i}) (knots)</th>
<th>Wind Direction (A_{W_i}) (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4</td>
<td>350</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>250</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>240</td>
</tr>
<tr>
<td>6</td>
<td>17</td>
<td>260</td>
</tr>
<tr>
<td>8</td>
<td>20</td>
<td>250</td>
</tr>
<tr>
<td>10</td>
<td>24</td>
<td>270</td>
</tr>
<tr>
<td>12</td>
<td>30</td>
<td>270</td>
</tr>
<tr>
<td>14</td>
<td>33</td>
<td>280</td>
</tr>
<tr>
<td>16</td>
<td>46</td>
<td>280</td>
</tr>
<tr>
<td>18</td>
<td>44</td>
<td>290</td>
</tr>
<tr>
<td>20</td>
<td>52</td>
<td>290</td>
</tr>
</tbody>
</table>

* The data were observed at Nantucket, which is an island in Northeastern U.S.

(2) Winds vs. Time and Place

The wind variation with the time and the place is considered in the model concept as follows:

1) The wind pattern which varies with the altitude is assumed to be steady for one hour and uniform in the terminal area.

2) Different wind patterns will be used for different hours and terminal areas.

The assumption above is based upon the following conditions: a) the meteorological observatory conducts periodical wind observations, so that it will be possible to obtain the wind variation data above the airport, b) but it is very difficult to obtain these data throughout the terminal area. Finally, GS can be calculated using this wind pattern and TAS, which is converted from IAS.

3.3.2 Aircraft Movement

As mentioned in 3.2.3, the controllers watch for the aircraft movement in the radar display, that is, GS, and as shown in Figure 6, aircraft fly along the arrival route composed of the linear and curved portion. Therefore, it is necessary to determine a control method of the aircraft movement and to derive GS when aircraft fly along the linear and curved portion.

Figure 13 shows a fundamental relationship between the TAS vector, the along-track speed vector, and the wind vector. That is, using the vectorial notation \(\vec{s}\).
Subscript, $t$: TAS
$g$: Along-track speed
$w$: Wind

**FIGURE 13** Relationship between TAS vector, along-track speed vector, and wind vector

\[ S_g = S_t + S_w \] ................................. (7)

where
\[ S_g = s_g (\cos \alpha_g, \sin \alpha_g) = \text{along-track speed vector}, \] .............................. (8a)
\[ S_t = s_t (\cos \alpha_t, \sin \alpha_t) = \text{TAS vector, and} \] ............................... (8b)
\[ S_w = s_w (\cos \alpha_w, \sin \alpha_w) = \text{wind vector}. \] ............................... (8c)

These three vectors are defined in a slanted plane, OABC in Figure 13. The magnitude and the direction relative to the reference axis, i.e., the magnetic north, are expressed by $s$ and $\alpha$ with the subscript $g$, $t$, and $w$. The horizontal projection of $\alpha$ is expressed by $\alpha^*$. GS is the horizontal component of $S_g$. The angle $\delta_t$ between $S_t$ and horizontal is slightly different from the angle $\delta_g$ between $S_g$ and horizontal. This difference is due to the wind effects. Here, $\delta_t$ and $\delta_g$ define the descent slope rate relative to the air mass and ground respectively. In addition, it is assumed in the model concept that the angle of attack and the sideslip angle are negligible. This assumption will be reasonable in case of normal aircraft operations in the terminal area.

(1) **Linear Portion**

Since aircraft receive different wind effects at different altitudes, they have to compensate for these effects when flying in a specific direction, i.e., a linear portion of the arrival route, and descending. In terms of three vectors in Figure 13, $S_g$ has to lie along that direction. For attaining this, $S_t$ has to be adjusted, since $S_w$ is not controllable, of course. $S_t$ has three related variables, $s_t$, $\alpha_t$, and $\alpha_i$. From them, $\alpha_i$ is chosen as the adjustable variable, since its adjustment will be the easiest and most realistic in view of aircraft maneuvering. This, therefore, essentially represents that aircraft

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* $\alpha_w$ directly corresponds with the wind direction mentioned in 3.3.1.
maintain a magnetic heading with reference to the ground navigational system. Thus, it is possible to control the aircraft movement in the linear portion of the arrival route by adjusting $\alpha'$.

With regard to the descent slope rate, it is considered that maintaining $\delta_t$ will be easier and more realistic than maintaining $\delta_g$ in view of aircraft maneuvering. Therefore, in the model concept, $\delta_t$ is chosen for adjusting the descent slope rate, and is assumed to be constant in each descent phase. This means that $\delta_g$ changes gradually due to the variations in TAS and winds. Also in view of aircraft maneuvering, it is difficult for the aircraft categorized in the weight classes, Heavy and Large, to descend and reduce their speed simultaneously. Therefore, in the descent phase, it is assumed that aircraft maintain IAS constant. This assumption, in other words, means that speed adjustment is made in the level flight phase.

(2) Curved Portion

Turning in the curved portion is dependent upon the aircraft attitude, the speed, the route segment structures, winds, etc. With regard to turning, the control method was developed so that the turning path is circular relative to the ground.13,14* But this method, presently, will be difficult for the aircraft categorized in the weight classes, Heavy and Large, since it will require the complicated bank angle control which utilizes the on-board computer. For the model concept, therefore, a different control method is applied in view of aircraft maneuvering. That is, it is assumed that aircraft turn; 1) in a level flight; 2) with a constant speed (IAS); and 3) with a constant bank angle. Since they receive the wind effects, these assumptions consequently indicate that the turning path is circular relative to the air mass, which is moving.

Figure 14 shows a turning scheme based upon these assumptions. A circular turning path relative to the air mass and the wind effects on the turn ending point are shown in broken line, and a resultant turning path is shown in curved solid line. In Figure 14, $P_{t0}$ and $P_{t1}$ are the turn starting and ending point respectively. $\Gamma$ is the turn ending point relative to the air mass. $\Gamma$ is the radius of turn. $\alpha_t$ and $\alpha_g$ at $P_{t0}$ are shown with the subscript 0, and those at $P_{t1}$ with the subscript 1. Here, from the assumption 1) above, $\alpha$ is equal to $\alpha'$, and from the assumptions 1) and 2) above, $s_t$ is constant.

![Turning scheme diagram]

* Extensive studies have been made on the aircraft control and guidance problems in the ATC terminal area.

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* Extensive studies have been made on the aircraft control and guidance problems in the ATC terminal area.
The angle difference between two route segments, $\overline{P_{i-1}P_i}$ and $\overline{P_iP_{i+1}}$ is shown by $\Phi$, which is equal to $|\alpha_{g1} - \alpha_{g0}|$, and the angle of turn relative to the air mass is shown by $\tilde{\Phi}$, which is equal to $|\alpha_{t1} - \alpha_{t0}|$.

Referring to Figure 14, a turning scheme is described as follows:

1) Aircraft fly along $\overline{P_{i-1}P_i}$, and start turning at $P_{i0}$. That is, they start to bank with an angle of $\beta$.

2) Then, $\beta$ is maintained to be constant. This means that $\alpha_t$ varies constantly, since $s_t$ is constant and

$$\beta = \tan^{-1} \frac{s_t \dot{\alpha}_t}{g}$$

where $\beta = \text{bank angle}$, $g = \text{acceleration of gravity}$, and $\dot{\alpha}_t = \text{time derivative of } \alpha_t = s_t / \Gamma$.

Eq. 9 is derived when the sideslip angle is negligible.*

3) During this process, $\alpha_g$ varies also depending upon $\alpha_t$. When $\alpha_g$ becomes equal to the direction of $\overline{P_iP_{i+1}}$, i.e., $\alpha_{g1}$, aircraft start to fly along $\overline{P_iP_{i+1}}$.

4) Also during this process, the air mass moves due to winds. Therefore, it becomes necessary to choose an appropriate turn starting point for a fixed bank angle or an appropriate bank angle for a fixed turn starting point in order that aircraft reach $\overline{P_iP_{i+1}}$ when $\alpha_g$ becomes equal to the direction of $\overline{P_iP_{i+1}}$.

**Remarks**

As the summary remarks, Table 4 shows the relationship between IAS, $\alpha_t$, $\delta_t$, and $\beta$ when aircraft fly along the linear and curved portion.

| TABLE 4 | Relationship between IAS, $\alpha_t$, $\delta_t$, and $\beta$ |
|----------|--------------------------|----------------|------------|------------|
| Linear Portion | IAS | $\alpha_t$ | $\delta_t$ | $\beta$ |
| 1) Descent | const.** | var.*** | const. | zero |
| 2) Level Flight | | | | |
| a) Speed Reduction | | | | |
| b) No Speed Reduction | | | | |
| Curved Portion | | | | |
| | const. | | | const. |
| ** constant |
| *** variable |

Since the flight profile and the wind pattern are specified as mentioned in 3.2 and 3.3.1, GS can be calculated by introducing an appropriate descent slope rate relative to the air mass and a speed change rate in terms of IAS.****

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* Reference 15.
**** A detailed description of the derivation of GS and the resultant position update of aircraft is being prepared in a separate paper.
4. COMMUNICATIONS

For modeling the air-ground communications, it is necessary to categorize the message elements presently used and consider their generation mechanism.

4.1 MESSAGE ELEMENTS

The categorization of the message elements used in the statistical analysis\(^1\) for approach control is shown in Table 5.

<table>
<thead>
<tr>
<th>Group</th>
<th>Abb.</th>
<th>Message Element Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>AC</td>
<td>Altitude (or altitude change)</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>Heading (or vector)</td>
</tr>
<tr>
<td></td>
<td>SA</td>
<td>Speed adjustment</td>
</tr>
<tr>
<td></td>
<td>AR</td>
<td>Altitude request and report</td>
</tr>
<tr>
<td>B</td>
<td>IC</td>
<td>Initial contact</td>
</tr>
<tr>
<td></td>
<td>TF</td>
<td>Transfer</td>
</tr>
<tr>
<td></td>
<td>CL</td>
<td>ATC clearance</td>
</tr>
<tr>
<td>C</td>
<td>ID</td>
<td>Radar re-identification</td>
</tr>
<tr>
<td></td>
<td>RF</td>
<td>Route of flight</td>
</tr>
<tr>
<td></td>
<td>PS</td>
<td>Position information</td>
</tr>
<tr>
<td></td>
<td>HD</td>
<td>Holding</td>
</tr>
<tr>
<td></td>
<td>SQ</td>
<td>Sequencing</td>
</tr>
<tr>
<td></td>
<td>MS</td>
<td>Miscellaneous (including traffic information)</td>
</tr>
<tr>
<td></td>
<td>MC</td>
<td>Missed contact</td>
</tr>
</tbody>
</table>

These message elements were categorized in view of their operational purpose. Here, the grouping in Table 5 means:

1) Group A: The HAS (Heading, Altitude, and Speed) instructions and the altitude request and report, of which occurrence would be determined by the control technique like metering and spacing.

2) Group B: Routine messages, which are not affected by traffic volume.

3) Group C: Supplemental information and instructions required in specific situations.

Since the basic communication data were gathered in the conventional radar control (pre-ARTS-III) environment, they include some message elements which will be seldom used in the ARTS-III operational environment. For example, AR and ID will be considerably reduced by the ARTS-III operation, since it can provide the controllers with aircraft identification and Mode-C reported altitude as mentioned in 2. In order to confirm this point and survey the present air-ground communications in the U.S., further analysis was made for two hours of communication data of the Boston approach control in 1978. The results showed that there were much fewer AR’s and no ID’s for 219 communication transactions observed.
4.2 STATISTICS OF COMMUNICATION TIME

The message element in Table 5 is sent in a communication transaction which has two or more transmissions of the controller and the pilot. Figure 15 illustrates a time series of communication transactions. Here, the communication transaction and transmission are shortened to CT and TR as Hunter et al. used in their analysis.\(^4\) \(t_{CT}, t_{TR},\) and \(t_{RD}\) in Figure 15 are the time required to complete a CT, a TR, and the response delay time respectively, and they have the following relationship:

\[
\Sigma t_{CT} = \Sigma t_{TR} + \Sigma t_{RD}
\]

and the channel utilization \(P_{CU}\) is defined by

\[
P_{CU} = \frac{\Sigma t_{CT}}{\text{(channel available time)}}
\]

TABLE 6 Data comparison (Single communication transaction)

<table>
<thead>
<tr>
<th></th>
<th>No. of CT’s*</th>
<th>Average time to Complete a CT (sec)</th>
<th>Rate of CT’s Initiated by Pilots</th>
</tr>
</thead>
<tbody>
<tr>
<td>N.Y. ARTCC(^4)</td>
<td>3,150</td>
<td>10.86</td>
<td>0.244</td>
</tr>
<tr>
<td>Tokyo &amp; Osaka(^1)</td>
<td>1,006</td>
<td>9.80</td>
<td>0.241</td>
</tr>
</tbody>
</table>

* Approach Control or Radar Arrival Control only

Table 6 shows statistics of a single CT obtained in the statistical analyses.\(^1,4\) Interesting is that they showed very similar results in spite of the differences in the data sampling and the types of the terminal area. Other statistics relating to a single CT, e.g., \(t_{TR}\), and the time required to complete a message element, will be considered to be similar, though they are not directly compared due to the difference in the data reduction process. The reason of this similarity will be that, as mentioned in 2, most of message exchanges are made in terms of the phraseology adopted by ICAO.

The abbreviations IC, AC, and AR above short solid lines in Figure 15 correspond with those in Table 5. In the first CT, an initial contact is made, and in the second CT, the controller initiates an altitude instruction, and the pilot replies to it with an altitude report. Figure 15 indicates that it will be reasonable to generate a CT with a combination of message elements. This, consequently, requires to consider the time required to complete a message element, \(t_{ME}\). Here, the subscript ME means the message element as a whole.

Hunter et al.\(^4\) concluded that the distribution of both \(t_{CT}\) and \(t_{TR}\) were found to be reasonably approximated with the gamma distribution. The following density function defines the gamma distribution:

\[
f(t) = \frac{\lambda^k}{\Gamma(k)} t^{k-1} e^{-\lambda t} \quad \text{for} \ t \geq 0.
\]

The two parameters \(k\) and \(\lambda\) are related to the mean and variance of the distribution. That is,
FIGURE 15 Communication transactions

Mean: \[ E(t) = \frac{k}{\lambda} , \] \hspace{2cm} \text{(13a)}

Variance: \[ V(t) = \frac{k}{\lambda^2} . \] \hspace{2cm} \text{(13b)}

The gamma distribution is useful to model statistical phenomena which vary over a wide range, since it has two adjustable parameters. The gamma distribution with \( k = 1 \) is the exponential distribution, and \( k \to \infty \) and \( \lambda \to \infty \), it approaches the delta function. In terms of the service time in the queuing theory, the exponential distribution expresses the random service time, and the delta function expresses the constant service time. In Figure 15, the times \( t_{ME} \) can be defined for the three message elements IC, AC, and AR as follows:

\[ t_{IC} = \sum_{i=1}^{3} t_{TR_{1i}} + \sum_{i=1}^{2} t_{RD_{1i}} , \] \hspace{2cm} \text{(14a)}

\[ t_{AC} = t_{TR_{21}} + t_{RD_{21}} + \Delta t_{TR_{22}} , \] \hspace{2cm} \text{(14b)}

and

\[ t_{AR} = (1 - \Delta) t_{TR_{22}} + t_{RD_{22}} + t_{TR_{23}} . \] \hspace{2cm} \text{(14c)}

They include the response delay time. The reason is that it is indispensable for message exchanges, though it is usually very short (one second or less), and the channel is substantially occupied in this time period by communication initiators (the controller and the pilot).

For the model concept, the assumption on the communication time is that the distribution of \( t_{ME} \) will be approximated with the gamma distribution, as will those of \( t_{CT} \) and \( t_{TR} \). This characterization will be reasonable, since \( t_{ME} \) is an element of \( t_{CT} \). For this, two parameters \( k \) and \( \lambda \) will be prepared for the message element by processing the communication data used in Reference 1.
4.3 MESSAGE GENERATION MECHANISM

In this section, an arrival time estimation method is first introduced for generating the HAS instructions. Then, a message generation mechanism is considered for the message elements in Table 5.

4.3.1 Arrival Time Estimation

GS, which is the horizontal component of $S_g$, is very important to estimate the arrival time of aircraft. The controller, therefore, will have to know how GS changes as aircraft progress, when he estimates the arrival time. As mentioned in 2, the ARTS-III can provide the controller with the GS information which is obtained by processing the beacon replies of aircraft. The controller may know what speed profiles are usually taken in his jurisdictional area, and he can request a speed report of the pilot, when necessary, by the air-ground communications. Also he will have the wind forecast and the real time surface wind data particularly at the airport. But it will be very difficult for him to estimate precisely winds and atmospheric variations (in conversion from IAS to TAS) which affect GS.

From these actual situations above, the following are assumed in the model concept for an arrival time estimation:

1) The controller will be able to estimate $s_g$, i.e., the magnitude of $S_g$, at $P_i$. But he can not estimate it between $P_i$ and $P_{i+1}$.
2) He knows $H_i$ and $H_{i+1}$, because he is to issue the altitude instruction.
3) In case of turning, the flight path is somewhat away from $P_i$. For the estimation purpose, this away distance is neglected, and $P_i$ is used as a reference point.
4) In the descent phase, $s_g$ and $s_{g_i}$ are set to be constant. That is, GS is constant.
5) In the level flight phase, the speed change rate $a$ is set to be constant or zero (no speed change).
6) Aircraft start descending from $H_i$ to $H_{i+1}$ at $P_i$, and start reducing their speed from $S_{g_i}$ to $S_{g_{i+1}}$ when they reach $H_{i+1}$, or they start reducing their speed from $S_{g_i}$ to $S_{g_{i+1}}$ at $P_i$, and start descending from $H_i$ to $H_{i+1}$ when they reach $S_{g_{i+1}}$. Here, $S_{g_i}$ and $S_{g_{i+1}}$ are the estimated along-track speed at $P_i$ and $P_{i+1}$, which are converted from $S_{a_i}$ and $S_{a_{i+1}}$, respectively. Since they are a fixed value, the notation in capital letter is used.

As a matter of course, the results of this estimation differ from those derived from the aircraft movement described in 3.3. This difference results from winds and atmospheric variations between $P_i$ and $P_{i+1}$, and the away distance in case of turning, etc.

Figures 16a and 16b show the altitude and speed profile of $P_{i+1}$ for this estimation method. Figure 16a corresponds with the first case and Figure 16b with the second case in Item 6) above. In Figures 16a and 16b, $T_{0i}$ and $T_{3i}$, which is equal to $T_{0i+1}$, are the estimated arrival time at $P_i$ and $P_{i+1}$ respectively. $T_{1i}$ corresponds with the starting time of the speed reduction in Figure 16a and with the ending time of the speed reduction in Figure 16b. $T_{2i}$ corresponds with the ending time of the speed reduction in Figure 16a and with the ending time of the descent in Figure 16b.

From the relationships in Figures 16a and 16b, the estimated GS $s_g$ at time $t$ is shown for two cases as follows:
a) Case 1
\[ \dot{s}_g = s_{gi} \cos \delta_g \quad \text{for } T_{0i} \leq t < T_{1i}, \]
\[ \dot{s}_g = s_{gi} \cos \delta_g \quad \text{for } T_{1i} \leq t \leq T_{2i}, \]
\[ \dot{s}_g = s_{gi+1} \quad \text{for } T_{2i} \leq t \leq T_{3i}. \]
\[ \dot{s}_g = s_{gi+1} \cos \delta_g \quad \text{for } T_{1i} \leq t < T_{2i}, \]
\[ \dot{s}_g = s_{gi+1} \quad \text{for } T_{2i} \leq t \leq T_{3i}. \]

b) Case 2
\[ \dot{s}_g = s_0 \quad \text{for } T_{0i} \leq t \leq T_{1i}, \]
\[ \dot{s}_g = s_{gi+1} \cos \delta_g \quad \text{for } T_{1i} \leq t < T_{2i}, \]
\[ \dot{s}_g = s_{gi+1} \quad \text{for } T_{2i} \leq t \leq T_{3i}. \]

FIGURE 16  Altitude and speed profile for arrival time estimation

Now, let \( L_i' \) be the horizontal projection of \( P_i P_{i+1} \). Then, it is expressed in an integral form for Case 1:

\[ L_i' = \int_{T_{0i}}^{T_{1i}} s_{gi} \cos \delta_g dt + \int_{T_{1i}}^{T_{2i}} (s_{gi} - at) dt + \int_{T_{2i}}^{T_{3i}} s_{gi+1} dt \]
where

\[ T_{1i} = T_{0i} + \frac{H_i - H_{i+1}}{S_{gi} \sin \delta_g} \]  \hspace{1cm} (17b)

and

\[ T_{2i} = T_{1i} + \frac{S_{gi} - S_{gi+1}}{a} \]  \hspace{1cm} (17c)

Integrating Eq. 17a and manipulating

\[ T_{3i} = T_{2i} + \frac{1}{S_{gi+1}} \left\{ L_{4'} - \left[ S_{gi} \cos \delta_g (T_{1i} - T_{0i}) + S_{gi}(T_{2i} - T_{1i}) \right] \right. \\
- \left. \frac{1}{2} a(T_{2i}^2 - T_{1i}^2) \right\} \]  \hspace{1cm} (18)

Therefore, \( T_{3i} (= T_{0i+1}) \) can be obtained by substituting Eq. 17b and 17c, and the specified values at \( P_i \) and \( P_{i+1} \) into Eq. 18. For Case 2, the same derivation process can be applied, and \( T_{3i} \) is

\[ T_{3i} = T_{2i} + \frac{1}{S_{gi+1}} \left\{ L_{4'} - \left[ S_{gi}(T_{1i} - T_{0i}) - \frac{1}{2} a(T_{1i}^2 - T_{0i}^2) \right] \right. \\
+ \left. S_{gi+1} \cos \delta_g (T_{2i} - T_{1i}) \right\} \]  \hspace{1cm} (19a)

where

\[ T_{1i} = T_{0i} + \frac{S_{gi} - S_{gi+1}}{a} \]  \hspace{1cm} (19b)

and

\[ T_{2i} = T_{1i} + \frac{H_i - H_{i+1}}{S_{gi+1} \sin \delta_g} \]  \hspace{1cm} (19c)

As an expansion of Eq. 18 or 19a, if there are \( n \)-1 route segments for an arrival route, the estimated arrival time at \( P_n \) is given by \( T_{3n-1} \), i.e., \( T_{0n} \). With regard to the difference between Case 1 and Case 2, Case 1 will produce earlier time in estimation than Case 2, since the portion of \( S_{gi} \) which is greater than \( S_{gi+1} \), is longer in Case 1 then in Case 2. The priority is given to Case 1 in the model concept.

4.3.2 Message Generation (Group A)

In the model concept, the HAS instructions in Group A are generated by the following two methods:

1) Basic method (flight profile).
2) Arrival time estimation method.

(1) Basic Method
This method includes the following instructions:

1) Altitude instruction from \( H_i \) to \( H_{i+1} \), which is generated when aircraft fly over \( P_i \) or its nearest point in case of turning.
2) Heading (vector) instruction generated before the intersection of two angled route segments.

The speed reduction which follows the speed profile (see Figure 11) is primarily managed by the aircraft side.
(2) Arrival Time Estimation Method

When traffic becomes congested, two or more aircraft may pass $P_i$ or its nearest point closely in time and at about same altitude. This situation causes a threat of conflict. For preventing this situation, it is necessary to give prior instructions to the aircraft concerned. This will be made by examining the difference in the estimated arrival time.

Figure 17 shows an example of the relationship between $T_{0i+1}$ and $S_{gi+1}$ for different $L_i$'s and $S_{gi}$'s, which is expressed in Eq. 18 (Case 1).

The conditions are:

\[ S_{gi} = \begin{cases} 350 \text{ knots} \\ 300 \text{ knots} \\ 250 \text{ knots} \end{cases}, \]

\[ H_i = 14,000 \text{ ft}, H_{i+1} = 10,000 \text{ ft}, \]

\[ \tan \delta_g = 0.062 \left(= \frac{375}{n.m.}\right), a = 0.125g, \]

and for convenience sake, $T_{0i}$ is set to be zero. Figure 17, in other words, shows a speed adjustment range defined by $\Delta S_{ai+1}$ at $P_{i+1}$, if the speed gate converted from that in IAS is as shown in the figure. For instance, if speed adjustment is applied from 300 knots to 180 knots, in stead of 200 knots (in terms of the along-track speed), a time difference in $T_{0i+1}$ becomes 53.8 seconds for an $L_i$ of 30 n.m. In the following, an example of the application of the arrival time estimation method is given for a specific traffic situation.

Figure 18 illustrates that the aircraft #3 and #4 are in a threat of conflict in terms of the estimated arrival time at $P_{i+1}$. These aircraft are named the aircraft pair. In resolving this situation, the following processes will be taken:

1) First check $T_{0i+1}$ of #3 (the leading aircraft in the aircraft pair) by giving her a speed of $S_{gi+1} + \Delta$, slightly faster than $S_{gi}$ and $S_{gi+1}$. If this assures the separation between #3 and #4 as well as that between #2 and #3, a speed adjustment instruction to a corresponding IAS value of $S_{gi+1} + \Delta$ is issued to #3.
2) If Item 1) is not feasible, check $T_{0i+1}$ of #4 (the following aircraft in the aircraft pair) by giving her a speed of $S_{6i+1} - \Delta$, slightly slower than $S_{6i+1}$. If this assures the separation between #3 and #4 as well as that between #4 and #5, a speed adjustment instruction to a corresponding IAS value of $S_{6i+1} - \Delta$ is issued to #4.

3) If Item 2) is not feasible, the second estimation method (Case 2) is applied, and check Items 1) and 2) above.

![Diagram](image)

**FIGURE 18** Illustration of HAS instruction issuance

4) If Item 3) is not feasible, an alternative altitude, e.g., 1,000 ft above $H_{i+1}$, is assigned temporarily to #4.

5) Then, the same processes from Items 1) to 4) are repeated for the next route segment referring to $T_{0i+2}$. If it is possible to expedite the aircraft proceeding the aircraft pair, namely #2 in Figure 18, an appropriate speed adjustment instruction is issued to this aircraft, and then a following speed adjustment instruction is issued to #3.

Here, $\Delta$ is taken so as to be included in the speed gate at $P_{i+1}$. In attaining these processes, a list of the estimated arrival time is necessary. This list will be made when aircraft fly into the terminal area, and will be updated for the succeeding points when they pass $P_1$ or its nearest point.

(3) Remarks

The remaining point which should be considered here is about AR in Table 5. If this message element is required, it will be under the situation when beacon replies become deteriorated, the so-called "COAST" situation in the ARTS-III display, and do not provide the controller with reliable altitude information. It will be possible to model this situation in a stochastic way, if necessary.

The arrival time estimation method described previously includes some errors. Therefore, it might happen that two aircraft are in a threat of conflict, even though their separation at $P_1$ is assured in terms of the estimated arrival time. For resolving this situation, a control method like spacing may be required. This is to check to see if there is any aircraft pair about to conflict with each other in a more accurate way, and will require a kind of short time prediction of the future aircraft position.

That is,
1) Predict the future aircraft position using the present GS.
2) Calculate the relative distance of the aircraft concerned.
3) Issue an appropriate speed adjustment instruction or a vector instruction combined with traffic information.

The necessity of this method will be examined by actually conducting the simulation.

4.3.3 Message Generation (Group B)

For the generation of the message elements in Group B, the following methods are taken in the model concept:

1) Initial contact: This is generated when aircraft arrive at a fixed point before the entry fix (see 3.2.5).
2) Transfer: This is generated when aircraft arrive at a fixed point before the runway end (see. 3.2.5).
3) ATC clearance: This message element is divided into two kinds. One is issued following IC to specify the arrival route when there are two alternative routes for one entry fix, and the other is issued to indicate the approach method, e.g., ILS, and the runway in use. The former is generated together with IC, if there are no higher priority messages in the communication queue. If there is any, it is separately generated after IC and when the channel becomes available. The latter is generated at an appropriate point and prior to TF, e.g., before aircraft get on the final approach course, if the channel is available. If not, it is generated together with TF.

4.3.4 Message Generation (Group C)

The message elements in Group C are supplemental information and instructions. Among them, RF and SQ would be considered as a rare and not so common message element. Therefore, for simplification sake, they are omitted, and other message elements are considered for their generation mechanism.

1) Position information: In the ARTS-III operational environment, position information from the pilot will not be necessary for the controller, but that from the controller to the pilot is issued. It is usually combined with the ATC clearance for final approach and landing, i.e., the second case of ATC clearance. Therefore, this is to be generated with this ATC clearance in the model concept.

2) Holding: This is required when traffic becomes heavily congested as shown in Figure 7. For this, it is necessary to estimate the number of aircraft which are to pass $P_n$. As mentioned in 4.3.2 (2), a list of $T_{0n}$ can be prepared. Therefore, the following processes are possible:
   a) The number of aircraft which are to pass $P_n$ reaches a limit, e.g., 7 aircraft for 10 minutes, a holding instruction is issued to the last arriving aircraft into the terminal area.
   b) That aircraft has to hold at the holding point until receiving a hold release instruction, which is issued when the number of aircraft mentioned above reduces.

If two or more aircraft are holding at the same point, the hold release instruction is issued to an aircraft which holds at the lowest (holding) altitude, and then the altitude instruction is issued successively to the aircraft which hold at higher altitudes.

3) Radar re-identification: This is seldom required in the ARTS-III operational environment. If this is required, it will be under the “COAST” situation. It will be possible to model this situation in a stochastic way like AR.
4) Miscellaneous: This includes several message elements of which occurrence rate is very low. For example, traffic information was one of them in the statistical analysis[1]. On the other hand, aircraft traffic advisory* was ranked as the third frequently occurring message element (12.4%) for the IFR room operation.4) This seems to result from the difference in traffic volume, mixture, and arrival route configurations, etc. Therefore, it will be necessary to treat this in a proper way. For this purpose, the following method will be used for generating traffic information, particularly relating to departing aircraft (see 3.1):

a) To a certain portion of a route segment, a time (interval) gate is assigned using an assumed departing aircraft series. This is applied to the area where arrival and departure routes are closely located.

b) When arriving aircraft fly this portion in the assigned time gate, traffic information is generated.

4.3.5 Others

When the voice communication quality becomes deteriorated, for example, a very noisy situation, and when the pilot or the controller is too busy to respond immediately, it is likely that the communication transaction is not completed. This is the message element categorized in MC in Table 5, and requires re-transmissions.

In the model concept, a probability of this event is given and is applied to all communication transactions generated. The same kind of consideration will be possible for the event, request for repeat, which results from a lack of understanding of the contents of the message element.

4.3.6 Message Priority

In the message generation, a priority rule is defined as follows:

<table>
<thead>
<tr>
<th>Priority</th>
<th>Group</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Group A</td>
<td>1.1 Arrival time estimation method</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(including Holding)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.2 Basic method</td>
</tr>
<tr>
<td>2</td>
<td>Group B</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Group C</td>
<td>(except for Holding)</td>
</tr>
</tbody>
</table>

Priority among each group or method in Group A is determined by means of a first come and first served rule.

* In Reference 4, "Aircraft traffic advisory" was used in place of "Traffic information".
5. CONCLUDING REMARKS

As the concluding remarks, a computer simulation aspect which combines each concept into a simulation program is described.

The computer simulation will be conducted in a discrete time basis with a short scanning time interval, and the FORTRAN (Formula Translator) is used as a programming language. From this point of view, the following procedures will be taken:

1) Generate a set of arriving aircraft as mentioned in 3.2.5.
2) Progress each aircraft based upon the flight profile, the control method of the aircraft movement, and the wind pattern.
3) Monitor the aircraft position.
4) Meter the estimated arrival time (T0i) at P1 and measure the separation of nearby aircraft. Then, determine whether the message generation is necessary or not, based upon the message generation mechanism.
5) Calculate the time required to complete a communication transaction. Here, the distribution of the time required to complete a message element (tME) is used.
6) Process the communication queues, if necessary, referring to the priority rule for the message generation (4.3.6).
7) Repeat Items 2) to 6) with a short scanning time interval, i.e., 4 seconds of the radar scan, and produce a set of communication data.
8) Process and sort a set of communication data in terms of the channel utilization.
9) Repeat Items 1) to 8) for different terminal areas and different traffic volume.
10) Conduct sensitivity analyses by varying the parameters used in the model concept.

In an actual ATC environment, the aircraft movement and the message generation will show some randomness. There will be fluctuations in maintaining a constant IAS, a constant descent slope rate, etc. Among them, fluctuations relating to the aircraft speed will affect the message generation, since they relate to the arrival time estimation, which is very important both in the actual ATC system and in the model concept. In addition, when initiating the communication, there will be some delays in a certain situation, e.g., the controller is very busy with other tasks. In order to express these fluctuations and delays, the uniform distribution may be useful.

Each concept was examined by using the computer, but they are not yet integrated into a simulation program. Also, for the application of this model concept to approach control in a specific terminal area, the following data collection and survey are necessary:

a) Traffic data for each entry fix.
b) Flight profile data including the STAR charts.
c) Wind and atmospheric data.

In the next stage, further studies and refinement together with the program design will be worked out. Then, the model evaluation will be conducted.
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REFERENCES

8) FAA, “Air Traffic Control,” 7110-65A.
Appendix 1: An arrival Route Configuration

This arrival route configuration is presently used in the Tokyo Terminal Area for Runway 33, which is the primary runway for arriving aircraft. It consists of linear and curved portions as mentioned in 3.2.1 of the text, and includes three holding points. The point “HONDA” is an intermediate point, and it is specified to cross HONDA at or above 8,000 ft. The holding altitude ranges from 8,000 ft to 14,000 ft at TLE.