A SIMULATION STUDY OF TIME-CONTROLLED AIRCRAFT NAVIGATION

BY

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ABSTRACT

A technique has been developed, simulated, and tested which assists an aircraft pilot in navigating along threedimensional routes and in complying with times of arrival specified by air traffic control agencies. This technique utilizes an on-board computer to determine the airspeeds required to arrive on time and the descent rates required to maintain the specified routes in the vertical plane. In this closed-loop system, the pilot determines the control inputs required to match his measured airspeed to a computer-controlled bug on the airspeed indicator; the required descent rate is shown as a bug on the vertical velocity indicator. The computer requires the aircraft's position in three dimensions, current true airspeed, present time, and the assigned route-time profile to compute command airspeed and command descent rate.

The navigation system was tested by professional pilots in a cockpit mockup of a Boeing 707 interfaced with an Adage AGT-30 digital computer. An aircraft simulation which accurately models a Boeing 707-320B over the full operating range of airspeeds and altitudes was developed specifically for these tests and is described here. The accuracy of the time of arrival at an initial approach fix was measured for a linear descent of three degrees from cruise altitude to 10,000 feet. Tests were conducted under zero wind conditions and the airspeed at the initial approach fix was constrained to 250 knots. The resulting error in arrival times, chosen from the range of achievable times, had a mean of +19 seconds and a standard deviation about the mean error of 5 seconds.

THESIS SUPERVISOR: Alan A. Willsky
TITLE: Assistant Professor of Electrical Engineering
NEVER JUDGE THE HEIGHT OF A MOUNTAIN UNTIL YOU HAVE
REACHED THE TOP; THEN YOU WILL SEE HOW SMALL IT WAS.

DAG HAMMERSKJOLD

A word of explanation... the computer programs contained
in the appendix were included, not to add bulk, but to serve
as a documented reference to the assembly language aircraft si-
mulation. The aircraft has proven itself a valuable tool for
any air traffic control study; however, experience has shown
that assembly language programming, without adequate documenta-
tion, is of small value to successive researchers.

I would like to acknowledge the people who have assisted
this effort by their counsel and encouragement. Mr. Mark Con-
nelly, project engineer, provided invaluable guidance and organi-
zational support. Captain Bud Vietor of American Airlines eva-
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cient flight management. Professor Alan Willsky supervised the
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to Linda, Caryn, and Christopher who make all the sacrifices and
reap few of the rewards.

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CHAPTER I

INTRODUCTION

The control of air traffic operating in the United States is the responsibility of the Federal Aviation Administration. Since its inception in the 1930's, it has been tasked with providing for the safe, orderly, and expeditious flow of ever-increasing numbers of aircraft. Within recent years these increases have caused several major airports to reach a saturation condition where increased capacity cannot be attained without revolutionary changes in the methods of controlling aircraft[1].

One proposed concept, known as four-dimensional (4D) strategic control, offers increased airport capacity and several other important advantages. By assigning to each aircraft non-conflicting times of arrival at a sequence of three-dimensional waypoints, strategic control can achieve separation between aircraft in space and in the fourth dimension - time. This would permit arrivals at the runway - the ultimate "bottleneck" at any airport - to be scheduled at a maximum rate. It would also permit safer and more efficient utilization of available airspace and lower aircraft operating expenses than the present system of heading and/or speed changes sent from a controller on the ground.
While assignment of a "route-time profile", as described here, must of necessity be done by the ground facility controlling all arrivals, a controversy exists over the role of the pilot in the execution of this schedule.

The FAA favors a totally centralized management concept with an automatic monitoring system on the ground to detect any aberration and issue corrections. Those favoring "distributed management" believe that the pilot should participate in the air traffic control process and advocate that he be provided an on-board capability to sense and correct for deviations from the 4D schedule. The Boeing Aircraft Company adopted the latter position in a recent study[2] in which they develop a route-time assignment algorithm for use by the controlling agency. This report states:

"The pilot has the responsibility to maintain adherence to a detailed route-time profile and has an airplane with airborne equipment to make this possible. The air traffic controller acts in a surveillance and advisory capacity when the pilot maintains conformance to the route-time profile and has the equipment necessary to quickly generate new route-time profiles for airplanes, rescheduling them when necessary". [2: p.3]

To aid the pilot in discharging this responsibility, an on-board navigation method has been designed, simulated, and tested at M.I.T. on the simulation facilities of the Electronic Systems Laboratory and the Flight Transportation Laboratory. This technique assists the pilot in complying with assigned
times of arrival at three-dimensional waypoints. A second ob-
jective was incorporated into the design so that the airs-speeds
commanded for meeting the assigned time at a waypoint would al-
so maximize the aircraft's capacity to arrive earlier or later
than that time. This flexibility was considered desirable in
the event that the controlling agency had to reschedule aircraft.
Through the testing of this concept and the preparation of the
majority of this report, it appeared that both objectives had
been met. At the last minute, new evidence revealed that the
present approach is only suitable for navigating to the assigned
time - a task which it performs admirably. Nevertheless, the
concept of optimizing flexibility is considered worthwhile and
the discussion is retained here.

The precise control of aircraft by specifying three dimen-
sional air routes and assigning times of arrival at intermediate
points is a logical candidate for the air traffic control sys-
tem of the 1980's and beyond. Irrespective of the source of
the final design, the requirements are universal; the route and
times assigned must be within the performance capabilities of
each aircraft and must not conflict with the routes and times
assigned to other aircraft. The latter aspect is ignored here
since it is undeniably a responsibility of the controlling agency;
however, the relationship between aircraft performances and the
route-time profile is central to the on-board navigation concept.
Therefore in the remainder of this chapter, the route and time assignment will be discussed and the on-board navigation concept designed and tested here will appear as a logical extension of these ideas. In succeeding chapters, the models for the aircraft and atmosphere are discussed, the implementation of the navigation concept is explained, and the test results are summarized. The computer programs for the aircraft model and navigation controller are contained in the Appendix along with a brief explanation of their component parts.

1.1 STRATEGIC CONTROL

While the generalized concept of strategic control is applicable to any phase of flight from departure to landing, the discussion most often centers on the descent from cruise altitude into the terminal area. It is this descent phase, and particularly the descent to congested airports, where the greatest benefits are foreseen.

Under the present system of radar vectoring, aircraft arrive randomly at the boundaries of the terminal area (airspace within approximately 40 nautical miles of the airport) and must be sequenced and spaced for landing by a series of heading and/or speed commands. These "path stretching" maneuvers are costly when performed at low altitudes and prolong the exposure of high performance aircraft to possible collision with lighter aircraft.
operating in the same airspace. In extreme cases, arriving aircraft may be asked to "hold" by flying in a racetrack pattern until they can be assured separation from other aircraft in the landing stream.

Strategic control, on the other hand, would "derandomize" arrivals in the terminal area by assigning times of arrival at an "initial approach fix" (IAF) or waypoint on the terminal area boundary. Aircraft would then adjust speed during the descent from cruise altitude to arrive at the assigned time. Aircraft entering at the same IAF would fly a common path (but separated in time) and proceed in an orderly stream to the runway. Aircraft from other IAFs would assume their position in the stream by merging with the common path at an intermediate waypoint and at a non-conflicting time.

The ability to adjust speed while descending and the range of arrival times that an aircraft can achieve by speed control alone are functions of the route geometry chosen and individual aircraft performance limits. Because the route must be specified before times can be calculated, the descent profile to be flown must be chosen first.

1.1.1 THE DESCENT PROFILE The etymology of many terms unique to aviation has been lost, but descent profile at least has a logical basis. The three-dimensional route to be flown during the descent to the terminal area can be plotted as a function
of altitude and distance - or in profile - as shown in Figure 1-1. Here the path in the horizontal plane is assumed to consist of straight-line segments with each turning point identified as an additional four-dimensional waypoint.

The Boeing study points out that "airplane performance is probably the single most important criterion in the design of the terminal area descent profile". [2: p. 63] The available drag, minimum thrust, and weight of the aircraft combine to limit the angle ($\gamma$) at which it can descend without accelerating due to gravity. The rate of descent ($\frac{dh}{dt}$) required to maintain that angle is a function of speed and is limited by the cabin repressurization schedule. Boeing, with their intimate knowledge of current jet transports, chose a vertical gradient of 250 feet per nautical mile for descents above 10,000 feet and 300 ft/n.mi. below that altitude as being well within the capability of all aircraft. Although their analysis was based on a "clean" airplane (landing gear and flaps retracted), it is important to the present discussion that they considered spoiler deployment to be an acceptable method of increasing drag in order to decelerate or to maintain the required descent slope when the clean aircraft drag is insufficient.

Other proponents of linear, fixed descent profiles have recommended other slopes with 300 ft/n.mi. at all altitudes being an oft-quoted choice [3,4,5]. The navigation concept to be
Fig. 1-1 Descent Profile

TH - Threshold
OM - Outer Marker
TF - Turn Fix
IAF - Initial Approach Fix
EF - Entry Fix

DISTANCE FROM THRESHOLD (NAUTICAL MILES)

ALTITUDE (1000 FEET)
described here uses (but is not restricted to) a 318 ft/n.mi. slope ($\gamma = 3^\circ$). Provision was made in the simulator cockpit to vary the slope but testing with values other than 318 ft/n.mi. was not undertaken.

The level flight segment at 10,000 feet shown in Figure 1-1 exists to facilitate transition from high-speed descent to a speed below 250 knots as required by the FAA. The Boeing study found a 10 nautical mile level flight segment to be just adequate for present day commercial transports, and they recommended a 15 mile segment to insure reliable deceleration performance [2]. The fifteen mile segment was also adopted for the purposes of this study.

Using this descent profile, the strategic control route can now be specified. It is described by the geographical position (in some convenient coordinate system) of each waypoint and the altitude required at that point to maintain the profile. The actual route chosen would depend upon an individual aircraft's direction of flight and would have to include, as a minimum, the following points:

1. The entry fix where strategic control commences. This point is fixed so that the assignment algorithm can compute times over a known distance.

2. The initial approach fix where aircraft join the common path to the runway.
3. The outer marker of the runway. At this point aircraft must adjust speed and assume the proper configuration for landing.

4. The runway threshold.

5. Any turning points required between straight line segments.

6. Additional points as required, particularly along the common path to insure that time separation is maintained.

Having specified the route of flight, it is only necessary to specify appropriate times of arrival to completely characterize the route-time profile.

1.1.2 ASSIGNMENT OF ARRIVAL TIMES To increase airport capacity, all times assigned must be based on the desired arrival time at the runway threshold. In the Boeing design, aircraft would be queried prior to the entry fix as to their expected final approach airspeed (which varies with landing weight and atmospheric conditions) in order to relate runway arrival times to the arrival time required at the outer market. The aircraft are assumed to fly a common airspeed along the common path and this is used to compute required arrival time at the initial approach fix.

To separate and sequence several aircraft arriving simultaneously, there must be a range of arrival times which each aircraft can achieve. This range is bounded on the lower side
by the earliest possible time of arrival (EPTA). This is the
time the aircraft would arrive if it accelerated to its maxi-
mum airspeed, flew the prescribed route at that maximum, and
then decelerated to comply with any airspeed constraints at
the assigned waypoint. The upper bound, or latest possible
time of arrival (LPTA), is achieved by decelerating, flying at
minimum speed, and then accelerating to comply with the end-
point constraints, if any. The difference between the two
flight-times is often called the "delay spread" available, and
the relative position of the assigned time of arrival (ATA) be-
tween these bounds is a measure of the aircraft's "time flexi-
bility". For example, an aircraft assigned to arrive at the
EPTA has no flexibility with respect to arriving sooner but may
have great flexibility in arriving later than assigned.

The maximum true airspeed that an aircraft can fly varies
with altitude and is defined by structural limits, by maximum
available thrust, or below 10,000 feet, by FAA directives. The
minimum airspeed is also a function of altitude and is usually
defined as the airspeed at which the aircraft can perform a
1.3 g maneuver without buffeting [2]. A general view of an
aircraft velocity profile is shown in Figure 1-2. The strate-
gic control scheduling algorithm would store this data for each
aircraft type in order to compute EPTA and LPTA for each arrival.
The conflict detection function would then sequence the aircraft
Fig. 1-2  Aircraft Velocity Profile
and assign a unique route-time profile to each aircraft with the time at the initial approach fix within the bounds of EPTA and LPTA. (A sample route time profile -- such as Boeing suggests sending via data-link to the pilot -- is shown in Table 1-1.)

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<tr>
<th>Index number</th>
<th>Altitude from entry fix (feet)</th>
<th>Distance to Ground Clock Control (nautical miles)</th>
<th>Ground speed (knots)</th>
<th>Clock time (seconds)</th>
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<td>455</td>
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<td>177</td>
<td>131</td>
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<td>7 (threshold)</td>
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Table 1-1 Sample Route-Time Profile

The flexibility inherent in this capacity to arrive earlier or later than the assigned time suggests a navigation concept which not only complies with the assigned time, but also optimizes in some sense this flexibility.
1.2 THE NAVIGATION CONCEPT

In the sample route-time profile of Table 1-1, Boeing has determined an à-priori groundspeed schedule that is required in order to comply with the assigned time. However, the pilot does not fly at a constant groundspeed. In fact, he flies at an indicated airspeed or Mach schedule that differs from groundspeed because of wind, temperature, and density of the atmosphere. These relationships are discussed in Chapter 3. Nevertheless, it is possible to relate required airspeed to the cockpit indications by using forecast winds and performing an iterative calculation for trial airspeed schedules. This could be done on the ground and sent to the aircraft as a series of speed-up or slow-down commands if winds different from forecast or pilot error took the aircraft off schedule. On the other hand, it is not a complex calculation and could be performed by an on-board computer knowing only aircraft position, current airspeed, and the route-time profile. Shifting the responsibility to the aircraft offers the following advantages:

1. Reduced communications requirement.
2. A feedback control system allowing continuous corrections to schedule.
3. Continued operation in the event of ground system failure.
4. A reduction in controller workload by making the pilot an active participant in air traffic control.
While an on-board navigation system was contemplated by Boeing, the method of implementation was not specified [2]. Collins Radio Company has conducted tests of a four-dimensional navigation computer which performs the iterative selection of an appropriate airspeed schedule [4]. However, the concept to be described here uses a modified approach to the computation and arrives at an airspeed schedule which incorporates flexibility in an innovative way.

1.3 THE NAVIGATION CONTROLLER

The delay spread available on any descent profile decreases monotonically with decreasing distance to the waypoint. This is shown schematically in Figure 1-3. (Variations of maximum and minimum airspeed with altitude would determine the actual delay spread; the values shown in Figure 1-3 decrease linearly for purposes of illustration.) Under perfect conditions the EPTA and LPTA would converge to the assigned time as the aircraft approaches the waypoint. In the presence of disturbances such as wind, pilot error, or inaccuracies in observing position and speed, the delay spread may converge to a value other than the ATA. In Figure 1-3, a perfect controller has computed an airspeed schedule such that the aircraft arrives on time, but note that, in this particular example, the aircraft can always be delayed more than it can be advanced, should ATC be forced to change the arrival time. For example, at a distance of 50 miles from the waypoint it could arrive 3 minutes later, but only one half minute earlier. Let us hypothesize an example in which this would be
Fig. 1-3 Normal Delay Spread

Fig. 1-4 Optimum Delay Spread
undesirable.

Suppose two aircraft, A and B, are 50 miles from the initial approach fix (on separate route-time profiles). Aircraft A is scheduled to arrive one minute prior to B, but due to errors in the wind forecast, is going to be late. Aircraft B has the delay spread shown in Figure 1-3. It is unable to advance its arrival time far enough to occupy A's assigned time slot. It can, however, easily delay one minute and relinquish its own time slot to A. If no gaps are available in the sequence of arrivals, air traffic control is now faced with re-scheduling all succeeding aircraft to arrive one minute later and the runway arrival time originally assigned to A goes unused.

Several alternatives appear in this hypothetical situation. The first is to choose the ATA for each aircraft near the midpoint of their respective delay spreads. Boeing has logically avoided this approach in their scheduling algorithm because it forces all aircraft to fly longer than necessary and increases net operating costs. Instead, they strive to schedule closer to the EPTA, traffic permitting; this corresponds to an efficient cruise and descent time of arrival.

The second alternative would be to fly an airspeed schedule which equalizes the flexibility on either side of the ATA. This is depicted in Figure 1-4. This is the approach adopted here and a sub-optimum control law was developed and tested for
the no-wind case. It will be argued, at least heuristically—since tests were not completed, that this approach is applicable in the presence of unknown winds.

1.4 THE AIRCRAFT SIMULATION

A consortium of three M.I.T. laboratories -- the Electronics Systems Laboratory, Flight Transportation Laboratory and the Man-Vehicle Laboratory -- have a fixed-base cockpit simulator resembling a Boeing 707. (see Figure 1-5) The cockpit has been used for several years to study the applications of an Aircraft Traffic Situation Display to the air traffic control system.[6] While this device has potential uses in both the terminal and enroute environment, its applications have been studied exclusively in the near-terminal area at low altitude. For this reason the aircraft dynamics were simplified and are only representative of a general large jet transport over the narrow range of airspeeds and altitudes required for the near-terminal area.* Its performance was woefully inadequate for the range of airspeeds and altitudes contemplated for time-controlled navigation. It thus was necessary to create an accurate aircraft model which would provide representative performance for the contemplated studies.

* A more accurate model has since been developed [7] but again it is only valid in the lower altitudes of the terminal area.
Fig. 1-5  Simulator Cockpit
The aerodynamic data required for full simulation is closely held by individual aircraft manufacturers. Nevertheless, a model of a Boeing 707-320B with Pratt and Whitney JT3D-1 turbofan engines has been developed from data obtained, deduced or derived from various sources.* This aircraft model development represents a major part of this research effort and the results are now available for other advanced air traffic control research as well as the current time navigation studies. The model is discussed in detail in the following chapter.

*Link Division of General Precision, Inc., American Airlines, the U.S. Air Force, Pratt and Whitney Aircraft, the Dept. of Aeronautics and Astronautics at M.I.T. and a Boeing publication, Jet Transport Performance Methods [8], each contributed pieces which, when combined, provided most of the important aerodynamic parameters.
CHAPTER II
THE AIRCRAFT MODEL

There are many similarities among jet transport aircraft manufactured today because they are all designed to perform a similar function - fast, efficient, and economical ferrying of passengers and cargo. While configurations and intended uses may dictate varied landing speeds and maximum ranges, the operating airspeed range and cruising altitudes for many types of aircraft are quite similar. As an illustration of this, Table 2-1 is a sampling of aircraft operating limits as contained in the Boeing Company study [2]. The conclusion to be drawn is that the airspeed flexibility which will be required for time-controlled navigation could be found in any modern jet transport.

The Boeing 707-320B was selected for modeling primarily due to the availability of aerodynamic data. However, it is an advanced member of the Boeing 707 family and is widely used for intercontinental and transcontinental routes. Table 2-2 shows that a total of 862 Boeing 707's have been built. Of these, 167 bear the designation 707-320B but there are 409 more 707's (-320s, -320Cs, -420s) that have the same wing structure, but different engines or fuselage configurations [9]. While not all of the 707-320B or related aircraft are flown by U.S. airlines, the number might be compared with the total number of transports owned by domestic air carriers - approximately 2500 -
### TABLE 2-1

**AIRCRAFT PERFORMANCE DATA**

<table>
<thead>
<tr>
<th>AIRCRAFT TYPE</th>
<th>ALTITUDE</th>
<th>MIN. SPEED(KTAS) AT MAX. WEIGHT</th>
<th>MAX. SPEED(KTAS) AT MAX. WEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>707</td>
<td>10,000</td>
<td>229</td>
<td>435</td>
</tr>
<tr>
<td></td>
<td>21,600</td>
<td>275</td>
<td>527</td>
</tr>
<tr>
<td>727</td>
<td>10,000</td>
<td>231</td>
<td>452</td>
</tr>
<tr>
<td></td>
<td>24,000</td>
<td>304</td>
<td>530</td>
</tr>
<tr>
<td>737</td>
<td>10,000</td>
<td>243</td>
<td>407</td>
</tr>
<tr>
<td></td>
<td>22,500</td>
<td>295</td>
<td>495</td>
</tr>
<tr>
<td>747</td>
<td>10,000</td>
<td>255</td>
<td>436</td>
</tr>
<tr>
<td></td>
<td>22,000</td>
<td>315</td>
<td>532</td>
</tr>
<tr>
<td>DC-10</td>
<td>10,000</td>
<td>262</td>
<td>430</td>
</tr>
<tr>
<td></td>
<td>25,000</td>
<td>330</td>
<td>526</td>
</tr>
<tr>
<td>720-B</td>
<td>10,000</td>
<td>200</td>
<td>420</td>
</tr>
<tr>
<td></td>
<td>22,000</td>
<td>240</td>
<td>530</td>
</tr>
</tbody>
</table>

*SOURCE: [2 pp. 212-213]*

### TABLE 2-2

**AIRCRAFT IN THE 707 FAMILY**

<table>
<thead>
<tr>
<th>TYPE</th>
<th>NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>707-120</td>
<td>20</td>
</tr>
<tr>
<td>-120B</td>
<td>121</td>
</tr>
<tr>
<td>-220</td>
<td>5</td>
</tr>
<tr>
<td>-320</td>
<td>90</td>
</tr>
<tr>
<td>-320B</td>
<td>167</td>
</tr>
<tr>
<td>-320C</td>
<td>283</td>
</tr>
<tr>
<td>-420</td>
<td>36</td>
</tr>
<tr>
<td>KC-135 &amp; OTHERS</td>
<td>140</td>
</tr>
<tr>
<td>TOTAL</td>
<td>862</td>
</tr>
</tbody>
</table>

*SOURCE: [9]*
to show that data for a Boeing 707-320B is applicable to a significant percentage of the aircraft in use today.

In this chapter, the equations governing aircraft motion are presented. The derivation is standard and is available from numerous references (see for example, [10,11]). The aerodynamic forces and moments are based on a standard derivation, but the terms and values used in their calculations are related specifically to the Boeing 707-320B by the data obtained from the sources listed in Chapter 1. Therefore, the assumptions and linearizations based on that data are discussed in detail as they bear on the validity of the model. The thrust available is an important parameter and is discussed along with the relationship between thrust and throttle position.

2.1 REFERENCE FRAMES

Four reference frames are used here in what is commonly known as the "flat earth" approximation. This simplification is generally valid under the following conditions:

1. The earth's rotation is small compared to the rotation of the vehicle. ($\omega_e = 7 \times 10^{-5}$ rad/sec which is smaller than any vehicle rotation of interest.)

2. Vehicle velocity does not exceed Mach 3.0 (Certainly true for subsonic transports.)

3. The vehicle is a rigid body. (Certainly not true, in fact, but aeroelastic effects are unlikely to influence the results of the present study.)
2.1.1 **WIND AXES** The wind axes system in a right-handed, orthogonal set of vectors with the origin fixed at the aircraft center of gravity. The +x wind axis is coincident with the total velocity vector of the aircraft (and hence opposite to the "relative wind"). This is depicted in Figure 2-1. This axes system is important in computing the aerodynamic forces acting on the aircraft.

2.1.2 **BODY AXES** The body axes are also right-handed and orthogonal and have their origin at the aircraft center of gravity. The x axis is fixed along the fuselage reference line as shown in Figure 2-1. The z axis is "downward" and the x-z plane in the body frame is taken as a plane of symmetry. The aerodynamic forces are rotated into the body axes from the wind axes and all forces and moments are computed in this frame.

2.1.3 **VEHICLE AXES** The vehicle frame is a right-handed, orthogonal reference system with origin at the aircraft center of gravity. The x-y plane is parallel to our "flat" earth with the +x axis pointing to magnetic north (assuming a fixed magnetic declination of approximately 15°W). The z vehicle axis is coincident with the gravity vector as shown in Figure 2-2.

2.1.4 **EARTH AXES** The earth axes reference is arbitrarily located for the simulation to be conducted. For the present work, the
Fig. 2-1 Wind and Body Axes
Fig. 2-2 Vehicle Axes and Euler Angles
origin is southwest of the Logan International Airport, Boston, Massachusetts, at approximately 71°11'W, 42°12'N. Unlike the vehicle axes, the +y earth axis points to magnetic north and the +x axis to east because of an anomaly of the computer map display. Altitude above sea level is then positive.

2.2 THE EULER ANGLES

Euler angles are used to designate the orientation of the body axes system with respect to the vehicle axes. The rotations are performed in the conventional order; 1) a rotation $\phi$ about the z vehicle axis is the "azimuth" angle; 2) a rotation $\theta$ about the now rotated y vehicle axis is the "elevation" angle; 3) a rotation $\psi$ about the resulting x axis is the "bank" angle. These are shown in Figure 2-2.

2.3 THE AERODYNAMIC ANGLES

Two angles are fundamental in determining the aerodynamic forces that act on the vehicle. These angles are $\alpha$, the fuselage angle of attack, and $\beta$, the sideslip angle. A second angle of attack – that of the zero lift line or wing chord plane, $\alpha_0$ – is used in the lift calculations, but the two differ only by a constant 2°, the angle of incidence. The angle of attack and sideslip angle rotate the wind axes system into the body axes in the order ($-\beta, \alpha, 0$) analogously to the Euler angles above. Thus in terms of the body axes velocity components shown in Figure 2-3,
Fig. 2-3 Notation for Body Axes
\[ \alpha = \tan^{-1} \frac{w}{u} \quad - \pi < \alpha < \pi \quad (2-1) \]

\[ \beta = \sin^{-1} \frac{v}{V} \quad - \pi < \beta < \pi \quad (2-2) \]

where \( V = \sqrt{u^2 + v^2 + w^2} \).

2.4 EQUATIONS OF MOTION

The classic equations of motion from Newtonian mechanics are summarized here as they are used in the simulation.

The force equations are written in the body axes. The velocity components \((u,v,w)\) and angular velocities \((p,q,r)\) are oriented as shown in Figure 2-3

\[
\begin{bmatrix}
\dot{u} \\
\dot{v} \\
\dot{w}
\end{bmatrix} = \frac{1}{M} \begin{bmatrix}
Ax \\
Ay \\
Az
\end{bmatrix} + g \begin{bmatrix}
-sin \Theta \\
cos \Theta \sin \phi \\
cos \Theta \cos \phi
\end{bmatrix} \begin{bmatrix}
o & r & -q \\
r & o & p \\
-q & p & o
\end{bmatrix} \begin{bmatrix}
u \\
v \\
w
\end{bmatrix} + \begin{bmatrix}
\text{THRUST} \\
\text{Mass}
\end{bmatrix}
\]

\[
(2-3)
\]

where \(Ax, Ay\) and \(Az\) are resultant aerodynamic forces after rotation into the body frame.

The moment equations are also written in the body axes system.

\[
\begin{bmatrix}
Ixx & o & -Ixz \\
o & Iyy & o \\
-Ixz & o & Izz
\end{bmatrix} \begin{bmatrix}
\dot{p} \\
\dot{q} \\
\dot{r}
\end{bmatrix} = \begin{bmatrix}
L \\
M \\
N
\end{bmatrix} \begin{bmatrix}
o & -r & q \\
r & o & -p \\
-q & p & o
\end{bmatrix} \begin{bmatrix}
Ixx & o & -Ixz \\
0 & Iyy & o \\
-Ixz & o & Izz
\end{bmatrix} \begin{bmatrix}
p \\
q \\
r
\end{bmatrix}
\]

\[
(2-4)
\]

where \(L, M,\) and \(N\) are the rolling moment, pitching moment, and
yawing moment respectively. Note here that the x-z plane is taken as a plane of symmetry thus eliminating all cross products of inertia except Ixz. The equations are decoupled by neglecting the Ixz ̇p and Ixz ̇r terms (a common practice where Ixz is small compared to the other inertia terms).

The Euler angle rates are computed from body axes angular velocities.

\[
\begin{bmatrix}
\phi \\
\theta \\
\psi
\end{bmatrix} = \frac{1}{\cos \theta} \begin{bmatrix}
\cos \phi & \sin \phi & \sin \theta \\
0 & \cos \phi & \cos \theta \\
0 & -\sin \phi & \cos \phi
\end{bmatrix}
\begin{bmatrix}
p \\
q \\
r
\end{bmatrix}
\] (2-5)

Since only the sine and cosine functions of the Euler angles and not the angles themselves are required for all computations and displays, the discrete Gilbert-Howe algorithm [12] is used to integrate Euler angle rates to obtain the sine and cosine of the Euler angles. This approach is illustrated here for the azimuth angle and an identical approach is used for pitch and roll.

\[
\begin{align*}
\cos \psi_{n+1} &= \cos \psi_n - \sin \psi_n \cdot \psi_n \cdot \Delta t - \mu \Delta t \cdot \epsilon \cdot \cos \psi_n \quad (2-6) \\
\sin \psi_{n+1} &= \sin \psi_n + \cos \psi_n \cdot \psi_n \cdot \Delta t - \mu \Delta t \cdot \epsilon \cdot \sin \psi_n \quad (2-7)
\end{align*}
\]

Here \( \Delta t \) is the time increment, \( \mu \) is a constant, and the product \( \mu \Delta t \) has an optimum value of \( \frac{1}{2} \) for any \( \Delta t > 0 \).

The correction term, \( \epsilon \), is computed by

\[
\epsilon = \cos^2 \psi + \sin^2 \psi - 1
\] (2-8)
Earth frame position is obtained by integrating the sum of vehicle frame velocity and wind velocity. Vehicle frame velocity is computed by performing the following series of axis rotations:

\[
\begin{bmatrix}
V_x \\
V_y \\
V_z
\end{bmatrix} = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos \phi & \sin \phi \\
0 & -\sin \phi & \cos \phi
\end{bmatrix} \begin{bmatrix}
\cos \theta & \sin \theta & 0 \\
0 & 1 & 0 \\
-\sin \psi & \cos \psi & 0
\end{bmatrix} \begin{bmatrix}
\mathbf{u} \\
\mathbf{v} \\
\mathbf{w}
\end{bmatrix}
\]

(2-9)

The aerodynamic angles are parameters of several aerodynamic coefficients and their sine and cosine functions are used to rotate the wind axes aerodynamic forces into the body frame. The sine and cosine are computed as follows:

\[
\sin \alpha = \frac{w}{v} = \alpha \\
\cos \alpha = \frac{u}{v} \\
\sin \beta = \frac{v}{v} = \beta \\
\cos \beta = 1 - \frac{\beta^2}{2!}
\]

(2-10) (2-11) (2-12) (2-13)

Here the small angle approximation is used to determine \( \alpha \) and \( \beta \) in radians. The maximum angle of attack for the 707 is about 16 degrees. At this point the approximation is in error by less than 4%. Sideslip angle, \( \beta \), seldom gets as large as 16° so the approximation is even better.
The aerodynamic forces, as previously mentioned, are rotated into the body axes by utilizing the aerodynamic angles in the order \( (\beta, \alpha, \phi) \).

\[
\begin{bmatrix}
Ax \\
Ay \\
Az
\end{bmatrix} =
\begin{bmatrix}
\cos \alpha & 0 & -\sin \alpha \\
0 & 1 & 0 \\
\sin \alpha & 0 & \cos \alpha
\end{bmatrix}
\begin{bmatrix}
\cos \beta & -\sin \beta & 0 \\
\sin \beta & \cos \beta & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
-Drag \\
Side Force \\
-Lift
\end{bmatrix}
\] (2-14)

2.5 AERODYNAMIC FORCES

The previous equations are applicable to any aircraft or other atmospheric vehicle with six degrees of freedom and subject to the previously stated assumptions. The aerodynamic force and moment equations, on the other hand, are based on dimensionless aerodynamic coefficients associated with a particular aircraft. Since the validity of the present simulation and its potential in future applications are heavily dependent on the accuracy of these coefficients, they are discussed in some detail in the following paragraphs. In all cases the coefficients are the result of a Taylor series expansion about a steady state flight condition. The derivation is available in several texts [e.g. 10, 11] and is omitted here in favor of an explanation of the particular terms in the expansion selected for modeling. Where possible the approximations used to fit the available data are contrasted with that data. Where data was not available or where median values were picked for highly non-linear effects, the model was tested by professional pilots to confirm the values chosen. The final tests of the model will be discussed in chapter five.
2.5.1 **LIFT** All of the aerodynamic forces are products of dynamic pressure \((1/2\rho V^2)\), the dimensionless coefficients, and appropriate geometric terms to satisfy the dimensional requirements.*

The lift equation as implemented in this simulation is:

\[
\text{Lift} = \frac{1}{2}\rho V^2 S \left[ C_L \alpha_0 + C_L \delta \epsilon + C_L \delta F \cdot (\delta F - 6^\circ) + C_L \delta F - \alpha_0 \right]
\]

\[
C_L \delta \epsilon = 0.0055/\text{degree}
\]

\[
C_L \delta F = \begin{cases} 
0 & \delta F \leq 6^\circ \\
0.0143/\text{degree} & \delta F > 6^\circ 
\end{cases}
\]

\[
C_L \delta F - \alpha_0 = \begin{cases} 
0 & \delta F \leq 6^\circ \\
1.081/\text{degree} & \delta F > 6^\circ 
\end{cases}
\]

The term \(C_L \alpha_0\) is the slope of the lift coefficient curve as a function of Mach number. (Mach number is the dimensionless ratio of aircraft velocity to the local speed of sound.) The particular approximation used is a second order polynomial,

\[
C_L \alpha_0 = 4.584 - 2.220 \cdot \text{MACH} + 5.387 \cdot (\text{MACH})^2
\]

for \(\alpha_0\) in radians. This is plotted in Figure 2-4 along with the actual curves for a Boeing 707-320B. It is important to note that sample points for this approximation (and those that follow) were obtained by iteration of the actual assembly language program. Therefore, it serves as a check of the program logic as well as a measure of the approximation's accuracy.

*For the 707-320B: WING AREA (S) = 3010 FT^2; WING SPAN (b) = 145.75 FT; MEAN CHORD (c) = 22.69 FT
Fig. 2-4  High Speed Lift Coefficient
The $C_{L_{\delta F}}$ term is an incremental increase in lift due to flap deployment. The particular approximation used is linear for flap angles ($\delta F$) over 6 degrees. This correction, along with $C_{L_{\delta F}-\alpha}$ (an addition to the slope of the force lift coefficient for flaps over 6 degrees), are shown in Figure 2-5.

The $C_{L_{\delta e}}$ term represents the variation in lift with elevator deflection ($\delta e$). This is a relatively small corrective term and is taken as a constant 0.0055/degree. Elevator deflection has the sign and maximum magnitude shown in Table 2-3.

<table>
<thead>
<tr>
<th>Control</th>
<th>Positive Sign Convention</th>
<th>Maximum</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevator ($\delta e$)</td>
<td>Trailing edge down</td>
<td>$+25^\circ$ - $15^\circ$</td>
<td></td>
</tr>
<tr>
<td>Rudder ($\delta R$)</td>
<td>Trailing edge left (Nose yaws left)</td>
<td>$+26.5^\circ$</td>
<td></td>
</tr>
<tr>
<td>Aileron ($\delta A$)</td>
<td>Rt trailing edge up (Aircraft rolls right)</td>
<td>$+18\frac{1}{2}^\circ$ inboard</td>
<td>Outboard available only in conjunction with flaps</td>
</tr>
<tr>
<td>60$^\circ$</td>
<td>$+20^\circ$ outboard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spoiler ($\delta B$)</td>
<td>Positive deployment</td>
<td>$60^\circ$</td>
<td>Maximum limited with indicated airspeed</td>
</tr>
<tr>
<td>Flaps ($\delta F$)</td>
<td>Positive deployment</td>
<td>$50^\circ$</td>
<td>Deploy fully in 30 seconds</td>
</tr>
</tbody>
</table>
Fig. 2-5  Low Speed Lift Coefficient
2.5.2 DRAG  Aircraft drag is modeled by the following equation:

\[ \text{Drag} = \frac{1}{2} \rho V^2 S [C_{D_{\text{min}}} (M) + k(M)C_L^2 + \Delta C_{D_{\text{gear}}} + C_{D_{\delta F}} \cdot (\delta F - 6^\circ) + C_{D_{\delta B}} \cdot \delta B] \]

\[
C_{D_{\text{min}}} = \begin{cases} 
0.012 & M \leq 0.7 \\
0.01233 + 0.0033(M - 0.8) & 0.7 < M \leq 0.8 \\
0.014 + 0.0371(M - 0.845) & 0.8 < M \leq 0.845 \\
0.014 + 0.1455(M - 0.845) & 0.845 < M 
\end{cases}
\]

\[ k = \begin{cases} 
0.0524 & M \leq 0.8 \\
0.063 + (0.2356)(M - 0.8) & 0.8 < M \leq 0.845 \\
0.063 + 0.8333(M - 0.845) & 0.845 < M 
\end{cases} \]

\[ \Delta C_{D_{\text{gear}}} = 0.0105 \]

\[ C_{D_{\delta F}} = \begin{cases} 
0 & \delta F \leq 6^\circ \\
0.0026/\text{degree} & \delta F > 6^\circ 
\end{cases} \]

\[ C_{D_{\delta B}} = 0.00083/\text{degree} \]

The common lift-drag relationship of \( C_D = C_{D_{\text{min}}}^2 + kC_L \) is used here. The \( C_L \) term is the total lift coefficient (as contained in the brackets of equation 2-15). By varying \( C_{D_{\text{min}}} \) and \( k \) with Mach, an approximation to the actual drag curves is obtained. This approximation is shown in Figure 2-6 for low Mach numbers and in Figure 2-7 for high Mach numbers. In both figures there is only a limited range of values which will be required for level flight. For example at Mach .7, the lift coefficient for level flight varies from about .15 to .46 with changes in altitude. Over this range the approximation is very good. A similar case can be made for the speed range from .80 Mach to .84 Mach where the lift coefficients vary between .1 and .3. The drag at .82 Mach is too high as a result of the linear variation of \( C_{D_{\text{min}}} \) and \( k \). Above .84 Mach the inaccura-
Fig. 2-6 Low Speed Drag Polar
Fig. 2-7  High Speed Drag Polar
cies are deemed less significant since this is on the fringe of the normal operating range and more accurate values would require significantly more computation time.

The additional drag due to flaps is represented by the $C_{D\delta_F}$ term. Here an increment proportional to flap deployment over $6^\circ$ is added to the drag coefficient. The effect of this is shown in Figure 2-6.

The drag due to the spoilers, $C_{D\delta_B}$, is taken as a constant $0.00083/\text{degree}$. However, the blowdown effect of the spoilers is incorporated by limiting maximum spoiler deflection as shown in the following equation:

$$\delta_{B\text{max}} = \begin{cases} 60^\circ & \text{KIAS} \leq 188 \text{ knots} \\ 60^\circ - 0.283(\text{KIAS} - 188) & \text{KIAS} > 188 \text{ knots} \end{cases} \quad (2-18)$$

where KIAS is the indicated airspeed in knots. (Indicated airspeed is defined in Chapter 3.)

2.5.3 SIDE FORCE The $y$ body axis force was considered less important in this simulation and is modeled by the following simplified equation:

$$\text{Side Force} = \frac{1}{2} \rho V^2 S \left[ C_{y\beta} \cdot \beta + C_{y\delta_R} \cdot \delta_R \right] \quad (2-19)$$

The coefficient due to side slip is taken as a constant $-0.917/\text{radian}$ which is accurate to within approximately 10% over the full range of Mach numbers. The coefficient due to rudder de-
flection is taken as +.004/degree which is at best a rough approximation of a very non-linear effect and was confirmed by flight test.

2.6 AERODYNAMIC MOMENTS

The aerodynamic moments determine the pitch, roll, and yaw characteristics of the particular aircraft studied. They are modeled here without correction for non-linearities or Mach variation because the present simulation is primarily concerned with steady state flight conditions, i.e. when the aircraft moments sum to zero. Variations in transient effects due to varied Mach numbers or altitude are therefore omitted in favor of simplified computation.

2.6.1 ROLL The roll equation used is:

\[ L = \frac{1}{2} \rho V^2 S \left[ C_{1\beta} \cdot \beta + C_{1\delta A} \cdot \delta A + C_{1\delta R} \cdot \delta R \right] + \frac{2}{3} \rho V S b^2 C_{1p} \cdot p \]  

(2-20)

\[
C_{1\beta} = -0.1719/\text{radian} \\
C_{1\delta A} = 0.0013/\text{degree} \\
C_{1\delta R} = 0.0002/\text{degree} \\
C_{1p} = -0.38/\text{radian}
\]

The coefficient of roll due to ailerons, \( C_{1\delta A} \), is the least accurate in this case. Insufficient data was available to model the inboard aileron, outboard aileron, and spoiler deflection variations which command rolls in the 707. The
outboard ailerons, which operate only when the flaps are deployed, and the inboard ailerons were combined into a single aileron deflection term ($\delta A$). The value for $C_{1\delta A}$ was chosen to give a reasonable roll rate for a clean aircraft at airspeeds near the midpoint of the normal operating range.

The $C_{1\delta A}$ term represents the aircraft's inherent resistance to roll and is accurate to within 35% in the flight envelope.

The roll coefficient due to the rudder, $C_{1\delta R}$, is highly non-linear and was finally chosen from representative values by trial and error.

2.6.2 PITCH The pitching moment is computed by the following equation:

$$M = \frac{1}{2} \rho V^2 Sc[C_{m_o} + C_{m_\alpha} \alpha + C_{m_\delta \epsilon} \delta \epsilon + C_{m_6} \delta F + C_{m_{\delta F}} (\delta F - 14)] + \frac{1}{2} \rho VSC^2[C_{m_q} + C_{m_\alpha}] \cdot q$$

$$C_{m_o} = .048$$
$$C_{m_\alpha} = -.955/\text{radian}$$
$$C_{m_\delta \epsilon} = -.009/\text{degree}$$
$$C_{m_{\delta F}} = \begin{cases} 0 & \delta F < 14^\circ \\ .0033/\text{degree} & \delta F > 14^\circ \end{cases}$$
$$C_{m_q} = -16/\text{radian}$$
$$C_{m_\alpha} = -3.7/\text{radian}$$

(2-21)
The basic pitch coefficient is a function of Mach number, but for the present study such variations are ignored. This may result in level flight pitch attitudes that are slightly different from the real aircraft. However, such effects are rarely noticeable to the pilot since relative attitudes in the aircraft are usually obtained by repositioning the level flight pitch reference. The line determined by $C_{m\alpha}$ and $C_{m\alpha}$ is plotted in Figure 2-8 for comparison with the pitching moment coefficient of the actual aircraft at Mach .6. To simulate changes in pitching moment with flap deployment, an increment, $C_{m\delta F}$, was added to $C_{m\alpha}$ for each degree of flaps over 14°.

While the actual aircraft uses stabilizer trim rather than elevator trim to preserve the aerodynamic effectiveness of the elevator, elevator trim is used in this simulation. This is justified because the sampled control-input voltages are not subject to aerodynamic losses and this approach permits the elevator to be positioned so that neutral column position represents level flight elevator deflection.

The $C_{m\alpha}$ and $C_{m\alpha}$ terms are combined on the assumption of zero side slip angle. This holds true for the majority of flight operations. While used here as constants they increase by up to 32% at high Mach numbers and high altitudes. These effects have been neglected.

2.6.3 YAW The yaw equation is:
Fig. 2-8 Pitching Moment Coefficient
\[ N = \frac{1}{2}\rho v^2 S_b \left[ C_{m\beta} \cdot \beta + C_{m\delta R} \cdot \delta R \right] + \frac{1}{2}\rho v S_b C_{m_r} \cdot r \] (2-22)

\[ C_{m\beta} = 0.115/\text{radian} \]
\[ C_{m\delta R} = -0.0011/\text{degree} \]
\[ C_{m_r} = -0.15/\text{radian} \]

Yaw - like the side force - is less important than the other forces and moments in the simulation. Therefore, while \( C_{m\beta} \) and \( C_{m\delta R} \) are accurate to within 34% and 22% respectively, the variation of \( C_{m_r} \) with changes in angle of attack have been neglected.

2.7 THE ENGINE MODEL

For time-controlled navigation, it was decided that the most significant engine parameters were maximum and minimum thrust. Knowing that these extremes are achievable insures that the simulated aircraft can fly maximum and minimum airspeeds and achieve realistic acceleration and deceleration rates.

The net thrust of a turbofan engine is a complex function of many factors. Rather than attempt to take all of these factors into consideration, the engine manufacturers performance data was used to determine maximum and idle thrust over the altitude and Mach ranges normally flown by the 707. Figure 2-9 shows one such performance graph for sea level.
Fig. 2-9  Sea Level Thrust

PRATT AND WHITNEY
JT3D-1 TURBOFAN ENGINE
\( W_a = \text{AIRFLOW} \)

\[
\begin{array}{c}
\text{NET THRUST (lbs)} \\
\hline
20000 \\
16000 \\
12000 \\
8000 \\
4000 \\
0 \\
\hline
\text{MACH NUMBER} \\
0 \\
0.2 \\
0.4 \\
0.6 \\
0.8 \\
1.0 \\
\end{array}
\]

\text{MAX CONT} 8 \text{ NORMAL RATING} \text{ MAX CRUISE} \text{ Wg = 500 lb/sec} \text{ IDLE} 150 200 250 300 350 400 450
The operating boundary considered for each altitude is shown in Table 2-4. At sea level, takeoffs were neglected to give

### TABLE 2-4
NORMAL OPERATING RANGE

<table>
<thead>
<tr>
<th>ALTITUDE</th>
<th>MINIMUM MACH&lt;sup&gt;1&lt;/sup&gt;</th>
<th>MAXIMUM MACH&lt;sup&gt;2&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea Level</td>
<td>.17</td>
<td>.51</td>
</tr>
<tr>
<td>5000</td>
<td>.17</td>
<td>.57</td>
</tr>
<tr>
<td>10000</td>
<td>.33</td>
<td>.63</td>
</tr>
<tr>
<td>15000</td>
<td>.37</td>
<td>.71</td>
</tr>
<tr>
<td>20000</td>
<td>.42</td>
<td>.79</td>
</tr>
<tr>
<td>25000</td>
<td>.47</td>
<td>.88</td>
</tr>
<tr>
<td>30000</td>
<td>.53</td>
<td>.88</td>
</tr>
<tr>
<td>35000</td>
<td>.61</td>
<td>.88</td>
</tr>
<tr>
<td>40000</td>
<td>.75</td>
<td>.88</td>
</tr>
</tbody>
</table>

1 Vref or initial buffet for 1.3g maneuver
2 Indicated airspeed structural limit converted to Mach below 25000ft. Mach limit above 25000.

a range of Mach .17 to Mach .51. Over this range one can see from Figure 2-9 that it is relatively easy to approximate the thrust variation with Mach. The inspection of similar charts for other altitudes lead to the following equation for approximating the variation of the thrust extremes with altitude and Mach:

$$T(h,M) = T(h_0,0) + \frac{\partial T}{\partial h} \bigg|_{m=0} (h-h_0) + \frac{\partial T}{\partial M} \bigg|_{h=h_0} M + \frac{\partial^2 T}{\partial h \partial m} \bigg|_{m=0, h=h_0} (h-h_0) \cdot M \quad (2-23)$$

To calculate maximum thrust let
Maximum Thrust = $T(h,M)$

using the following values:

$$h_o = \begin{cases} 
0 & 0 \leq h < 15,000 \text{ ft.} \\
15,000 & h \geq 15,000 \text{ ft.}
\end{cases}$$

$T(h_o, o) = 13,800$ lbs.

$$\left. \frac{\partial^2 T}{\partial h^2} \right|_{m=o} = 0.281 \text{ lbs/ft}$$

$$\left. \frac{\partial T}{\partial M} \right|_{h=ho} = \begin{cases} 
-7800 \text{ lbs/Mach} & h_o = 0 \\
-3125 \text{ lbs/Mach} & h_o = 15,000
\end{cases}$$

$$\left. \frac{\partial^2 T}{\partial h \partial M} \right|_{m=o} = \begin{cases} 
+0.312 \text{ lbs/Mach-ft} & h_o = 0 \\
+0.185 \text{ lbs/Mach-ft} & h_o = 15,000
\end{cases}$$

For idle thrust, let

Idle Thrust = Max [$T(h,M)$, o]

using the following values:

$$h_o = \begin{cases} 
0 & 0 \leq h < 15,000 \text{ ft.} \\
15,000 & h \geq 15,000 \text{ ft.}
\end{cases}$$

$T(h_o, o) = 1,000$ lbs all $h_o$

$$\left. \frac{\partial T}{\partial M} \right|_{m=o} = 0$$

$$\left. \frac{\partial T}{\partial M} \right|_{h=ho} = -2,000 \text{ lbs/Mach} \text{ all } h_o$$

$$\left. \frac{\partial^2 T}{\partial h \partial M} \right|_{m=o} = \begin{cases} 
0 & h_o = 0 \\
+0.07 \text{ lbs/Mach-ft} & h_o = 15,000
\end{cases}$$
To check the accuracy of this approximation, the manufacturers maximum thrust values versus Mach for several altitudes are consolidated in Figure 2-10. Figure 2-11 shows a similar compilation of the idle thrust values. In each figure the dotted lines represent values obtained from the actual simulation logic over the speed ranges of interest for that altitude (cf. Table 2-4).

While the computed values are very close to the actual maximum thrust at all altitudes, there appears to be some error in the idle thrust approximation shown in Figure 2-11. In examining these curves, it is important to note that the actual idle thrust data is no more accurate than what can be extracted from Figure 2-9. In particular, the unlikely value of zero idle thrust above .5 Mach in Figure 2-9 led to the conclusion that the solid lines of Figure 2-11 were too inaccurate to warrant a better approximation.

With the two extremes of maximum and idle thrust established it is only necessary to relate intermediate throttle positions to a representative thrust value. The throttles generally command engine speed by regulating the engine fuel control. Engine speed and, hence, throttle position variations with altitude are small enough to be neglected. Unfortunately, engine speed and thrust are not linearly related. However, air flow through the engine (labeled $W_a$ and measured in lbs/sec in Figure 2-9) may be considered proportional to engine speed.
Fig. 2-10 Maximum Thrust Variation
Fig. 2-11 Idle Thrust Variation
[13]. Then by normalizing the airflow for a given altitude and Mach, throttle position can be related to thrust. Polynomial approximations of various orders were attempted on this basis for a representative altitude and Mach. In each case the coefficient of the second order term dominated. So for ease of computation without significant loss in pilot "feel" the thrust was equated to throttle position by the following relationship:

\[ \text{Thrust} = \frac{\text{Idle Thrust} + (\frac{\text{Max Thrust} - \text{Idle Thrust}}{\text{Thrust} - \text{Thrust}})(\text{Throttle})^2}{\text{Position}} \quad 0 < \text{Throttle} < 1 \]

(2-26)

where Idle Thrust and Max Thrust are defined by equations 2-24 and 2-25. This relationship obeys an old cockpit adage that 70% RPM yields 50% thrust and was found quite acceptable in actual tests. Using the assumption that airflow is proportional to engine speed and engine speed to throttle position, the thrust data of Figure 2-9 is related to throttle position by the solid curve in Figure 2-12. Equation 2-26 is depicted in the same figure as a dashed curve.
Fig. 2-12  Thrust Related to Throttle Position
CHAPTER III
THE ATMOSPHERE MODEL

The variations of the atmosphere are very important in aircraft simulations for altitudes much above 5000 feet. The atmospheric density ($\rho$) is a factor in all the calculations of aerodynamic forces and moments. Many of the individual terms are functions of Mach number which varies with ambient temperature. This simulation is performed entirely under the assumption of the standard ICAO* atmosphere [14]. The equations used to approximate variations of density and speed of sound are outlined in this chapter. The cockpit airspeed indications, because they are functions of atmospheric variables, are also explained here.

3.1 DENSITY

The ratio of local density to sea level density ($\frac{\rho}{\rho_o}$) in the standard atmosphere varies as shown in Figure 3-1. The actual relationship (from [11]) can be expressed as

$$\frac{\rho}{\rho_o} = (1 - \frac{\zeta h}{T_o}) \frac{m g}{\xi R} - 1$$

(3-1)

where

- $h =$ altitude
- $\zeta =$ temperature lapse rate
- $R =$ universal gas constant
- $m =$ equivalent molecular weight for air

*International Congress of Aeronautical Organizations
Fig. 3-1  Density and Speed of Sound Ratios
g = acceleration of gravity
T₀ = sea level temperature
ρ₀ = sea level density (0.002378 slugs/cu.ft.)

For fast real-time simulation, it is more efficient to avoid this precise equation and instead to approximate the curve by the following polynomial:

\[
\frac{\rho}{\rho_0} = 1 - 1.835 \left( \frac{h}{65536} \right) + 1.0 \left( \frac{h}{65536} \right)^2
\]

(3-2)

where 65536 is a power of 2 (2¹⁶) used as a normalization constant. This approximation does not appear in Figure 3-1 because below 40,000 feet the approximation lies precisely on the actual curve.

3.2 SPEED OF SOUND

Mach number is defined as the ratio of the aircraft's true velocity to the ambient speed of sound. The ratio of local speed of sound to sea level speed of sound varies, in air as (from [11])

\[
a/a_0 = \begin{cases} 
\sqrt[\lambda]{\frac{\rho}{\rho_0}} \sqrt{T_0 - \frac{\rho}{\rho_0} h} & \text{if } h \leq 36,089 \text{ ft.} \\
\sqrt[\lambda]{\frac{\rho}{\rho_0}} \sqrt{T_0 - \frac{\rho}{\rho_0} (36,089)} & \text{if } h > 36,089 \text{ ft.}
\end{cases}
\]

(3-3)

where \( \lambda \) = adiabatic constant for air
a₀ = sea level speed of sound (1116.4 ft/sec)

Because temperature remains constant above 36,089 feet in the standard atmosphere, the speed of sound is constant as well. Once again this function was approximated in order to increase
the speed of computation. The relationship chosen was:

\[ \frac{a}{a_o} = \begin{cases} 
1 - (3.683 \times 10^{-6}) \cdot h & h \leq 36,089 \text{ ft.} \\
0.867 & h > 36,089 \text{ ft.}
\end{cases} \] (3-4)

The actual curve and the approximation are indistinguishable in Figure 3-1.

3.3 AIRSPEED CALCULATIONS

3.3.1 INDICATED AIRSPEED Because of atmospheric variations there are several airspeeds besides true airspeed (true velocity relative to the air) and Mach that are used in aviation. The airspeed read in the cockpit is termed indicated airspeed (IAS) and is proportional to the dynamic pressure caused by the aircraft's forward velocity [8]. But to measure the dynamic pressure, the ambient static pressure must be subtracted from the total pressure at the airspeed sensor. There is some error (position error) involved in determining static pressure due to the disturbed airflow around the aircraft. This error is measured experimentally for each aircraft type and is used to correct the indicated airspeed to a calibrated airspeed (CAS). However, the error seldom exceeds 1% and is usually neglected so that calibrated and indicated are used synonymously. Because it is proportional to dynamic pressure, calibrated airspeed is an invaluable reference to the pilot in avoiding a stall. The constant of proportionality is chosen
so that calibrated airspeed and true airspeed are equal at sea level.

If the atmosphere were incompressible and, hence had a constant density, calibrated airspeed and true airspeed would always be equal. However, the true nature of air requires that as the aircraft's forward velocity increases, the calibrated airspeed reading must be corrected to equivalent airspeed (EAS) by a suitable compressibility factor. And then, because the proportionality constant was valid only at sea level the equivalent airspeed is corrected for the density variations of equation 3-1 or 3-2 to find true airspeed. The equation for true airspeed is

\[
\text{TAS} = \frac{\text{EAS}}{\sqrt{\frac{\rho}{\rho_0}}}
\]  

(3-5)

An accurate simulation over a wide range of altitudes thus requires a cockpit readout of calibrated (or indicated assuming no position error) airspeed rather than true airspeed. The non-linear nature of the compressibility correction makes it more desirable to relate calibrated airspeed to Mach by an approximation of the precise equation (from [8]):

\[
M^2 = 5 \left[ \left( \frac{1}{5} \left( 1 + 0.2 \frac{V_C}{661.5} \right)^2 \frac{3.5}{1} + 1 \right) ^{0.2861} - 1 \right]
\]  

(3-6)

where \( M \) = Mach number
\( \delta \) = \( P/P_0 \) = pressure ratio in standard atmosphere
\( V_C \) = calibrated airspeed in knots
This function is plotted in Figure 3-2 and the following equation was derived by inspection:

\[
\frac{V_C}{M}(h) = \frac{V_C}{M} \bigg|_{h=0} + \frac{d(V_C)}{dh} \cdot h
\]

where \( \frac{V_C}{M} \bigg|_{h=0} = 656 \text{ knots/Mach} \)

\[
\frac{d(V_C)}{dh} = 0.0091 \text{ knots/Mach-ft}
\]

This approximation is shown as the dotted lines in Figure 3-2.

3.3.2 COCKPIT MACH INDICATION

Besides indicated airspeed, the pilot uses a Mach indicator at high altitude to maintain efficient cruise conditions. A combination indicated airspeed and Mach meter as employed in the Boeing 707 is shown in Figure 3-3. Note that the Mach indicator has a fixed scale which rotates with altitude changes to align with the corresponding indicated airspeed. The linearized Mach-to-indicated-airspeed relationship of Equation 3-6 was used to create a similar Mach indicator for the present simulation. The angular rotation of the Mach scale is proportional to the difference in knots between \(.7\) Mach and 300 knots indicated. The 300 knots is fixed on the face of the display at the nine o'clock position. By the following formula one can see that the \(.7\) Mach indication is at the 9 o'clock position at approximately 26,000 feet.

\[
\text{Mach Angle} = 0.7 \frac{V_C}{M} - 300 = 159.2 - 0.0064 \cdot h
\]
Fig. 3-2  Mach to Calibrated Airspeed Conversion
Fig. 3-3  Boeing 707 Airspeed/Mach Indicator
where \( \frac{V_C}{M} \) is defined by Equation 3-7.

The displayed airspeed-Mach indicator is shown in the upper left-hand corner of Figure 3-4. There is some error inherent in this approach because the airspeed difference between successive Mach graduations is not constant at all altitudes. However, in this respect, it is no different from the fixed scale employed in the actual aircraft.
Fig. 3-4 Simulator Instrument Panel
CHAPTER IV
THE NAVIGATION CONCEPT

The accurate models of the aircraft and atmosphere described in Chapters II and III were developed in order to provide a realistic basis for the measurement of the accuracy of any time-controlled navigation system. The four-dimensional navigation concept introduced in Chapter I is highly dependent on the performance capabilities of the airplane. In this chapter the navigation control systems developed and tested during this research are described. During their development, it was necessary to make assumptions and linearizations in order to arrive at a computationally feasible solution. These assumptions and linearizations are presented here also but the justification for their employment was demonstrated by testing the solution in the independently developed aircraft simulation.

The requirement to navigate accurately in four dimensions was quickly separated into three parts - navigating in the horizontal plane, in the vertical plane, and in time. Navigation in the horizontal plane is performed every day by pilots using a variety of on-board navigation equipment - VOR, DME, RNAV, inertial, etc.* Using the cockpit simulator

*VHF omnirange, distance measuring equipment, area navigation equipment, and inertial navigation equipment respectively.
described in Chapter I, it would have been possible to simulate any of these. But VOR and DME were judged to be the most common horizontal navigation aids and programs and cockpit controls for using them were already available. Therefore, this was the horizontal navigation method used.

Vertical navigation, the second part of the navigation problem, is relatively simple if restricted to the linear, fixed, descent profile described in Chapter I. While this may not be the most efficient descent for aircraft (see, for example, [3] for an alternative), a simple feedback system was designed and simulated to assist the pilot in maintaining this profile. Vertical navigation devices are commercially available which perform the same function - possibly in the same way - but are not widely used because they are not required in the present ATC system. The particular approach used here will be described primarily as a reference.

Accurate navigation in time was the ultimate objective of this research and, because of the many atmospheric variables which affect and alter the flight path, particularly during climbs and descents, it was not considered a simple task. As explained in Chapter I, the present approach assumes that there is an advantage attendant to being able to arrive at the waypoint earlier or later than the assigned time by an equal amount. An example was formulated in which one aircraft was asked to arrive earlier because another would be late. Even if the on-board navigation systems used
become so precise that all aircraft meet their assigned arrival times, occasional circumstances will arise in which the controlling agency will have to reschedule aircraft. Emergencies, weather in the terminal area, runway changes, or blunders might necessitate a schedule change. Under these circumstances it seems as likely that an aircraft would be asked to advance as to delay. As was shown in Figure 1-4, an airspeed schedule which meets the time of arrival without concern for this aspect loses flexibility in one direction or the other unless scheduled to arrive at the midpoint of its range of achievable times. This is unlikely since aircraft will generally be scheduled - traffic permitting - to arrive close to, but not at, the earliest possible arrival time. (Assigning the EPTA increases the likelihood of being late.) Therefore, the design described in this chapter seeks to not only meet the assigned time of arrival but to preserve flexibility as it is defined here. The description will include an intuitive argument as to why this may be a good approach in the presence of unknown winds.

4.1 THE VERTICAL NAVIGATION CONTROLLER

The feedback system designed to maintain the fixed descent profile is shown in Figure 4-1. Note here that the pilot is shown in the closed loop. This could also be the aircraft autopilot in which case the pilot would be outside the loop and would act as a monitor. In either case, the
Fig. 4-1  Vertical Navigation Controller

Fig. 4-3  Timed Navigation Controller
control input to the aircraft consists of the elevator position (δε) set by the pilot (or autopilot). The pilot is actually part of the controller and he seeks to minimize the error between his measured descent rate (h_m) and the commanded descent rate (h_C) as determined by the computer. The computer requires only aircraft position (in three dimensions), true airspeed (V_m), and the three-dimensional route to determine h_C. The computation is based on a technique often used by pilots. The technique consists of making corrections to a required altitude at a vertical velocity rate which will put the aircraft at the altitude in 30 seconds. This was changed to 32 seconds for ease of computation and the following formula was derived:

\[ h_C = \frac{h_p(t+32) - h_m(t)}{32} \text{ ft/sec} \]  

(4-1)

where h_m(t) is the current measured altitude and h_p(t+32) is the altitude required by the descent profile after 32 seconds of flight. This is calculated in the following manner:

\[ h_p(t+32) = (D-d-V_m \cdot 32) \cdot \tan \gamma + h_{WP} \]  

(4-2)

where

- D = distance to waypoint (ft)
- d = 15 mile deceleration segment if applicable (ft)
- V_m = measured true airspeed (ft/sec)
- h_{WP} = altitude assigned at the waypoint (ft)
- \( \gamma \) = angle of descent
These computations are performed in the subroutine PROFL in the FOURD computer program of Appendix B.

This approach is beset with inaccuracies. The measured true airspeed is not the horizontal component of velocity as assumed here. It is always in error by the tangent of \( \theta \) where \( \theta \) is the angular difference between the aircraft velocity vector and the horizontal plane. However, this angle equals \( \gamma \) when the aircraft is on the profile and won't exceed about 5° (9% error) when making corrections. (Pitch angles greater than about 5° will cause the aircraft to accelerate due to the effect of gravity [2].) In any case, \( V_m \) is not the aircraft groundspeed which would accurately predict the aircraft position after 32 seconds. Nevertheless, the position predicted using instantaneous true airspeed was sufficiently accurate to determine the required altitude, \( h_p(t+32) \), for the tests conducted here. Many of the inaccuracies are offset by the feedback nature of the design and the fact that command descent rate is updated three times per second. The commanded descents are very stable for this reason and it is easy to maintain the required profile.

Wind would probably induce a bias in the deviation such that the average flight path would be off the profile a distance proportional to wind speed. Whether or not winds would be strong enough to cause deviations outside the normal buffer area required for pilot error was not studied.
However, these inaccuracies could all be eliminated by substituting for \( V_m \) the present groundspeed based on last position and time between position updates. Because groundspeed is unlikely to vary quickly over the time interval of interest (32 seconds), it is more easily applied in vertical navigation than in time control where the time interval of interest is generally far larger.

4.2 TIME-CONTROLLED NAVIGATION

Several design objectives for the time-controller follow naturally from the discussion in Chapter I:

1. The system should be closed-loop so that in the presence of wind, inaccurate equations, or pilot error it issues continuous corrections to the required airspeed. A feedback system will compensate for inaccuracies in the equations by not permitting errors to propagate.

2. The system should optimize the flexibility of the aircraft to arrive earlier or later than the assigned time by equal amounts.

The latter objective implies that the system will periodically compute the earliest possible time of arrival and the latest possible time of arrival. Using these, let us define the time differences \( \tau_1 \) and \( \tau_2 \) in the following manner:

\[
\tau_1 = \text{ATA} - \text{EPTA} \quad (4-3)
\]
\[
\tau_2 = \text{LPTA} - \text{ATA} \quad (4-4)
\]

This is shown schematically for some arbitrary distance from the waypoint in Figure 4-2.
Using these terms, the system is required to minimize $|\tau_1 - \tau_2|$ by choosing an appropriate airspeed. It should be obvious that this objective initially requires the aircraft to change airspeed to one extreme, minimum or maximum airspeed, in order that the corresponding time bound, LPTA or EPTA, does not change until $\tau_1 = \tau_2$ (i.e. if $\tau_2 > \tau_1$, we will fly as fast as possible in order to decrease $\tau_2$ and to maintain the same value of $\tau_1$). This process was shown in Figure 1-4.

A controller based on these objectives was constructed, but, as is sometimes the case when striving to optimize a quantity, it produced a "bang-bang" type of control which commanded either minimum or maximum airspeed for any condition other than equality of $\tau_1$ and $\tau_2$. In other words, the relative size of the difference between $\tau_1$ and $\tau_2$ was ignored; the controller responded identically to a difference in the time flexibilities of one minute or one second. This repetitive acceleration or deceleration was totally unacceptable as a method of controlling the aircraft. Therefore, a
third objective was added:

3. The airspeed changes commanded to optimize flexibility should be sensitive to the magnitude of the error.

A controller designed to meet these three objectives is described in Section 4.2.4 following the discussion of the feedback nature of the system and the method of computation of EPTA and LPTA.

4.2.1 FEEDBACK CONTROL The time control system is shown in Figure 4-3. The feedback loop has been broken into parts labeled A and B to designate the separate functions performed at each stage. In block A the EPTA and LPTA are computed using distance to the waypoint (determined from aircraft position), present airspeed, and the desired airspeed at the waypoint if specified. Block B uses the ATA to compute $\tau_1$ and $\tau_2$ as required for determining the command airspeed. By using present position and airspeed to compute EPTA and LPTA the system corrects for pilot error or wind disturbances which enter in the forward loop. Errors in measuring position or airspeed are in the feedback path and will affect the accuracy of the solution.

The two feedback loops of Figure 4-1 and 4-3, the vertical navigation controller and the time navigation controller, have common inputs to the feedback path of three-dimensional position and measured true airspeed. Increased airspeeds commanded for time control purposes are sensed as
changes in both position and measured airspeed by the vertical navigation controller. These require greater command descent rates and result in new altitude values for the next cycle of command airspeed computations. Both controller computations are accomplished three times per second (see the calling subroutine FORD1 in Appendix B) so that the changes in command indications transition smoothly. In one third of a second, the horizontal position changes by less than 300 feet; the altitude changes less than 30 feet; and the airspeed by less than 1 ft/sec.

4.2.2 COMPUTATION OF EPTA AND LPTA Figure 4-3 shows that the commanded airspeed is a function of EPTA and LPTA; therefore errors in their determination directly influence the time accuracy achieved. The ATC scheduling algorithm described in Chapter I performs a one-time computation of EPTA and LPTA while the aircraft is at a large distance from the waypoint. The on-board computation, on the other hand, is performed repetitively for shorter and shorter distances as the aircraft approaches the waypoint. Therefore, the method of computation varies with the remaining distance. This will be illustrated for the computation of EPTA, but the same logic applies in computing LPTA with acceleration and deceleration interchanged and minimum airspeed substituted for maximum.

Figure 4-4 depicts the velocity profile for a Boeing
Fig. 4-4 Velocity Profile 707-320B
The heavy lines indicate the extremes of airspeed permitted in the present simulation. (These are inside the permissible operating range for a 225,000 pound aircraft, allowing a buffer zone for pilot error.) This data is stored in the on-board computer so that maximum (or minimum) airspeed at any altitude is available for the computation of EPTA (or LPTA). Ignoring temporarily the effect of a change in altitude, the computation has three stages:

1. At large distances from the waypoint, the aircraft can accelerate to maximum airspeed for that altitude \( V_{\text{MAX}}(h_0) \), cruise at that maximum and then decelerate to comply with airspeed restrictions at the waypoint \( V(h_{WP}) \). However, at some point the distances required to accelerate and decelerate leave no distance to cruise.

2. After this point the aircraft can only accelerate to some airspeed less than \( V_{\text{MAX}}(h_0) \) and still decelerate in the remaining distance.

3. Finally the aircraft reaches a point where it can only decelerate (or accelerate if below the required final airspeed) in the remaining distance to achieve the desired airspeed at the waypoint.

The computation of EPTA is performed in the subroutine MXASP in Appendix B.

In the present study, the acceleration and deceleration values used in computing EPTA and LPTA are assumed to be equal and invariant with altitude. The value chosen was 1.75 ft/sec\(^2\) and was based on some experimental measurements done with the aircraft model of Chapter II. The Boeing study [2] makes the same assumptions and chooses a value of .125 g
(4 ft/sec\(^2\)) which was not achievable in the aircraft model described here. In his studies [3], Capt. Victor measured deceleration values for the actual Boeing 707-323 aircraft and the American Airlines 707-323 simulator at various altitudes. The deceleration decreased with altitude and varies with airspeed but he obtained an average value at 10,000 feet of 1.4 knots/sec (2.37 ft/sec\(^2\)).

The acceleration and deceleration values chosen could be made unequal without any additional programming of the simulation. They could be made a function of altitude with some increased complexity. To assume that they were anything other than constant for one altitude would make the present computation intractable. The beauty of the feedback solution is that actual deceleration or acceleration other than the assumed value will be sensed as an error in position and corrected for by changing the commanded airspeed. It is only when very close to the waypoint that the assumed acceleration and deceleration rates may affect the time accuracy. For example, in stage 3 of the computation described above, an actual deceleration greater than the 1.75 ft/sec\(^2\) value used in predicting EPTA would put the aircraft into stage 2 and the commanded airspeed would adjust accordingly. An actual deceleration less than 1.75 ft/sec\(^2\) in stage 3 would not meet the time or airspeed desired at the waypoint, but this is a conservative value and could be attained by deploying the spoilers. Actual acceleration at
maximum thrust which is below the assumed 1.75 ft/sec$^2$ is a more difficult problem. There is no penalty associated with being below 250 knots (the waypoint airspeed restriction generally considered here), but the time accuracy would suffer if the chosen value of acceleration for stage 3 used in the calculations could not be achieved in practice. (This did not appear to be a factor in any of the tests conducted here, but the assumption that 1.75 ft/sec$^2$ acceleration could be achieved at high altitude led to errors in computing EPTA during stage 1.)

4.2.3 AVERAGE AIRSPEED DURING DESCENT If the remaining distance to the waypoint includes a descent the computation of EPTA (or LPTA) is adjusted for the variation in maximum (or minimum) airspeed with altitude. As shown in Figure 4-4 the aircraft can fly at its greatest true airspeed ($V_{\text{MAX}(25K)}$) at approximately 25,000 feet. To exploit the full performance window of the aircraft and gain the maximum delay spread the computation must include the variation of maximum airspeed at each altitude.

Because the descent is confined to the linear descent profile of Figure 1-1, the rate of descent required to maintain the profile is greater for higher true airspeeds. Thus the aircraft spends less time at altitudes of high true airspeed and this factor must be included when computing the average true airspeed during the descent. The average true
airspeed for a descent from current to final altitude can be determined by summing the times required to traverse small increments of altitude ($\Delta h$) during the descent and dividing the result into the horizontal distance travelled:

$$V_{\text{AVE}} = \frac{\text{horiz slope distance}}{\sum_{i=0}^{n} \Delta h \cdot \cot \gamma \left/ V_{\text{MAX}}(h_i) \right.}$$  \hspace{1cm} (4-5)$$

where $n = \text{number of altitude increments}.$

In the present simulation, this variation in rate of descent was ignored in favor of a computationally simple approximation. As it is presently computed in the subroutine MXAVR of Appendix B, average airspeed is determined by the following weighted average:

$$V_{\text{AVE}} = \left\{ \frac{V_{\text{MAX}}(h_0) + V_{\text{MAX}}(25K)}{2} \cdot (h_0 - 25,000) + \right.$$

$$\left. \frac{V_{\text{MAX}}(25K) + V_{\text{MAX}}(h_{WP})}{2} \cdot \left(25,000 - h_{WP}\right) \right\} \div \left( h_0 - h_{WP} \right)$$

for $h_0 > 25,000$ ft.  \hspace{1cm} (4-6)

And,

$$V_{\text{AVE}} = \frac{V_{\text{MAX}}(h_0) + V_{\text{MAX}}(h_{WP})}{2} \text{ for } h_0 \leq 25,000 \text{ ft.} \hspace{1cm} (4-7)$$

Although this was originally felt to be the source of some
error in the computation of EPTA prior to the descent, the value of $V_{AVE}$ computed for 1,000 feet altitude increments in Equation 4-5 differs from this approximation by a maximum of 1.4% for $h_0 = 35,000$ ft and $h_{WP} = 10,000$ ft.

4.2.4 COMPUTATION OF COMMANDED AIRSPEED The relationship governing commanded airspeed ($V_C$) was chosen by inspection of the design objectives and is expressed by the following equation:

$$V_C = \frac{\tau_1^2 V_{MIN} + \tau_2^2 V_{MAX}}{\tau_1^2 + \tau_2^2}$$

(4-8)

In this expression $\tau_1$ and $\tau_2$ are defined by equations 4-3 and 4-4 and the airspeed extremes $V_{MAX}'$ and $V_{MIN}'$ are determined as follows:

1. During stage 1 of the computation of EPTA and LPTA as described above, the airspeed extremes $V_{MAX}'$ and $V_{MIN}'$ are the aircraft's maximum and minimum airspeeds for the current altitude ($V_{MAX}(h_0)$ and $V_{MIN}(h_0)$) as shown in Figure 4-4.

2. During stage 2 of that computation, the airspeed extremes are the maximum or minimum airspeed which can be achieved in the remaining distance and still decelerate or accelerate to the desired airspeed at the waypoint.

3. During stage 3, the airspeed extremes are both set equal to the desired final airspeed so that the aircraft will decelerate or accelerate to achieve that airspeed.

Thus the values of $V_{MAX}'$ and $V_{MIN}'$ are set in the MXASP and MNASP subroutines of Appendix B and the commanded airspeed.
is computed in the CMSPC subroutine.

The relationship of equation 4-8 was expected to meet all the design objectives. The true airspeeds commanded (converted to Mach above 25,000 feet and indicated airspeed below 25,000) are very stable and the only large airspeed change required is the initial change to near maximum or minimum airspeed when the quantity $|\tau_1 - \tau_2|$ is large. The experimental results using this approach will be presented in the next chapter.

4.2.5 **EFFECT OF WIND DISTURBANCES** This control scheme was tested under zero wind conditions and subsequent studies might reveal that some modifications are required when wind effects are included. For example, the Boeing scheduling algorithm [2] converts the true airspeed profile of Figure 4-4 to a groundspeed profile by applying forecast winds. This is necessary because any along-track winds (headwinds or tailwinds) will alter the achievable EPTA and LPTA. But the controller design contemplated here will attempt to hold the time differences $\tau_1$ and $\tau_2$ equal based on its best available estimate of EPTA and LPTA. The flexibility implied by this approach and the closed loop nature of the solution suggest that it might have the capacity to correct very well for any along-track wind disturbances that would alter the EPTA or LPTA.
CHAPTER V

EXPERIMENTAL RESULTS

The cockpit mockup interfaced with the Adage digital computer, as described in Chapter I and in Appendix A, is ideal for testing the on-board navigation scheme described in the previous chapter. The flight instruments are drawn by the computer and may be changed at will to present new information to the pilot. Also, the moving map display (which was developed and tested as an Airborne Traffic Situation Display but is used here without traffic information) occupies the weather radar position between the pilot and copilot (cf. Figure 1-5) and provides an immediate reference to the aircraft's horizontal position. For the present study, "bugs" were added to the vertical velocity indicator to display commanded airspeed and commanded descent rate ($V_C$ and $h_C$ as described in Chapter IV). The pilot's task was reduced to making control inputs which would align the airspeed needle or vertical descent needle with the command bug. This was judged quite acceptable by the pilots as it was easily incorporated into their normal scan of the flight instruments (known as the instrument crosscheck). The testing which has been done on the aircraft model and of the algorithm which positions these command bugs are summarized in this chapter.
5.1 AIRCRAFT MODEL EVALUATION

As described in Chapter II, the aircraft model was designed to closely approximate the aerodynamic characteristics of a Boeing 707-320B. Therefore, one of the first performance evaluations consisted of flight tests by pilots familiar with the performance of the real aircraft. The primary purpose of these tests was to compare climb, descent, acceleration, and deceleration of the simulation to that of the real aircraft. Unbiased tests of the roll and pitch response to control column inputs were not considered possible because these control coefficients (\(C_{1\delta A}\) and \(C_{m\delta \epsilon}\) of Equations 2-20 and 2-21 respectively) were chosen for lack of accurate data — by trying various values until the desired response was obtained.*

There is no quantitative way of measuring the total performance of the aircraft model but in no case was it rated less than satisfactory by anyone engaged in the testing. The consensus was that it adequately simulated the real aircraft in the parameters required for the present study. Captain Carl W. Vietor of American Airlines, who has 26,000 hours of

*It must be pointed out here that, while the aircraft model was designed to be accurate over all altitudes, airspeeds, and configurations normally flown by the 707, the final value chosen for \(C_{1\delta A}\) was judged by the pilots in these tests to be insufficient in the landing configuration. In the actual aircraft, additional aileron surfaces (the outboard ailerons) become operative when the flaps are extended. These may need to be modeled by anyone employing this simulation in the landing phase.
flying time and 6,000 hours of that in the Boeing 707-320B offered this comment:

"The aircraft is accurate in its inertial functions, power functions, and control functions so that it is an acceptable base for extracting the data needed. In short, the simulation is quite realistic."

5.1.1 DECELERATION PERFORMANCE A quantitative evaluation is available for the time required to decelerate - a crucial factor in the time-controlled navigation concept. The basis for comparison is data from flight tests made in the American Airlines 707-323 simulator by Capt. Vietor and supplied by him. The results are shown in Table 5-1. Note that the weight of the American Airlines simulator varies while the MIT simulation is fixed at 225,000 pounds. However, Capt. Vietor's experiments [3] have shown that weight differences have only a small effect on deceleration time. For example, in one test at 10,000 feet, a deceleration from 365 knots to 200 knots took only 5 seconds longer at 247,000 pounds than at 190,000 pounds [3].

The results shown in Table 5-1 are in error by as much as 14% at 10,000 feet (an important altitude due to the deceleration segment). The results are generally better at higher altitudes, but are consistently greater than the times used for comparison. A mitigating factor is that times may differ as much as 10 seconds from test to test because of pilot error
# TABLE 5-1

DECELERATION CAPABILITY RESULTS

<table>
<thead>
<tr>
<th>ALTITUDE</th>
<th>WEIGHT* (lbs)</th>
<th>TRUE AIRSPEED (KNOTS)</th>
<th>TIME (SECS.)</th>
<th>AMER. AIRL. SIMULATOR</th>
<th>MIT SIMULATOR</th>
<th>ERROR</th>
</tr>
</thead>
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<tr>
<td>35000</td>
<td>247,000</td>
<td>509</td>
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<td>0</td>
<td>0</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>447</td>
<td>60</td>
<td>54</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>402</td>
<td>120</td>
<td>120</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>358</td>
<td>157</td>
<td>168</td>
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<td></td>
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<td>247,000</td>
<td>513</td>
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<td>0</td>
<td>0</td>
<td>8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>435</td>
<td>60</td>
<td>61</td>
<td></td>
<td></td>
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<tr>
<td></td>
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<td>371</td>
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<tr>
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<tr>
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<td>213</td>
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<tr>
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<tr>
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<td>14%</td>
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<td>210,000</td>
<td>433</td>
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<td>0</td>
<td>0</td>
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<td>135</td>
<td>159</td>
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<td></td>
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<td>240</td>
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<td>176</td>
<td></td>
<td>14%</td>
</tr>
<tr>
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<td>194,000</td>
<td>270</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</tr>
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<td></td>
<td></td>
<td>238</td>
<td>33</td>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>220</td>
<td>53</td>
<td>59</td>
<td></td>
<td>11%</td>
</tr>
</tbody>
</table>

* MIT SIMULATOR WEIGHT 225,000 lbs IN ALL CASES
in correcting to level flight (all tests were flown manually and Table 5-1 is an average over several trials). Nevertheless, the model was shown to decelerate slower than the commercially-produced simulator.

The difference between the force due to idle thrust and the opposing force due to drag determines the deceleration in level flight. Because the approximation of Equation 2-25 so nearly matches the available idle thrust data (shown in Figure 2-11) and the drag approximations shown in Figures 2-6 and 2-7 are, if anything, greater than the actual aircraft, the time error is surprising. The program logic and scaling have been proved correct and only an error in the low speed drag can be advanced as an explanation. The drag on the aircraft changes at a Mach number of .7 (see Equation 2-17). The times in Table 5-1 indicate that the drag is slightly high above this value. For example, 509 knots at 35,000 feet is .88 Mach and the time to decelerate to 447 knots or .78 Mach is 6 seconds too fast. Whereas, the deceleration from .7 Mach (402 knots) to .62 Mach (358 knots) is 11 seconds too slow. Therefore, it is supposed that the low speed drag of Figure 2-6 is not used in the American Airlines simulator or that there are significant drag terms which the MIT simulation has failed to model.

5.1.2 **CLIMB PERFORMANCE**  The most difficult test that could be imposed on this simulation is probably to compare time and
distance climb performance to the flight manual values. This tests not only the variation of maximum thrust with altitude but the linearized atmospheric variables and airspeed conversions as well. The climb schedule used is stated in the 707 flight manual [15] as a constant 320 knots indicated until reaching .78 Mach and then a constant .78 Mach to cruise altitude. It was not clear if the 250 knot FAA restriction was complied with below 10,000 feet or if the climb was measured from takeoff. Therefore, the climb schedule was flown as stated and the error values shown in Table 5-2 are computed from the difference between each successive altitude and the 11,000 feet value where there is no doubt about the climb schedule being followed. For example, the flight manual indicates that the actual aircraft requires 7 minutes (13-6) to climb from 11,000 to 25,000 feet. The MIT simulation requires 8 minutes (11-3) for the same climb. The error is +1 minute or one minute over the flight manual value. Distance errors are computed in the same manner. The flight manual values are obviously rounded to the nearest minute and the distance values were computed by the author using the published average climb airspeed and these imprecise times. The error obtained is not to be considered exact for these reasons but the general climb performance shown in Table 5-2 was considered very good.

There was no data available for comparing accelerations or descent performance of the model to the real aircraft. But
### TABLE 5-2

**SIMULATOR CLIMB PERFORMANCE**

<table>
<thead>
<tr>
<th>ALTITUDE (1000 ft)</th>
<th>AIRCRAFT* TIME (MINS.)</th>
<th>SIMULATOR TIME (MINS.)</th>
<th>ERROR** (MINS.)</th>
<th>AIRCRAFT* DISTANCE (N. Mi.)</th>
<th>SIMULATOR DISTANCE (N. Mi.)</th>
<th>ERROR** (N. Mi.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>6</td>
<td>3</td>
<td>--</td>
<td>26</td>
<td>20</td>
<td>--</td>
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<td>7</td>
<td>4</td>
<td>0</td>
<td>32</td>
<td>26</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>8</td>
<td>5</td>
<td>0</td>
<td>38</td>
<td>30</td>
<td>-2</td>
</tr>
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<td>9</td>
<td>6</td>
<td>0</td>
<td>45</td>
<td>36</td>
<td>-3</td>
</tr>
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<td>19</td>
<td>10</td>
<td>7</td>
<td>0</td>
<td>52</td>
<td>41</td>
<td>-5</td>
</tr>
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<td>21</td>
<td>10</td>
<td>8</td>
<td>+1</td>
<td>54</td>
<td>49</td>
<td>+1</td>
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<td>23</td>
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<td>9</td>
<td>0</td>
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<td>13</td>
<td>11</td>
<td>+1</td>
<td>75</td>
<td>66</td>
<td>-3</td>
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<td>29</td>
<td>15</td>
<td>13</td>
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<td>92</td>
<td>89</td>
<td>+3</td>
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<tr>
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<td>15</td>
<td>+2</td>
<td>100</td>
<td>102</td>
<td>+8</td>
</tr>
<tr>
<td>33</td>
<td>17</td>
<td>17</td>
<td>+3</td>
<td>108</td>
<td>113</td>
<td>+11</td>
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<td>35</td>
<td>19</td>
<td>18</td>
<td>+2</td>
<td>129</td>
<td>123</td>
<td>0</td>
</tr>
</tbody>
</table>

* AT 230,000 lbs (FROM 707-300 SERIES OPERATING MANUAL[15])

** SEE TEXT FOR METHOD OF COMPUTATION
acceleration is a measure of the difference between maximum thrust and aircraft drag and these same forces determine climb performance for small angles of climb. Descent performance is related to deceleration in much the same way, so the previous results were considered applicable to the four flight conditions of interest. Because of the error in deceleration, the aircraft model was not expected to maintain the same angle of descent as the real aircraft in a clean configuration (gear, flaps and spoilers retracted).

5.2 TIME-CONTROLLED NAVIGATION EVALUATION

Because accurate navigation in time was the primary goal of this research, many aspects of the solution which might have been tested were not. For example, thumbwheel switches were installed on the throttle quadrant between the pilot and copilot to communicate the ATC assigned route-time profile to the simulated on-board computer. But this data was entered by the test evaluator and the increased pilot workload which might have been required was not evaluated. Programming was provided to enter any assigned altitude, airspeed, or time of arrival at one of four waypoints. However, only two waypoints were used and the assigned altitude and airspeed were 10,000 feet and 250 knots in all cases. The assigned time of arrival was varied over the range of times achievable and descents were conducted from cruise altitudes of 25,000 and 35,000 feet. The routes flown are shown in
Figure 5-1. The 35,000 foot cruise along J152 (the air route from Hampton to Providence) was initiated approximately 30 miles prior to intercepting the descent profile. These are the 120+ initial distance values shown in Table 5-3. The 25,000 foot cruise along V-2-14 (the air route from Albany to Gardner) also began approximately 30 miles prior to the descent point. The total distances traveled influence the range of achievable arrival times but not the accuracy of the time-controlled navigation. Note that, along V-2-14, there is an intermediate fix at Griswoldville. This fix was not emphasized and most pilots flew directly from Albany to Gardner. The 11 degree heading change that should be made at Griswoldville would have little effect on the time accuracies achieved here because of the large distance remaining after Griswoldville for the feedback control to correct the aircraft to the time schedule.

Four pilots were tested and are designated by the numbers in the first column of Table 5-3. Pilot Number 1 is an airline captain with 26,000 hours of flying time. Pilot Number 2 is an airline pilot with 2,000 hours of flying time. Pilot Number 3 is a military Senior Pilot with 5,000 hours. The fourth pilot is the author, a military pilot with 2,000 hours.

Two of the pilots tested, Numbers 1 and 4, had previous experience performing unrecorded time control tests during
Fig. 5-1  Map of Routes Flown
<table>
<thead>
<tr>
<th>TEST NO.</th>
<th>DIST (N.Mi.)</th>
<th>EPTA</th>
<th>LPTA</th>
<th>ATA</th>
<th>ARRIVAL TIME ERROR (SECS.)</th>
<th>AIRSPEED ERROR (KTS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>125.4</td>
<td>17+10</td>
<td>26+10</td>
<td>22+00</td>
<td>+ 26</td>
<td>- 6</td>
</tr>
<tr>
<td>1B</td>
<td>95.4</td>
<td>12+41</td>
<td>21+04</td>
<td>18+00</td>
<td>+ 22</td>
<td>- 3</td>
</tr>
<tr>
<td>1C</td>
<td>124.8</td>
<td>17+12</td>
<td>26+11</td>
<td>18+30</td>
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<td>21+06</td>
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<td>+ 20</td>
<td>- 5</td>
</tr>
<tr>
<td>2A</td>
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<td>12+52</td>
<td>20+26</td>
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<td>+ 26</td>
<td>+ 2</td>
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<td>2B</td>
<td>121.5</td>
<td>17+16</td>
<td>26+07</td>
<td>19+30</td>
<td>+ 25</td>
<td>+ 2</td>
</tr>
<tr>
<td>2C</td>
<td>122.8</td>
<td>17+16</td>
<td>26+12</td>
<td>25+00</td>
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<td>- 6</td>
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<td>21+01</td>
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<td>+ 5</td>
</tr>
<tr>
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<td>94.8</td>
<td>12+45</td>
<td>21+10</td>
<td>17+00</td>
<td>+ 20</td>
<td>+ 11</td>
</tr>
<tr>
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<td>26+09</td>
<td>22+00</td>
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<td>+ 9</td>
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</tr>
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<td>20+59</td>
<td>15+00</td>
<td>+ 21</td>
<td>- 1</td>
</tr>
</tbody>
</table>
development. Pilot Number 2 had not flown the aircraft simulation described in Chapter II but has participated in other tests using the cockpit mockup. Both Numbers 2 and 3 were permitted one unrecorded practice test before commencing recorded runs. It is considered significant that Number 3 with only 2 hours of experience in this simulator and Number 2 with no experience flying this particular aircraft simulation achieved comparable results to the pilots who were more familiar with the aircraft model and the navigation command bugs. This is a measure of the similarity between the actual aircraft and the simulation and attests to the simplicity of the method of communicating the command airspeed and descent rates by bugs on the instruments.

The assigned times of arrival were chosen at various points in the range of achievable times. Tests number 1D, 2C, and 2D are examples of the time difference $\tau_1$ being greater than $\tau_2$. Tests number 2A, 2B, and 4B are examples of $\tau_2 > \tau_1$. Tests number 1A, 3A, and 3B are examples of $\tau_1 = \tau_2$. In all cases, the commanded airspeed, when the time-control mode was selected, reflected the desired characteristics. A large difference between $\tau_1$ and $\tau_2$ results in a commanded airspeed of one of the extremes while small differences require less correction. As the $|\tau_1 - \tau_2|$ gets smaller the commanded airspeed adjusts smoothly to an intermediate value.
The tests performed here were flown under no-wind conditions. The number of tests required to obtain statistically significant data under various wind conditions could not be performed in the time available. Nevertheless, the present results are a necessary step in confirming the validity of the navigation concept.

5.2.1 TEST RESULTS  The results achieved in the formal tests shown in Table 5-3 and in numerous unrecorded tests during the final stages of development show in principle that the navigation controller assists the pilot in navigating along four-dimensional routes. Unfortunately, some refinement of the logic is necessary for the present simulation to work perfectly. The initial value of EPTA computed at cruise altitude is not actually achievable because the assumed rate of acceleration at high altitude, as discussed in Chapter IV, is unattainable. Test number 1C in Table 5-3 was not included in the accuracy calculations for this reason. Shortly after descending through 25,000 feet during test 1C, the EPTA displayed on the moving map indicated that the time assigned was not achievable and the remainder of the route was flown in such a manner that the actual time of arrival has no significance.

Deviation from the assigned descent profile was not measured but was judged to be within the bounds of any buffer zone allotted to pilot error. In all cases, the vertical
descent controller "flared" the aircraft by decreasing the rate of descent in the last 1,000 feet. Thus the aircraft intercepted the final altitude approximately 14 miles from the waypoint. However, in no case were the entire 14 miles required to decelerate or accelerate to the final airspeed.

Pilot reaction to the control system was generally favorable. Pilots 2 and 3, who were not familiar with the navigation concept described here, were upset to find that the initial commanded airspeed might be far different from the cruise airspeed they were maintaining. However, only finite acceleration and decelerations are used in the computations and the pilots soon discovered that smooth airspeed changes would catch and subsequently maintain the bug speed. The program logic could be modified to smoothly command the initial airspeed change but this was not considered necessary.

5.2.2 ACCURACY ACHIEVED The overall error for the tests listed in Table 5-3, excluding test 1C, is described by a mean of +19 seconds and a standard deviation (1σ) about the mean of 5 seconds. It is believed that the bias could be eliminated with further refinement of the logic for computing EPTA and LPTA. (These are computed in subroutines MXASP and MNASP of Appendix B.) Many of the subroutines developed during this research were tested off-line by iterating the assembly language logic through a wide range of possible inputs. This should also have been done for the subroutines.
which compute EPTA and LPTA, but this check was not accomplished in the time available. The alphanumeric readout of EPTA and LPTA presented to the pilot shows three discontinuous jumps at distances from the waypoint which are known decision points in the logic. This, of course, causes a discontinuous jump in the commanded airspeed as it tries to optimize flexibility. Refining the logic to eliminate these discontinuities might eliminate the bias and result in a more accurate determination of EPTA and LPTA at cruise altitude as well.

The merit of closed-loop continuous corrections was particularly noticeable during the last stages of approach to the waypoint. The pilot's diligence in flying the commanded airspeed during the final minutes of the approach largely determined the arrival accuracy in seconds.

5.2.3 FAILURE TO OPTIMIZE FLEXIBILITY The time navigation controller was designed to optimize the aircraft's flexibility. From early November when Equation 4-8 was finally derived, through the testing, and through the writing of the bulk of this report, it was assumed that this objective had been met. The EPTA and LPTA displayed in the cockpit both changed with time but the airspeeds commanded appeared to equalize the flexibility. It was considered unlikely that the idealistic form of the delay spread shown in Figure 1-4 (with EPTA remaining constant) would be achieved in practice.
The flexibility of the approach was demonstrated numerous times by changing the assigned time of arrival during the descent. The commanded airspeed would immediately change and the EPTA and LPTA would begin to converge (optimally, it was thought) to the new ATA. Several attempts had been made to obtain an analog plot of the time history of EPTA and LPTA during a test but this was not accomplished. Finally, after most of the testing was completed, a digital program was written to save EPTA and LPTA at 30 second intervals during the test. The result for test 4C is shown in Figure 5-2. It is now obvious that the controller will navigate quite consistently to any achievable assigned time of arrival (plus a 19 second bias), but is not optimizing the flexibility in the manner desired.

One possible explanation for this failure could be that the bang-bang type of control system described in Chapter IV with its undesirable qualities was actually the optimal solution. The commanded airspeeds of Equation 4-8 are more stable and easier to fly but sacrifice flexibility as it is defined here. However, a complete analysis of this failure and the source of the bias, so clearly demonstrated in Figure 5-2, must await further study.
Fig. 5-2  Delay Spread Time History
CHAPTER VI

ACCOMPLISHMENTS, RECOMMENDATIONS, AND CONCLUSION

In the course of this research, the following objectives have been achieved:

1. The creation of an aircraft model which closely approximates the available aerodynamic design data for the Boeing 707-320B for altitudes from sea level to above 35,000 feet and airspeeds within the 707's operating range (excluding takeoff).

2. The creation of an atmosphere model in which density and the speed of sound (a function of temperature) vary in accordance with the ICAO standard atmosphere.

3. The development of analytic relationships and display programs which permit cockpit indications of indicated airspeed and Mach.

4. The design of a feedback control system which assists the pilot in maintaining a fixed, linear descent profile in space.

5. The design of a feedback controller which assists the pilot in meeting assigned times of arrival at three dimensional waypoints subject also to a speed constraint at the destination.

An additional objective, that the airspeeds commanded would optimize the amount the aircraft can be advanced or delayed around the assigned time of arrival, was not achieved.

The aircraft model and navigation controller were simulated on an Adage AGT-30 computer interfaced with a fixed-base 707 cockpit mockup. The simulation was coded in highly-efficient assembly language programs which:
1. Solve the aircraft equations of motion 15 times per second using sampled pilot control inputs.

2. Solve the navigation equations 3 times per second and display a command airspeed bug and a command descent bug on the corresponding cockpit instruments. In addition, an alphanumeric readout of the earliest possible time of arrival and the latest possible time of arrival are presented to the pilot.

3. Update the flight instrument readings (7.5 times/sec), translate and rotate a moving map (15 times/sec), and draw all cockpit displays at 30 frames per second. (The flight instrument and map programs were modified and adapted for this study, but are not the original work of the author.)

The aircraft simulation was flown manually by professional pilots to test the accuracy of the navigation controller. Simulated approaches from cruise altitude to initial approach fixes for Logan International Airport were flown under no-wind conditions. The aircraft was judged to be a very realistic model of the Boeing 707 and the controller was found to be helpful in complying with assigned times at the initial approach fix. In a total of 14 tests the following accuracy was achieved in meeting specified arrival times (for complete results see Chapter V):

1. A mean error (or bias) of 19 seconds.

2. A standard deviation (1σ) about the mean error of 5 seconds.

As explained in Chapter V, the bias value can be reduced or eliminated by further refinement of the program logic. The variation about the mean was considered to be well within
the accuracy requirements of an air traffic control system based on assigned times of arrival. However, the five second value is primarily a measure of the navigation controller under the influence of pilot error. If errors in position and airspeed are introduced and wind errors are included, this number will increase.

During the development of the controller, the following simplifying assumption was made which bears directly on the results:

1. The acceleration and deceleration capabilities of the aircraft were assumed to be constant, equal, and invariant with altitude.

The assumption of constant acceleration and deceleration between any two airspeeds was felt to have only a minor effect on the accuracy of the controller (especially considering the feedback nature of the system). However, the value of acceleration in level flight is generally lower than the value of deceleration. Also, acceleration decreases with increasing altitude because of the reduced thrust available. This led to one invalid test result (see Chapter V) because the computed earliest possible time of arrival was based on an unattainable level-flight acceleration of 1.75 ft/sec$^2$ at 35,000 feet.

Both acceleration and deceleration could be more accurately specified by further study. The aircraft model developed here was felt to be sufficiently accurate to provide
meaningful data, but time constraints precluded more than a cursory experimental investigation. The time accuracy achieved in the tests, using a constant value for acceleration and deceleration, may be due to the error-correcting nature of the feedback control. Also the last 14 miles of all tests were flown at 10,000 feet where the value of acceleration and deceleration chosen \((1.75 \text{ ft/sec}^2)\) was approximately correct.

6.1 RECOMMENDATIONS

The next step in this research is to test the navigation concept described here under a variety of wind conditions. The particular approach routes flown for these tests require 15 to 30 minutes each. It was decided that in order to obtain statistically significant results in the time available, only the no-wind case would be tested. The accuracies obtained under this condition reflect the merit of the design. Conceptually, the feedback nature of the system and the method of determining the command airspeed should achieve similar results in the presence of wind. If this can be confirmed experimentally, then a major question arises. How do commanded airspeeds, which are chosen to equalize the aircraft's time flexibility, achieve such accuracy in the time of arrival without equalizing the flexibility? The answer may lie in the mathematical analysis of the optimization problem which was not performed here.
Along this line of reasoning, the following recommendations for further research are offered:

1. Compare the results cited here to tests conducted in the presence of wind and in the presence of uncertainty in observation of position and airspeed.

2. Perform the mathematical optimization. This might provide insight into why the flexibility was not equalized; it might suggest alternate designs in the presence of wind or position errors; and it might provide a benchmark of the best obtainable performance.

It is felt that the present approach could be improved and extended in the following ways:

1. Study and define the acceleration and deceleration capabilities of the aircraft model over the full range of airspeeds and altitudes for inclusion in the calculations.

2. Modify the program logic so that the 15 mile deceleration segment can be varied or eliminated for time-controlled navigation inside the terminal area - possibly to the runway threshold.

6.2 CONCLUSIONS

This report summarizes the design, simulation, and testing of an on-board navigation concept that might be employed in the air traffic control system of the future. If aircraft are required to navigate along three dimensional routes and to meet assigned times of arrival at intermediate waypoints, then this "navigation controller" would aid the pilot in complying with minimal assistance from the ground.

The concept was tested by professional pilots on a
simulated Boeing 707-320B described herein. Tests were run for no-wind conditions during descents from cruise altitude to 10,000 feet. Because of the way the controller uses the aircraft's flexibility in computing command airspeeds, it is argued that it will correct for unforecast winds along the route of flight. The time-control concept, adjusted for particular descent, climb, or cruise profiles, is considered to be applicable to any phase of flight.
APPENDIX A

THE AIRCRAFT SIMULATION PROGRAM

The aircraft simulation was programmed specifically for the Adage AGT-30 digital computer. (For an explanation of the coding of the program, see [16].) The basic structure was created for a VTOL aircraft by Gordon Kemp in 1969 [17]. Robert Anderson adapted Kemp's program to a Boeing-supplied, fixed-base simulator using simplified jet transport dynamics, sophisticated flight instrument displays, and the Airborne Traffic Situation Display [18]. This work has been used extensively in the current simulation. The flight instrument displays are contained in the program titled "FNST2". A Mach indicator was included and several instruments were rescaled for the present simulation, but the basic program is relatively unchanged and is not included here. Likewise, the traffic situation display program, "MMAP2", and the alphanumerics display program, "CRGD2", were only modified and rescaled and are not included here. The aircraft dynamics were extensively revised to accurately model the performance of a Boeing 707-320B over the full range of operating conditions. This program is included and explained here under the premise that it is sufficiently accurate to serve as a basis for research beyond the scope of the present effort.
The program, "ACSM2", alternates between two sequences of subroutines ("SIM1" and "SIM2") under the control of a line-frequency, clock-interrupt. These sequences are shown and documented on the third page of the computer program. The subroutines are briefly described in the paragraphs which follow.

**INIT** The INIT subroutine initializes the program variables, establishes control input biases, specifies interrupt pivots, and starts the clock. The clock then assumes control of the program by periodic interrupts. Although the instrument display programs are not discussed here, it is important to note that the command "DIALS" must be entered into the computer prior to the command "INIT" since it is an initialization routine in the CRGD2 program which creates several of the vector display lists.

**ASPD1** The first subroutine called after the clock-interrupt is ASPD1. This routine is common to both program sequences and is actually the first of the display routines. After this call the displays proceed independently of the main program interrupting the foreground computations only to load another vector or to initiate a new vector list.

**FNSW** The AGT-30 computer has a set of function switches which are used to input program commands that are administrative in nature as opposed to the cockpit discrete inputs described under RDISC. The function switch assignment is
shown in Figure A-1. The large geographical area and altitude ranges used in the simulation dictated the fast move capability indicated on switches 6, 7, 10, 11, 14 and 15. The clock switch, number 4, displays the aircraft clock and strobed time used in the time-control studies. Switch number 8 displays a spare instruction count representing the unused computation time in each sequence. Function switch 5 permits the simulation to execute a programmatically set number of cycles and then "freezes" the aircraft dynamics. This is a useful feature for debugging new subroutines. The dynamics are frozen by trapping the SIM1 sequence in the FNSW routine until the next clock interrupt.

**RDISC** One 30-bit register of the AGT-30 is shared by the cockpit discrete inputs. A novel switching arrangement permits the continuously monitored inputs to be temporarily replaced with up to 4 alternate 30-bit sources. One of these represents frequencies selected on the navigation radios. The remaining three are used in the four dimensional studies to communicate the selected waypoint, assigned time of arrival, assigned altitude, and desired airspeed to the onboard computer. The RDISC subroutine converts the selected register or normally connected source to flags or variables for the program. It also traps the SIM2 sequence to freeze the aircraft dynamics.
Fig. A-1  Function Switch Assignment
VCD1 and VCD2 The variable control dial subroutines sample analog cockpit inputs for use in the aircraft dynamic equations or for manipulating the instrument displays. Spoiler blowdown, flap deployment (50 degrees in 30 seconds), and throttle normalization are computed in VCD1.

AERO The AERO subroutine computes total velocity, indicated airspeed, Mach number, and the aerodynamic angles. Total velocity is determined by an approximation discussed in Gordon Kemp's original work [17]. The aerodynamic angles are computed as shown in Equations 2-10 through 2-13. Indicated airspeed is determined from Mach number by the relationship of Equation 3-7.

TRNSL The TRNSL subroutine computes the translational aerodynamic forces (lift, drag, and side force) of Equations 2-15, 2-17, and 2-18. In addition, it computes thrust in the manner of Equation 2-26 and the dynamic pressure terms using ambient density (from the ATMOS subroutine), true velocity, and the physical dimensions of the 707-320B.

The remaining aircraft dynamics subroutines are straightforward solutions of the equations of Chapter II. In all cases accelerations are integrated using the trapezoidal rule:

\[ V_n = V_{n-1} + \Delta t \cdot \left( 3\dot{V}_n - \dot{V}_{n-1} \right) / 2 \]  

(A-1-1)
The earth frame position is obtained by rectangular integration of the vehicle frame velocities:

\[ X_n = X_{n-1} + \Delta t V_n \]  \hspace{1cm} (A-1-2)

The program is thoroughly documented so that the definition of variables and their scaling is available through the associated comments. Scaling is necessary because the computer stores values as a signed binary number between zero and one. The scaling is performed using "B" numbers where the number associated with the "B" represents the position of an imaginary binary point in a 30-bit computer word with the first bit, or sign bit, being zero. The B number may also be thought of as the power of two used as a normalization constant. For example, the aircraft velocity, VT, is shown in the comments to be a B10 number. This implies that the imaginary binary point would be located to the right of bit 10 or that \(2^{10} (=1024 \text{ ft/sec})\) was used as a normalization constant. A "B" number followed by an "R" means that the number is represented by the right 15 bits of the 30-bit word, hence a number with its binary point to the right of bit 15 would be a BOR number if its most significant bits were only in the right half word.

The control input coefficients are difficult to decode using the documented program alone. Rather than convert sampled pilot inputs to the associated control deflections
in degrees, the maximum anticipated sample voltages were related to the maximum control deflection times the associated control coefficient. The resulting constant of proportionality is the value used in the program. The maximum control deflections for the 707-320B were shown in Table 2-3 and the anticipated maximum voltages (as normalized by the computer) are shown in Table A-1.

TABLE A-1
ANTICIPATED MAXIMUM CONTROL VALUES

<table>
<thead>
<tr>
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<th>Absolute Value</th>
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</thead>
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<tr>
<td>SPOILER</td>
<td>.3197</td>
</tr>
<tr>
<td>FLAPS</td>
<td>.3984</td>
</tr>
<tr>
<td>ELEVATOR</td>
<td>.4820</td>
</tr>
<tr>
<td>AILERON</td>
<td>.2290</td>
</tr>
<tr>
<td>RUDDER</td>
<td>.4490</td>
</tr>
</tbody>
</table>
THIS PROGRAM CONTAINS THE BASIC INITIALIZATION OF FLIGHT VARIABLES,
AND THE SIMULATION OF THE AIRCRAFT DYNAMICS,
AND THE REQUIRED NAVIGATIONAL ROUTINES.
SUFFICIENT EXTERNAL VARIABLES ARE HOPEFULLY SPECIFIED THAT
IT CAN BE USED AS A WORKING BASE FOR ANY FORM OF INSTRUMENTATION
AND FLIGHT REQUIREMENTS.
THE BASIC STRUCTURE IS FROM GORDON KEMP'S VTOL SIMULATION OF 6/69
AND WAS ORIG. ADAPTED FOR MORE GENERAL USE BY BOB ANDERSON 6/70
REVISED 7/74 TO ACCURATELY MODEL THE BOEING 707-320B WITH
P&W JT3D ENGINES AT ALL ALTITUDES AND MACH NO.5 BY CHUCK CORLEY

ENTRY DIRCS,CLK,RETRN,MTIM1,MTIM2,KIAS,
TTIME,CLIFT,QS,VT,VDOT,GS,ANGLE,SPD,ALPHA,SIM1,
INIT,VC1,OVERF,NOF,SS10,M2IAS,SPDNS,
D.L.R,VX,YY,VZ,UB,RS,RLD,ES,LS,YS,LD,RPB16,
SICOS,EUER,DIRCS,SIM1,DTHRO,RCAR,ENTRY

TRINC=25
IXZIX=30736; IXZIY=23505; IXZIZ=27346
IXMIZ=43513; IYMIX=20203; IZM1Y=33310
IXX=35111; IYY=22400; IZ2=36763
SAREA=27410
SSPAN=32615
SCORD=32531
SSPN2=36372
SCRD2=27512
MASS=33230
CLFLA=16300
CLELE=22204
CDFLP=3473
CDSPL=2401
CYBET=42517
CYRUD=17070
CBETA=51776
CRUDD=14446
CPRT=47534
CMELE=64417
CMFLP=63746
CMQRT=54231
CNRT=54631
CNRUD=56536
CNRUD=56536
CNRBET=35341
DLP=4114
DFL14=3443
DT15=21042
RH00=22360

ELEVATOR TRIM DEFINED
INERTIA CROSS PRODUCTS
INERTIA QUOTIENTS
AIRCRAFT INERTIAS
WING AREA B11R
AREA TIMES SPAN B18R
AREA TIMES CHORD B16R
AREA * SPAN SQRD B24R
AREA * CHORD SQRD B19R
MASS OF AIRCRAFT
INCREMENTAL C SUB L W/FLAPS B2R
LIFT COEF. DUE ELEVATOR B-1R
DELTA CDMIN DUE FLAPS B1R
SIDE SLIP ANGLE COEF. B0R
SIDE FORCE DUE RUDDER B-1R
ROLL COEF. W/SIDE SLIP B-2R
ROLL COEF. DUE RUDDER B-5R
ROLL COEF. DUE ROLL RATE B-1R
PITCH COEF. DUE ELEVATOR B0R
PITCH COEF. DUE FLAPS B0R
DUE PITCH RATE AND ALPHA DOT B5R
YAW COEF. DUE YAW RATE B-2R
YAW COEF, DUE RUDDER B-3R
YAW COEF. DUE SIDE SLIP B-3R
6 DEGREES OF FLAPS B0
14 DEGREES OF FLAPS B0
DELTA T /2 15'S PER SEC B-4R
SEA LEVEL DENSITY B-8R
TITLE ACSM2

THIS PROGRAM CONTAINS THE BASIC INITIALIZATION OF FLIGHT VARIABLES,
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ENTRY DIRCS,CLKC,RETRN,MTIM1,MTIM2,KIAS,
TTIME,CLIFT,QS,VT,VDOT,GS,ALPHA,SIM1,
INIT,VCD1,OVERF,SOUND,SSIX0,M2IAS,SPDSN,
P,Q,R,VX,VY,VZ,UB,RSLD,RCLD,ELSD,YSLD,YCLD,EB16,
SICOS,EULER,DIRCS,SIM1,DTHRO,CA

TRINC=25
IXZIX=30736; IXZIY=23505; IXZIZ=27346
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ENTRY DIRCS,CLKC,RETRN,MTIM1,MTIM2,KIAS,
TTIME,CLIFT,QS,VT,VDOT,GS,ALPHA,SIM1,
INIT,VCD1,OVERF,SOUND,SSIX0,M2IAS,SPDSN,
P,Q,R,VX,VY,VZ,UB,RSLD,RCLD,ELSD,YSLD,YCLD,EB16,
SICOS,EULER,DIRCS,SIM1,DTHRO,CA

TRINC=25
IXZIX=30736; IXZIY=23505; IXZIZ=27346
IXMZ=43513; IYMX=20203; IZMII=33310
IXX=35111; IYY=22400; IZZ=36763
[ENTER HERE TO START AIRCRAFT]
[MAKE SURE CLOCK IS OFF]

[ZERO FOLLOWING VARIABLES]

[TURN OFF MPX 0]

[SET FLIPS = -0]

[COS PHI = 1 B1]

[COS THETA =1]

[ANGLE Rudder]

[Sample Rudder]

[Sample Elevator]

[Sample Aileron]

[Sample Current Rudder Bias]

[Sample Current Aileron Bias]

[Sample Current Elevator Bias]

[Initialize Flight Inst.]

[Return to Monitor in The]

[Event of Overflow But Save]

[Location and Values]

[Start Clock]
CLCK:
  ARMD  HOLD1  [STORE AR]
  MDAR'X  CLK1  [INCREMENT CLK1]
  MDAS'N'F  4  [SUBTRACT 4]
  JPAN  BACK  [IF NOT 4TH INTERRUPT]
  ARMD  CLK1  [RETURN ELSE ZERO]
  MDAR  FLIPS  [FLAG TO ALTERNATE]
  ARMD'N  FLIPS  [BETWEEN SEQUENCES]
  JPAN'I  . 2  [WHEN FLIPS = -0]
  JUMP'I  . 2  [DO SIM1]
  SIM1  1  [ELSE]
  SIM2  1  [DO SIM2]

BACK:
  MDAR  HOLD1  [RESTORE AR]
  JUMP'I  CLK  [GO TO INTERRUPTED S/R]
  0  [COUNT SPARE INSTRUCTIONS]
  0  [SAVE LEAST OF LAST COUNT]
  -0  [OR MINIMUM COUNT]

CLK1:
  MDAR  MTIM1  [ZERO COUNTER]
  MDER  TIME1  [NOW ADD ONE AND JUMP]
  BRAE'F'N  MTIM1  [BACK UNTIL CLOCK INTER.]
  ANBR  MTIM1  [SPARE COUNT IN SIM2]
  BRMD  MTIM1
  NOOP
  ARXO'F
  ARMD  TIME1
  ARAR'X  TIME1
  JUMP  . -1

CONT1:

CONT2:

MTIM1:  9999.  [LARGE INITIAL]
MTIM2:  9999.
TIME1:  9998.  [SLIGHTLY SMALLER]
TIME2:  9998.
<table>
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<th>JUMP</th>
<th>[READ FUNCTION SWITCHES]</th>
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<tr>
<td></td>
<td>JPAN</td>
<td>IC</td>
</tr>
<tr>
<td></td>
<td>ARAR’B’F</td>
<td>2'S</td>
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<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>JPLS</td>
<td>MOVE</td>
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<th>[+0 IF F. BY F. MODE]</th>
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<tbody>
<tr>
<td></td>
<td>JPAN</td>
<td>. 6</td>
<td>[ADD UNTIL +0]</td>
</tr>
<tr>
<td></td>
<td>MVAR’X</td>
<td>FRONT</td>
<td>[THEN FREEZE]</td>
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<tr>
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<td>JPLS</td>
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<td>JPAN</td>
<td>FNSW</td>
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<td>NOOP</td>
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<td>JUMP</td>
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<th>ARXO’F</th>
<th>[EXECUTE REST OF SIM1]</th>
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<td>ARM’D’</td>
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<th>MVAR’H’F</th>
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<th>[RETURN TO THE MONITOR]</th>
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<td>MVAR’F</td>
<td>KILL</td>
<td>[CHANGE CLOCK PIVOT]</td>
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<td>ARM’D’</td>
<td>77755</td>
<td>[CHANGE EOL PIVOT]</td>
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<td>ARM’D’</td>
<td>77757</td>
<td>[RETURN TO CALLING PGRM]</td>
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<td>JUMP</td>
<td>INIT</td>
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| KILL: | JUMP’I | .-1 |
FNSW:
JUMP .
MDIC'O'L; 401H
SSMD FNSWS
MDAR FNSWS
ARBR'K'F
JPN IC
ARAR'B'F
JPN START
ARAR'B'F
JPN FREEZ
ARAR'B'F
JPN TIMED
ARAR'B'F
JPN FB
BRAR'B'F
JPLS TMCLR
MDAR FNSWS
MDAR'H'A'F 1463
JPLS FMOVE

[READ FUNCTION SWITCHES
[READ FNS 1-15
[STORE FUNCTION SWITCH STATUS
[EXAMINE STATUS
[S5(6) FIRST IN AR
[SET INITIAL CONDITIONS
[S5(1) FIRST IN AR
[START DYNAMICS FNSW 2
[S5(2) FIRST IN AR
[FREEZE DYNAMICS FNSW 3
[S5(3) FIRST IN AR
[DISPLAY CLOCK FNSW 4
[S5(4) FIRST IN AR
[EXECUTE FRAME BY FRAME
[S5(7) FIRST IN AR
[SPARE TIME DISPLAY FNSW 8
[S5(12) FIRST IN AR
[RETURN TO CALLING PGRM FNSW 13
[RETURN TIME DISPLAYS FNSW 12
[CHECK FOR FAST MOVE
[FNSW 6,7,10,11,14,15

STATS:
MDAR FBFFL
JPN . 6
MDAR'X FRCCNT
JPLS . 4
ARXO'F
ARMD FBFFL
READY
MDAR READY
JPN'I FNSW
NOOP
NOOP
JUMP

[+0 IF F. BY F. MODE
[ADD UNTIL +0
[THEN FREEZE
[EXECUTE REST OF SIMI
[IF DISPLAY IS NOT FROZEN
[ELSE PREVENT DYNAMIC UPDATE
[AT THIS POINT IN SIMI AND
[AT END OF RDISC IN SIM2

FREEZ:
ARXO'F
ARMD READY
JUMP STATS

[SET FREEZ MODE
[FREEZE IS READY = +0

RETRN:
MD10'H'F 0
MDAR'F KILL
ARMD 77755
ARMD 77757
JUMP'I INIT

[RETURN TO THE MONITOR
[CHANGE CLOCK PIVOT
[CHANGE EOL PIVOT
[RETURN TO CALLING PGRM

KILL: JUMP'I .1
FMOVE: 
MDAR' A  MSK          [ENTER IF ANY FAST MOVE
ARR ' F     FUNCTION SWITCH IS ON
ARRS 1       
JPLS FDOWN   [FNSW 15
ARRS 1       
JPLS FSOUT   [FNSW 14
ARRS 3       
JPLS FUP     [FNSW 11
ARRS 1       
JPLS FNORT   [FNSW 10
ARRS 3       
JPLS FEAST   [FNSW 7
ARRS 1       
JPLS FWEST   [FNSW 6
JUMP STATS   [INSURED RETURN

FUP:    MDAR R          [GET ALTITUDE B23
MDAE FRINC   [ADD ALTITUDE INCREMENT
ARBR'F       
ARBR'N       RLIM     [SUBTRACT MAX ALTITUDE
JSPAN . 4    
MDAR RLIM    [IF GRT THAN LIMIT
ARMD R       [STORE LIMIT
JUMP FFNSH   
BRMD R       [IF LESS THAN LIMIT
JUMP FFNSH   [STORE NEW ALTITUDE

FDOWN:  MDAR R          [SUBTRACT R INCREMENT
MDAE'N       FRINC    [IF NEGATIVE SET = 0
ANAR ZERO    [ADD HORIZ INCREMENT
ARMR R       
JUMP FFNSH   

FNORT:  MDAR Q          [SUBTRACT INCREMENT
MDAE'N       FHINC   
ANAR'P        [SUBTRACT INCREMENT
ARMR Q       
JUMP FFNSH   

FSOUT:  MDAR Q          [SUBTRACT INCREMENT
MDAE'N       FHINC   
ANAR'P        [SUBTRACT INCREMENT
ARMR Q       
JUMP FFNSH   

FEAST:  MDAR P          [ADD INCREMENT
MDAE FHINC   [ADD INCREMENT
ARMR P       
JUMP FFNSH   

FWEST:  MDAR P          [SUBTRACT INCREMENT
MDAE'N       FHINC   
ARMR P       
JUMP FFNSH   

FMOVE:  MDAR'A  MSK  ENTER IF ANY FAST MOVE
ARAR'H'F  MDAE'N  IFNSW 15
ARRS  R  FUNCTION SWITCH IS ON
JPLS  FDOWN  IFNSW 14
ARRS  1
JPLS  FSOUT  IFNSW 11
ARRS  3
JPLS  FUP  IFNSW 10
ARRS  1
JPLS  FNORT  IFNSW 7
ARRS  3
JPLS  FEAST  IFNSW 6
ARRS  1
JPLS  FEAST  INSURED RETURN
JUMP  STATS

FUP:  MDAR  R  IGET ALTITUDE B23
MDAE  FRINC  IADD ALTITUDE INCREMENT
ARBR'F  MDAE'N  RLFNSW 15
JPNAN  RLFNSW 14
MDAR  ARMD  CINSURED RETURN
JUMP

FDOWN:  MDAR  R  [SUBTRACT R INCREMENT
MDAE'N  FRINC  IIF NEGATIVE SET = 0
ANAR  ZERO
ARMD  R
JUMP

FNORT:  MDAR  Q  [ADD HORIZ INCREMENT
MDAE  FHINC
ARMD  Q
JUMP

FSOUT:  MDAR  Q  [SUBTRACT INCREMENT
MDAE'N  FHINC
ARMD  Q
JUMP

FEAST:  MDAR  P  [ADD INCREMENT
MDAE  FHINC
ARMD  P
JUMP

FEWEST:  MDAR  P  [SUBTRACT INCREMENT
MDAE'N  FHINC
ARMD  P
JUMP
FFNSH:
MDAR
JPAN'I
MDAR
ARMD
MDAR
ARMD
JPSR
JUMP

MDAR READY
FNSW
P
$XP
0
$YP
$INIFI
STATS

[READY = - IS DYNAMICS
[READY = + IS STATIC
[SO THAT MAP WILL INDICATE FAST MOVE

TIMED:
ARXO'F
ARMD
JUMP

$CLCKF
STATS

[IFLAG TO DISPLAY
[CLOCK FROM "CRG02"
[+0 TO DISPLAY

SPARE:
ARXO'F
ARMD'N
JUMP

$STIMF
STATS

[IFLAG TO DISPLAY SPARE
[TIME FROM "CRG02"
[-0 TO DISPLAY

TMCLR:
ARXO'F
ARMD'N
JUMP

$STIMF
STATS

[TURN OFF CLOCK,
[STROBE TIME,
[AND SPARE TIME

START:
ARMD'O
JUMP'I

READY
FNSW

[START DYNAMICS
[READY = - 0

FBF:
MDAR'H
ARMD'F'N
ARMD
ARMD'O
ARXO'F
JUMP

FRCNT
STATS

[IF NEG THEN ALREADY
[COUNTING SO DISREGARD
[COUNT ONE FRAME
[READY = -0 (UNFREEZE)
[IFLAG +0 FOR F, BY F

FBFFL:
0

FRCNT:
0
RDISC:  
S6MD  SSIX0  [READ DISCREAT CHANNELS]
MDAR 'H  SSIX0  [SAMPLE SOURCE 6]
JPLS  .2  [PREVENT TRANSIENTS BY]
JUMP  EOFRD  [IGNORING IF L.H. IS]
MDAR 'A'F  70000  [CALL 0'S (GEAR UP/DOWN)]
JPLS  CHK6  [IF NOT REGISTER 0]
JPSR  SSCL  [SOF SOURCE 6 GO CHECK]
JPSR  SCLUT  [SET TSD SCALE]
JPSR  ACDIS  [CHOOSE DATA FOR DISPLAY]
JPSR  $S60UP  [AIRCRAFT EQUIP DISCRETES]
JPSR  [DISCRETE 4D INPUTS]
EOFRD:  
MDAR  READY  [IF DISPLAY IS FROZEN]
JPAN'I  RDISC  [STOP SIM2 SEQUENCE HERE]
JUMP  [ELSE DO DYNAMICS]
ACDIS:  
MDBR'B  SSIX0  [READ AIRCRAFT INPUTS]
MDAR 'H  SSIX0  [$S6(1) FIRST IN BR]
JPAN  NAV1  [S6(15) 1ST IN AR]
MDAR  SVR0P  [- IF CAPTAINS SW IN VOR]
MDAR  SVR0P;  [OUTER MARKER ON]
MDAR  SVR0Q;  ARMD  [$SVORP]
MDAR  SVR0Q;  ARMD  [$SVORQ]
JUMP  .5  [OUTER MARKER ON 4R HAS BEEN SELECTED]
NAVI:  
MDAR  $PVORP;  ARMD  [$SVORP]
MDAR  $PVORQ;  ARMD  [$SVORQ]
BRAR'H'F  [SAME STATION AS HSI HAS BEEN SELECTED]
JPAN  ADFSS  [- IF 1ST OFF SW IN VOR]
ARM'D'N  $ADFFL  [- GARBAGE FOR 1ST OFF]
MDAR  SVR2P  [$SW IN ADF CAUSING]
ARM'D  $ADFP  [DISPLAY$OF LYNNFIELD]
MDAR  SVR2Q  [BEACON ON FAT NEEDLE]
ARM'D  $ADFO  [SAME STATION AS HSI HAS BEEN SELECTED]
DNEDS:  
MDBR'B  SSIX0  [RETURN FROM ADFSS]
BRAR'F  [S6(2) 1ST IN AR]
MDAR 'A'F  4000  [MASK FOR BIT 19]
JPLS  .2  [IN BIT 18 OF AR]
JUMP  ACOII  [DISPLAY$OF LYNNFIELD]
MDAR  DAILE  [BEACON ON FAT NEEDLE]
ARM'D'N  ABIAS  [SAME STATION AS HSI HAS BEEN SELECTED]
ARMD  $SVORQ;  ARMD  [$SVORQ]
ACDI1:  
BRBR'B'F  [RETURN FROM ADFSS]
ARXO'F  [S6(2) 1ST IN AR]
ARM'D  GFLG  [I+ 0 IF UP]
BRAR'N'K'F  [S6(8) 1ST IN AR]
JPAN  .2  [IF GEAR DOWN GFLG = -0]
ARM'D'O  GFLG  [S6(17) 1ST IN AR]
BRAR'H'F  [TRIM NOSE UP]
JPAN  TRIMU  [S6(18) 1ST IN AR]
ARAR'B'F  [SET TIME TO BE STROBED]
JPAN  TRIMD  [IF DISPLAY IS FROZEN]
RDIS1:  
BRAR'F  [STOP SIM2 SEQUENCE HERE]
MDAR 'A'F  4000  [ELSE DO DYNAMICS]
JPLS  STROT  [IF DISPLAY IS FROZEN]
JUMP'I  ACDIS  [STOP SIM2 SEQUENCE HERE]
RDISC:
S6MD  SSIX0  [READ DISCREAT CHANNELS]
MDAR'H SSIX0  [SAMPLE SOURCE 6]
JPLS  . 2    [PREVENT TRANSIENTS BY]
JUMP  EOFRD  [IGNORING IF L.H. IS]
MDAR'A'F 70000  [CALL 0'S (GEAR UP/Down)]
JPLS  CHKS6  [IF NOT REGISTER 0]
JPSR  SCL    [OF SOURCE 6 GO CHECK]
JPSR  SCLUT  [SET TSD SCALE]
JPSR  ACDIS  [CHOOSE DATA FOR DISPLAY]
JPSR  $S6UMP  [AIRCRAFT EQUIP DISCRETES]

EOFRD:
MDAR  READY  [DISCRETE 4D INPUTS]
JPN '1 RDISC  [IF DISPLAY IS FROZEN]
JUMP  .      [STOP SIN2 SEQUENCE HERE]

ACDIS:
MDBR'B SSIX0  [ELSE DO DYNAMICS]
MDAR'H SSIX0  [READ AIRCRAFT INPUTS]
JPA N NA?1  [S6(1) FIRST IN BR]
MDAR SVROP  [S6(15) 1ST IN AR]
MDAR SVRO:  [ - IF CAPTAINS SW IN VOR]
MDAR SVROQ: [OUTER MARKER ON]
JUMP  . 5    [ARM MD $SVORP]
NAV1:
MDAR  $PVORP: [ARM MD $SVORQ:]
MDAR  $PVORQ: [ARM $SVORQ:]
BRAR'H'F ADFSS [IF DISPLAY ON 4R HAS BEEN SELECTED]
JPN  $ADFFL [ARM $SVORQ:]
ARM D'N  $ADFP [ARM $SVORQ:]
MDAR  $ADFO  [SAME STATION AS HSI HAS BEEN SELECTED]
MDAR SVR2P [ - IF 1ST OFF SW IN VOR]
ARM D'N  $ADFN [CSW IN ADF CAUSING]
MDAR SVR20 [DISPLAYOF LYNNFIELD]
ARM D'N  $ADFO [BEACON ON FAT NEEDLE]

DNEDS:
MDBR'B SSIX0  [RETURN FROM ADFSS]
BRAR'F 4000  [S6(2) 1ST IN AR]
JPLS  . 2    [MASK FOR BIT 19]
JUMP  AC Dis  [IN BIT 18 OF AR]
MDAR  DAILE [GIVE CURRENT AILERON]
ARM D'N  ABIAS [TO ABIAS]
ACD11:
BRBR'B'F GFLG [S6(2) 1ST IN BR]
ARK'O'F  [+ 0 IF UP]
ARM D'N'K'F  S6(9) 1ST IN AR
JPN  . 2    [IF GEAR DOWN GFLG = -0]
ARM D'O' GFLG [S6(17) 1ST IN AR]
BRAR'H'F TRIMU [TRIM NOSE UP]
JPN  TRIMU [S6(18) 1ST IN AR]
JUMP  TRIMD [DISPLAY OF LYNNFIELD]
RDIS1:
BRAR'F 4000  [BEACON ON FAT NEEDLE]
MDAR'A'F  S6(19) [SAME STATION AS HSI HAS BEEN SELECTED]
JPLS  STROT [ - IF 1ST OFF SW IN VOR]
JUMP  AC DIS  [GARbage FOR 1ST OFF SW IN ADF CAUSING]

[DISPLAY OF LYNNFIELD]

[SET TIME TO BE STROBED]
ILS - 4R  GDM  BOS  HTM
SMK00=2454:  SMK01=2445:  SMK10=3203:  SMK11=1051
[ PV  HTO  ALB
SMK02=2305:  SMK20=2605:  SMK22=2162
PVRSS:
  ARMD'0  $PVRFL
  MDBR'H  SSIX1
  MDBR'A'F  3777
IREPEAT  NN.(00,01,10,11,02,20,22)
  BRAR'F
  MDX0'F  SMK\NN
  JPLS  .2
  JUMP  PVR\NN
ENDI

ARX0'F
ARMD  $PVRFL
JUMP'I  PVRSS

PVR00:
  MDBR  VRP00;
  MDAR  VR000;
  MDAR  $HSIS
  JSAN  $APPRM
  JUMP'I  PVRSS
IREPEAT  NN.(01,02,11,02,20,22)
  PVR\NN:
  MDAR  VRP-NN;
  MDAR  VRO-NN;
  MDAR  $HSIS
  JSAN  $VORLM
  JUMP'I  PVRSS
ENDI

ADFSS:
  ARMD'0  $ADFFL
  MDBR  SSIX1
  MDBR'A'F  3777
IREPEAT  NN.(00,01,10,11,02,20,22)
  BRAR'F
  MDX0'F  SMK\NN
  JPLS  .2
  JUMP  ADF\NN
ENDI

ARX0'F
ARMD  $ADFFL
JUMP  DNEDS
IREPEAT  NN.(00,01,10,11,02,20,22)
  ADF\NN:
  MDAR  VRP-NN;
  MDAR  VRO-NN;
  JUMP  DNEDS
ENDI
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<th>TRIMD:</th>
<th>MDAR'N</th>
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<td>ARX0'F</td>
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<td>SET STROBE FLAG</td>
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<td>CHKS6:</td>
<td>MDAR'K</td>
<td>SSIX0</td>
<td>$S6(0-2) NOW IN AR(24-26)</td>
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<tr>
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<td>MDAR'A'F</td>
<td>70</td>
<td>EXTRACT $S6(0-2)</td>
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<td>ARRS</td>
<td>3</td>
<td>PUT IN AR(27-29)</td>
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<td>ARBR'F</td>
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<td>ADD REGISTER NUMGER</td>
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<td>MDAR'L;</td>
<td>JPSR'I</td>
<td>CHK6L</td>
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<td>BRAS'F</td>
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<td>TO GET LOCATION CHK6L</td>
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<td>ARIR'F</td>
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<td>EXECUTE SUBROUTINE</td>
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<td>JUMP</td>
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<td>SET60</td>
<td>REGISTER 0, ETC.</td>
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<td>SET61</td>
<td>SET62; SET63; SET64; KILL; KILL</td>
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<td>ERROR HAS OCCURRED</td>
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<td>SET61</td>
<td>KILL</td>
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<td>JUMP'1</td>
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<td>JPSR</td>
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<td>SET62</td>
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<td>MDAR</td>
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<td>MDAR'H</td>
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<td>1</td>
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<td>$SSC</td>
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<tr>
<td></td>
<td>JUMP'</td>
<td>SCLUT</td>
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</table>

| SCLUT:    | MDAR'H'N | SSIX0 |
|           | MDAR'A'F | 1000  |
|           | JPLS     | 3     |
|           | ARXO'F   | 3     |
|           | JUMP     | 3     |
|           | MDAR'L;  | JUMP  |
|           | ARMD     | $TDP  |
|           | BRAR'F   |       |
|           | MDAR'A'F | 4000  |
|           | JPLS     | 3     |
|           | ARXO'F   | 3     |
|           | JUMP     | 3     |
|           | MDAR'L;  | JUMP  |
|           | ARMD     | $TDP  |
|           | BRAR'F   |       |
|           | MDAR'A'F | 2000  |
|           | JPLS     | 3     |
|           | ARXO'F   | 3     |
|           | JUMP     | 3     |
|           | MDAR'L;  | JUMP  |
|           | ARMD     | $TSP  |
|           | BRAR'F   |       |
|           | MDAR'A'F | 400   |
|           | JPLS     | 3     |
|           | ARXO'F   | 3     |
|           | JUMP     | 3     |
|           | MDAR'L;  | JUMP  |
|           | ARMD     | $TSP  |
|           | JUMP'    | SCLUT |
IC1: 
MDAR'H'X ICCCNT [COUNT ONE SECOND BEFORE ENTERING NEXT INITIAL CONDITION
JPAN STATS
MDAR'F 15
ARM'D'N ICCCNT
ARXO'F
ARM'D TTME [LEVEL FLIGHT INITIAL CONDITIONS
ARM'D'N $SDISF [ZERO CLOCK
ARM'D RSLD [AND KILL STROBE DISPLAY
ARM'D PRATE [SIN PHI = 0 (WINGS LEVEL)
ARM'D QRATE [ANGULAR VELOCITIES
ARM'D RRATE
ARM'D VZ
ARM'D GFLG [+0 FOR GEAR UP
ARM'D VB [Y BODY VELOCITY
ARM'D ATCNT [FORCE ATMOS TO DO ATM01
ARM'D READY [FREEZE ON RETURN
ARM'D $SDISF

ICL1: 
MDAR'I'X ICPTR [LAST ENTRY LEG
JPAN ICL2 [INITIAL ALTITUDE B23
ARM'D R [INITIAL ALTITUDE B23
MRBR'H'F 17777
ARLS 7
BRMD RCLD [COS PHI = +1
ARM'D RB16 [ALTITUDE B16
MDAR'I'X ICPTR [INITIAL X POSITION B23
ARM'D P [IN FEET
ARM'D $XP [FOR "MMP2"
MDAR'I'X ICPTR [INITIAL Y POSITION B23
ARM'D 0
ARM'D $YP
MDAR'I'X ICPTR [INITIAL X BODY VELOCITY
ARM'D UB [TO PREVENT DIV BY ZERO
ARM'D VT [TOTAL VELOCITY THE SAME
MDAR'I'X ICPTR [INITIAL Z BODY VELOCITY
ARM'D WB
MDAR'I'X ICPTR [SIN Theta (PITCH)
ARM'D ESLD
MDAR'I'X ICPTR [COS Theta
ARM'D ECLD
MDAR'I'X ICPTR [SIN PSI (HEADING)
ARM'D YSLD
MDAR'I'X ICPTR [COS PSI
ARM'D YCLD
JPSR ATMOS [INITIALIZE ATMOSPHERE
MDAR ATCNT [RECALL UNTIL COMPLETE
JPLS ?.2
JPSR AERO [INITIALIZE AIRSPEED
JPSR $INIFI [INITIALIZE FLIGHT INSTRUMENTS
JUMP STATS [RETURN TO FUNCTION SWITCHES
JUMP ICL1 [RECYCLE I.C.S

ICL2: 
MDAR'I'X ICLST-1
ARM'D ICPTR
JUMP ICL1
<table>
<thead>
<tr>
<th>ICLST:</th>
<th>35000.1K</th>
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<tr>
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<td>-72021.1K</td>
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<td>-61102.31K</td>
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<td>311001H</td>
<td>IX BODY VELOCITY 804 FT/SEC B10</td>
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<tr>
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<td>774711H</td>
<td>IZ BODY VELOCITY B9</td>
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<tr>
<td></td>
<td>10!H</td>
<td>SIN PITCH B1</td>
</tr>
<tr>
<td></td>
<td>20000!H</td>
<td>ICOS PITCH B1</td>
</tr>
<tr>
<td></td>
<td>14616H</td>
<td>SIN HEADING B1</td>
</tr>
<tr>
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<td>11501H</td>
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[17 N.M. W OF ALBANY AT .82 MACH (494 KTAS) (359 KIAS)]

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<td>320601H</td>
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<td>10!H</td>
<td>SIN PITCH</td>
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<tr>
<td></td>
<td>20000!H</td>
<td>ICOS PITCH</td>
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<tr>
<td></td>
<td>17232!H</td>
<td>SIN HEADING</td>
</tr>
<tr>
<td></td>
<td>732441H</td>
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[10 N.M. W OF GRISWOLDVILLE (SHORT TEST CASE)]

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<td>273942.1K</td>
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<td>14360!H</td>
<td>IX BODY VELOCITY</td>
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<td></td>
<td>13111H</td>
<td>IZ BODY VELOCITY</td>
</tr>
<tr>
<td></td>
<td>711!H</td>
<td>SIN PITCH</td>
</tr>
<tr>
<td></td>
<td>17763!H</td>
<td>ICOS PITCH</td>
</tr>
<tr>
<td></td>
<td>17232!H</td>
<td>SIN HEADING</td>
</tr>
<tr>
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<td>73244!H</td>
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[20 N.M. S.W. OF MILLIS AT 236 KTAS (220 KIAS)]

<table>
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<td>-8683.1K</td>
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<td>14360!H</td>
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<td>711!H</td>
<td>SIN PITCH</td>
</tr>
<tr>
<td></td>
<td>17763!H</td>
<td>ICOS PITCH</td>
</tr>
<tr>
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<td>15442!H</td>
<td>SIN HEADING</td>
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<tr>
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<td>10364!H</td>
<td>ICOS HEADING</td>
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<tr>
<td></td>
<td>-0</td>
<td>ASSURED RECYCLE</td>
</tr>
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[FOLLOWING SUBROUTINE EMPLOYS THE ANALOG - DIGITAL CONVERTER TO SAMPLE ANALOG CONTROL INPUTS FROM THE COCKPIT]

[SPOILER BLOWDOWN: MAX SPOILER = 60 DEG KIAS L.T. 188]

\[ 60 - \frac{.283 \times (KIAS - 188)}{G.T. 188} \]

VCD1:

FPRI
MD07'L; 11H [TURN OFF MPX 8-15]
NOOP;
MD07'L; 0 10 [SAMPLE MPX 3 (SPEED BRAKE)]
MDAR'B KIAS [KIAS TO B9]
UPRI
MDAE'H'H'F 13600 [188 KTS B9]
JPAN NODEC
ARAR'H'F
MPYI 30446 [.283(1 DEGSpoiler) B-9R]
NOOP
MDAE'H'H'F 12135 [ANTICIPATED MAX SPOILER]
ARBR'N'F
76560'H
JPAN NODEC
BRMD'H DSPOL [STORE DECREASED MAX B0R]
JUMP . 2
NODEC:
SSMD DSPOL [STORE ACTUAL SPOILER]
FPRI
MD07'L; 240 [MPX 4-7 (THROTTLES)]
NOOP
MDAR'H'H'F 11574 [EXPECTED IDLE THROTTLE]
76560'H
MD07'L; 0 [TURN OFF MPX 0-7]
ANAR ZERO
UPRI
ARAR'H'F
MPYI 25012 [INVERSE EXPECTED MAX B2]
MDBR'H FS [I.E. NORMALIZE]
ARMD'B DTHRO [STORE TEMP B1]
MDAR'B DTHRO [RECALL B0]
JPAN . 3 [IF L.T. 1]
ARMD DTHRO [STORE B0]
JUMP . 2
BRMD DTHRO [ELSE STORE 1 B0]
FPRI
MD07'L; 11H 1 [SAMPLE MPX 8 (FLAPS)]
MDAR'N'H DFLAP [CURRENT FLAP POSITION]
MDBR FRATE [EXTEND/RETRACT RATE]
SSAS'F [COMMANDED FLAP POSITION]
MD07'L; 11H 2 [SAMPLE MPX 9 (ELEVATOR)]
UPRI
JPAN . 5 [IF COMMAND FLAP POSITION]
BRAR'F [G.T. CURRENT FLAP POSITION]
MDAE DFLAP [ADD INCREMENT TO CURRENT]
ARMD DFLAP [ELSE SUBTRACT INCREMENT]
JUMP . 4 [FROM CURRENT]
134

BRAR'N'F
MDAR
ARMD
MDAR'L

EBIAS:
SSAS'F
FPRI
MD07'L; 1!H 4
ARMD
MDAR'L

ABIAS:
SSAS'N'F
MD07'L; 1!H 10
ARMD
UPRI
MDAR'L

RUDB:
SSAS'N'F
ARMD
JUMP'I VCD1

[FOLLOWING SAMPLES COURSE SET, HEADING BUG AND SPEED SET BUG]

VCD2:

FPRI
MD07'L; 1!H
NOOP; NOOP
MD07'L; 2!H 10
NOOP; NOOP
SSAS'F
MPYI; 14400
MD07'L; 2!H 20
ARMD
$SPSET
NOOP
SSMD
$PTCHT
MD07'L; 2!H
NOOP; NOOP
MD07'L; 1!H 20
NOOP; NOOP
SSAR'H'N'F
MD07'L; 1!H 40
NOOP; NOOP
SSBR'H'F
MD07'L; 1!H200
UPRI
JPSR
$SCINV
SSBR'H'F
FPRI
MD07'L; 1!H 100
ARMD
$DHANG
NOOP
UPRI
SSAR'H'N'F
JPSR
$SCINV
ARMD
$PVORA
JUMP'I VCD2
AERO:  [AIRSPEED AND ALPHA CALC.
[FOLLOWING IS AN APPROXIMATE SQ ROOT SEE KEMP'S THESIS
[VT(N) = 1/2 (VT(N-1) + (U*U + V*V + W*W)/VT(N-1) )

MDAR'H  UB  IUB FROM FORCE TO B1OR
MPYU   UB  [SQUARED B20
NOOP  
ARMD  UBSQ  
MDAR'H  VB  [VB FROM FORCE TO B9R
MPYU   VB  [SQUARED B18
MDBR   WB  
ARRS  2  [STORE B20
ARMD  VBSQ  
BRAR'H'F  WB  [UB TO B9R
MPYU   WB  [SQUARED B18
MDBR   UBSQ  
ARRS  2  [STORE B20
ARMD  WBSQ  
BRAE'F  VBSQ  [NEW VSQR=U**2+V**2+W**2
MDAE  VBSQ  [IF OLD VSQR G.T. NEW
ABR'B'F  W**2  [THEN DV= -(NEW-OLD)
MDAE'N  VSQR  [ELSE DV = NEW-OLD
ANIR  NEGAT  
ARLS  3  
NOOP  
MDAE'N  VSQR  [SUBTRACT 1/8TH OLD
ARRS'N'F  IIF DV L.T. 1/8TH OLD
JPAN  SQRRT  [THEN TAKE SQRT OF NEW
BRAR'F  IELSE DIVIDE (NEW + 1/2)
ARRS  1  [BY OLD
DIVU  VT  [QUOTIENT B10R
NOOP  
ARRS'H'F  VB  [BR=.5(VSQR/VT) AS B10
MDAR  VT  
ARRS  1  [VT TIMES 1/2
BRAE'F  VT  [VT/2 + (VSQR/VT)/2
ARMD  VT  [NEW VT AS B10
ARRS'H'F  

AER01:  MPYU  VT  [RETURN FROM SQRT
NOOP  [NOTE: IF SQRT USED
ARMD  VSQR  [IT UPDATES VT

[SINA = WB/VT = ALPHA  ASSUMES COSB = 1
[COSA = UB/VT
[SINB = VB/VT = BETA
[COSB = 1 - BETA SURED/2

ATTACK:  MDAR  WB  [WB AS B9
DIVU  VT  [DIVIDE BT VT
MDBR  UB  
ARRS'H'F  IQUOTIENT TO B-2
ARMD  ALPHA [ANGLE OF ATTACK B-1
ARRS  2  


\[ XBM = \frac{1}{\text{MASS}} \left( \text{CAB}(-\text{DRAG}) - \text{CASB}(\text{YAERO}) - \text{SA} \right) \left( \text{LIFT} + \text{THRST} \right) \]
\[ YBM = \frac{1}{\text{MASS}} \left( \text{SB} \left( -\text{DRAG} \right) + \text{CB} \left( \text{YAERO} \right) + 0 \right) \]
\[ ZBM = \frac{1}{\text{MASS}} \left( \text{SACB}(-\text{DRAG}) - \text{SASB}(\text{YAERO}) + \text{CA} \right) \left( \text{LIFT} \right) \]

\[ \text{WTOB:} \]

MDAR'N'H DRAG INEG DRAG TO B17R
MPYU COSB ITIMES COS BETA B1
NOOP
ARBR'F
MDAR'N'H YAERO IYAW FORCES B16
MPYU SINB ITIMES SIN BETA B1
NOOP
ARRS 1
BRAE'F [-SB*DRAG+CB*YAERO] B18
ARBR'F [USING BR SAVES 1 WI. SEC]
MDAR'N'H DRAG INEG DRAG TO B17R
MPYU SINB ITIMES SIN BETA B1
BRMD YBM ISTORE ABOVE SCALAR B18
ARBR'F [-SB*DRAG]
MDAR'H YAERO ITIMES COS BETA
MPYU COSB
NOOP
ARRS 1
BRAE'F [-SB*DRAG+CB*YAERO] B18
DIVI MASS IDEFINED MASS B13R
NOOP
ARRS 4
ARBR'F . ITOS B9
MDAR'H DTEM IRECALL ABOVE SCALAR B18R
MPYU COSA ITIMES COS ALPHA B1
BRMD YBM \left( \frac{\text{(-SB*DRAG+CB*YAERO)}}{\text{MASS}} \right) B4
ARRS 3 IPRODUCT TO B22
ARBR'F ICAB(-CB*DRAG-SB*YAERO) B22
MDAR'H LIFT I LIFT FROM AERO TO B21R
MPYU SINA ITIMES SIN ALPHA
NOOP
BRAE'F \left( \frac{\text{(CB*DRAG-SB*YAERO)}}{\text{MASS}} \right) B22
MDAEN THRST \left( \frac{\text{SA*LIFT} + \text{THRST}}{\text{MASS}} \right) B22
DIVI MASS \left( \text{DIVIDED BY MASS B13R} \right)
NOOP
ARBR'N'H IQUOTIENT TO B5
MDAR'H DTEM ISHME SCALAR
MPYU SINA
BRMD'B XBM ISTORE AS B0
ARRS 3 IPRODUCT TO B22
ARBR'F
MDAR'N'H LIFT INEG LIFT TO B21R
MPYU COSA ITIMES COS ALPHA
NOOP
BRAE'F \left( \frac{\text{SA*(-CB*DRAG-SB*YAERO)}}{\text{MASS}} \right) B22
DIVI MASS \left( \text{SA*(-CB*DRAG-SB*YAERO)} \right)
NOOP
ARBR'H ZBM ISTORE B9
JUMP'I WTOR
[PDOT = \( L/IX - RQ(IZ-IY)/IX \) + \( PQ \) IXZ/IX
[QDOT = \( M/IV - PR(IX-IZ)/IV - \langle PSQR-\text{RSQR} \rangle IXZ/IY \)
[RDOT = \( N/IZ - PG(IX-IX)/IZ - RQ \) IXZ/IZ

COMM:

MDAR'\( H \) PRATE [MOMENT EQUATIONS OLD P TO B0R
MPYU ORATE [TIMES OLD Q B0
NOOP [PRODUCT IS B0
ARBR'H'F [MOVE MOST SIGNIFANT
BRAR'F [FIGANT TO R.H. B0R
MPYI IXZIX [DEFINED QUOTIENT B-3R
BRRD'N PQ [STORE PG PRODUCT NEG.
ARRS 2
ARBR'F [HOLD PG*IXZIX B2
MDAR'H'N RRATE \( [- OLD R TO B-1R \)
MPYU ORATE [TIMES OLD Q B0
NOOP
ARAR'H'F [MOST SIGNIFANT
ARMD RQ [STORED NEG AS B-1R
MPYI IZMIY [DEFINED B0R
NOOP [PRODUCT B-1
BRAE'F [ADD -RQ(IZ-IY)/IX B-1
ARRS 3
MDAE'N LMOM [TO PG*IXZ/IX + L/IX B2

[Integration Rule: \( x(n) = x(n-1) + \frac{h}{2} (3x\dot{d}(n) - x\dot{d}(n-1)) \)]

INTPD:

ARBR'F [HOLD NEW PDOT B2
MDAE'N PDOT [SUBTRACT OLD PDOT B2
BRAE'B'F [ADD TWO MORE NEW PDOTS
ARAR'H'F
MPYI DT15 [\( <\text{DELTA T}>/2 \) B-4R
NOOP
ARRS 2
MDAE PRATE [ADD OLD P B0
ARMD PRANW [STORE
MDAR'H PRATE [OLD P TO B0R
MPYU PRATE [SQUARE IT B0
BRRM PDOT [UPDATE PDOT B2
ARBR'N'F [HOLD - P SQUARED B0
MDAR'H RRATE [OLD R TO B-1R
MPYU RRATE [SQUARE IT B-2
NOOP [ADD R SQUARED
ARRS 2 [AS B0
BRAE'F [ITO -P SQUARED B0
ARAR'H'F [RESULT TO B0R
MPYI IXZIY [TIMES QUOTIENT IXZ/IY
NOOP
ARRS 4
ARBR'F [HOLD RESULT B1
MDAR'H'N PRATE \( [- OLD P TO B0R \)
MPYU RRATE [TIMES OLD R B-1
NOOP [PRODUCT IS B-1
ARAR'H'F [ITO B-1R
| MPYI | IXMIZ | QUOTIENT \( \frac{IX-IZ}{IY} \) |
| NOOP | 2 | |
| ARRS | MDAE | NMOM |
| BRAE 'F | MDAE | MM04 |
| INTOR: | ARBR 'F | NOOP |
| MDAE 'N | QDOT | |
| BRAE 'B'F | QDOT | |
| ARAR 'H'F | QDOT | |
| MPYI | DT15 | DEFINED AS B-4R |
| NOOP | 3 | |
| ARRS | MDAE | QRATE |
| ARMD | QRATE | |
| MDAE | PQ | SAVED ABOVE AS NEG B0 R |
| MPYI | IYMX | QUOTIENT \( \frac{IY-IX}{IZ} B-2R \) |
| BRMD | QDOT | UPDATE Q DOT |
| ARRS | 2 | |
| ARBR 'F | MDAE | NMOM |
| MDAE | RQ | SAVED ABOVE AS NEG B-1R |
| MPYI | IXZIZ | QUOTIENT IXZ/IZ B-4R |
| NOOP | 5 | |
| ARRS | BRAE 'F | |
| MDAE | DT15 | |
| BRMD | RDOT | UPDATE RDOT |
| ARMD | 3 | |
| MDAE | RRATE | ADD OLD R B-1 |
| ARMD | RRATE | UPDATE R |
| MDAE | PRANW | NOW YOU CAN UPDATE |
| ARMD | RRATE | IP AS WELL |
| JUMP 'I | JUMP | HERE ON OVERFLOW |
| ARMD | JRMS | |
| MDAE 'L | ARMD | |
| MD10 'H'F | ARMD | STOP CLOCK AND DISPLAYS |
| ARIR 'F | ARMD | |
| BRMD | 0 | SAVE BR |
| JUMP | JUMP | RETURN TO MONITOR |
| ARS: | 0 | |
| BRS: | 0 | |
FORCE:

\[
\begin{align*}
\text{MDAR}'F & \quad G \\
\text{MPYU} & \quad \text{ECLD} \\
\text{NOOP} & \\
\text{ARBR}'F & \\
\text{BRAR}'H'F & \\
\text{MPYU} & \quad \text{RSLD} \\
\text{NOOP} & \\
\text{ARRS} & \quad 1 \\
\text{ARMR} & \quad \text{GECRS} \\
\text{BRAR}'H'F & \\
\text{MPYU} & \quad \text{RCLD} \\
\text{MDBR} & \quad \text{RRATE} \\
\text{ARRS} & \quad 1 \\
\text{ARMR} & \quad \text{GECRS} \\
\text{BRAR}'H'F & \\
\text{MPYU} & \quad \text{VB} \\
\text{NOOP} & \\
\text{MDAE} & \quad \text{XBM} \\
\text{ARRS} & \quad 1 \\
\text{ARBR}'F & \\
\text{MDAR}'N'H & \quad \text{ORATE} \\
\text{MPYU} & \quad \text{WB} \\
\text{NOOP} & \\
\text{BRAE}'F & \\
\text{ARBR}'F & \\
\text{MDAR}'N'F & \quad G \\
\text{MPYU} & \quad \text{ESLD} \\
\text{NOOP} & \\
\text{ARRS} & \quad 2 \\
\text{BRAE}'F & \\
\text{ARLS} & \quad 3 \\
\text{NOOP} & \\
\text{ARBR}'F & \\
\text{MDAE}'N & \quad \text{UDOT} \\
\text{BRAE}'F'F & \\
\text{ARRH}'H'F & \\
\text{MPYU} & \quad \text{DT15} \\
\text{NOOP} & \\
\text{ARRS} & \quad 8. \\
\text{MDAE} & \quad \text{UB} \\
\text{ARMR} & \quad \text{UBN} \\
\text{MDAR}'N'H & \quad \text{RRATE} \\
\text{MPYU} & \quad \text{UB} \\
\text{BRMD} & \quad \text{UDOT} \\
\text{MDAE} & \quad \text{YBM} \\
\text{ARBR}'F & \\
\text{MDAR}'H' & \quad \text{PRATE} \\
\text{MPYU} & \quad \text{WB}
\end{align*}
\]

\[G=20063\]

FRICITION:

\[\text{IFORCE EQUATIONS}\]

\[\text{IGRAVITY}\]

\[\text{ITIMES} \cos \Theta\]

\[\text{RESULT TO B7}\]

\[\text{RESULT TO B7R}\]

\[\text{ITIMES} \sin \Phi\]

\[\text{ITEMP STORE B9}\]

\[\text{EG} + \cos \Theta \quad \text{B9}\]

\[\text{ER FROM} \quad \text{S/R EQMM B-1}\]

\[\text{EG} + \cos \Theta + \Phi\]

\[\text{EY VELOCITY COMP B9}\]

\[\text{IFROM WTOB S/R B8}\]

\[\text{NEGQ FROM EQMM TO B0R}\]

\[\text{IZ VELOCITY COMP B9}\]

\[A = -R \times VB - Q \times WB + XBM\]

\[B = G \times S \Theta + A\]

\[\text{SUBTRACT OLD UDOT B6}\]

\[\text{ADD TWO MORE NEW UDOTS}\]

\[\text{DELTA T OVER 2 B-4R}\]

\[\text{ADD X COMP B10}\]

\[\text{ISTORE UNTIL END}\]

\[\text{I-R FROM EQMM S/R B-1}\]

\[\text{ITIMES X COMP B10}\]

\[\text{UDOT} = B\]

\[\text{ADD YBM FROM WTOB}\]

\[\text{IC} = -R \times UB + YBM\]

\[\text{IP TO B0R}\]

\[\text{ITIMES} \text{Z COMP B9}\]
<table>
<thead>
<tr>
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<td>JUMP'I</td>
<td>FORCE</td>
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**INTVD:**

- ID = P+WB+GECRS+C
- ISUBTRACT OLD VDOT B7
- IADD TWO MORE NEW VDOTS
- IDELTA T FOR 15X'S /SEC

**INTWD:**

- IG = GECRC+F+ZBM
- IADD NEG OLD WDOT
- IADD TWO NEW WDOTS
- IWDOT = G
- UPDATE WB B9
- NOW CHANGE UB
- IAND VB
REQUIRES ANGULAR RATE IN RADIANS PER SECOND (B2)
PREVIOUS SIN.COS
SOLVES SIN(N+1) = SIN(N) + HR COS(N) - EMH SIN(N)
& COS(N+1) = COS(N) - HR SIN(N) - EMH COS(N)
E = SIN2(N) + COS2(N) - 1
WHERE R IS ANGULAR RATE, H IS TIME INCREMENT, M IS
A CONSTANT SUCH THAT MH = 1/2, AND E IS ERROR TERM

SICOS:
IREPEAT NN,(R,E,Y)
MDAR'H NN\CLD [OLD COS TO B1R
MPYU NN\CLD [SQUARED GIVES B2
NOOP
ARBX'F MDAR'H NN\SLD [OLD SIN TO B1R
MPYU NN\SLD [SQUARED GIVES B2
NOOP
BRAE'F MDAE'N'H'F ONEB2 [SUBTRACT 1 AS B2
ARRS 15 [SHIFT TO B15 OR B0R
NOOP
MPYI 17777 [M+H (JUST UNDER 1/2) B0R
NOOP
ARBR'F ARBR'F

NN\COS:
MPYU NN\CLD [FORM EMH COS(N) B1
BRMD MEH [STORE ERROR TERM B0R
MDAE'E NN\CLD [SUBTRACT COS(N)
ARMR NN\CNW [TEMP STORAGE B1
MDAR NN\RLD [ANGULAR VELOCITY (N-1) B2
MDAE NN\RNW [AVERAGED WITH A.V.(N) B2
ARAR'H'F MPYI DT15 [DELTA T / 2 FOR AVG. B-4R
NOOP
ARAR'H'F ARMD NN\HR [PRODUCT TO B-2R
MPYU NN\SLD [SAVE HR*B=2R
NOOP
ARRS 2 [FORM HR SIN(N) AS B1
MDAE NN\CNW [HR SIN(N) + (EMH COS(N)
ARMR'N NN\CNW [I- COS(N) ] NEGATED B1

NN\SIN:
MDAR MEH [RECALL ERROR COEF. B0R
MPYU NN\SLD [TIMES SIN(N)
NOOP
ARBX'F
MDAR NN\HR [RECALL HR AS B-2R
MPYU NN\CLD [HR COS(N)
NOOP
ARRS 2
BRAE'N'F [HR COS(N) - EMH SIN(N)
MDAE NN\SLD [PLUS SIN(N)
ARMR NN\SLD [EQUALS SIN(N+1) B1
IREPEAT NN, (R, E, Y)
ENTRY NN\CLD, NN\SLD, NN\CNW, NN\SNW, NN\RLD, NN\RNW
NN\CLD: 200001H
NN\SLD: 0
NN\CNW: 200001H
NN\SNW: 0
NN\RLD: 0
NN\RNW: 0
[IN RADIANS PER SECOND B2
[ garbage in LHS
ENDI
MEH: 0

[computes euler angle rates
[ needs P, Q, R rates
[ gives RR, ER, YR
[ rates must be under 1B1 when angles are 45 degrees

ERR = 1  SIN PHI TAN THETA  COS PHI TAN THETA  P
IER = 0  COS PHI  - SIN PHI  Q
IYR = 0  SIN PHI SEC THETA  COS PHI SEC THETA  R

EULER:
RR:
MDAR'H RSLD [old sin phi to b1r
MPYU QRATE [times q b0
NOOP ECLD [product b1
NOOP [quotient b0r
ARBR'F
MPYU ESLD [old sin theta b1
BRMD RSECQ [(sphi*q)/ctheta b0r
ARRS 1
ARBR'F
MDAR'H RCLD [old cos phi to b1r
MPYU RRATE [times r b-1
NOOP ECLD [product b0
NOOP [quotient b-1r
ARMD RCECR [sphi*r/ctheta b-1r
MPYU ESLD [old sin theta
NOOP [product b0
ARRS 2
ARRS 2
BRAE'F [(stheta*rcecr)+
ARBR'F [stheta*rsec0]
MDAR PRATE [p as b0
ARRS 2 [to b2
BRAE'F [added to above
ER: MDAR'N'H RSLD IOLD SIN PHI TO B1R
MPYU RRATE ITIMES R B-1
BRMD RRNW ISTORE PHI DOT B2
ARRS 1
ARBR'F
MDAR'N'H RCLD IOLD COS PHI TO B1R
MPYU QRATE ITIMES Q B0
NOOP
BRAE'F
ARRS 1
ARMD ERNW INEW THETA DOT B2

YR: MDAR'N'H RCOCR [FROM ABOVE B-1R
ARRS 1
MDE'N'H RSECQ ITO B0
ARRS 2 [SHIFT TO B2
ARMD YRNW INEW PSI DOT JUMP'I EULER

ICONVERTS BODY VELOCITY COMPONENTS TO VEHICLE FRAME
IVX YC -YS O EC O ES 1 O 0 UB
IVY = YS YC 0 0 1 0 0 RC -RS VB
IVZ 0 0 1 -ES O EC O RS RC WB

DIRCS:

ROLTP: MDAR'N'H VB [Y COMPONENT TO B9R
MPYU RCLD [TIMES COS PHI B1
NOOP [PRODUCT B10
ARBR'F
MDAR'N'H WB [INEG Z COMPONENT TO B9R
MPYU RSLD ITIMES SIN PHI B1
NOOP [B10
BRAE'F [A=(VB*CPHI)-(WB*SPHI)
ARBR'F
MDAR'N'H VB [VB TO B9R
MPYU RSLD ITIMES SIN PHI B1
BRMD YTEM [YTEM = A B10
ARBR'F [VB*SPHI B10
MDAR'N'H WB [WB TO B9R
MPYU RCLD ITIMES COS PHI B1
NOOP
BRAE'F [B = (VB*SPHI)+(WB*CPHI)
ARBR'F

ELVTR: BRAR'H'F ECLD [B TO B10R
MPYU 2TEM [TIMES COS THETA B1
BRMD ZTEM [ZTEM = B B10
ARBR'F
MDAR'H'N UB [UB TO B10R
MPYU ESLD ITIMES SIN THETA B1
NOOP
BRAE'F [ADD ZTEM*STHETA B11
ARLS 2
NOOP
[FOLLOWING SUBROUTINE COMPUTES DYNAMIC FORCES FROM VELOCITY AND
AIRCRAFT DIMENSIONS AS WELL AS TRANSLATIONAL AERODYNAMIC FORCES]

TRNSL:

MDAR'H RHO [FROM ATMOS TO B-9R
MPYU VT [FROM AERO TO B10
NOOP
ARBR'H'F BRAR'F
MPYU SCRD2 [1/4 * S * C * C B19R
NOOP
ARMD QSC6Q [.25*V*S*C*C B21
BRAR'F MPYU SGPN2 [.25*S*B*B B24R
NOOP
ARMD QSBSQ [TIMES V B26
BRAR'F MPYU VT [FORM V SQUARED
NOOP [PROD B12 (NEVER G.T. B10)
ARLS 2 [DUE TO VARIATION OF MAX
NOOP
ARAR'H'F ARBR'F [AIRSPEED & DENSITY WITH
[ALTITUDE SO SHIFT TO B10

ARBR'F
MDAR'H ZTEM [C = (UB*STHETA)+ZTEM*STHETA
MPYU ESLD [ZTEM TO B10R
BRMD VZ [CVZ = C B9
ARBR'F
MDAR'H UB [UB TO B10R
MPYU ECLD [ITIMES C*S THETA B1
NOOP
BRAE'F ARBR'F'B [ADD STHETA*ZTEM
ID = UB*CTHETA + ZTEM*CTHETA

YAWTR:

BRAR'H'F ID TO B10R
MPYU YCLD [TIMES COS PSI B1
BRMD XTEM [XTEM = D B10
ARBR'F
MDAR'H'N YTEM [TIMES SIN PSI B1
MPYU YSLD
NOOP
BRAE'F ARBR'F [ADD D*CPSI
ID = CPSI*ZTEM + SPSI*YTEM
MDAR'H'N XTEM [XTEM TO B10R
MPYU YSLD [TIMES SIN PSI B1
BRMD VX [VX = E B11
ARBR'F
MDAR'H YTEM [YTETM TO B10R
MPYU YCLD [TIMES COS PSI B1
NOOP
BRAE'F ARMD VY [VY = F B11
JUMP'I DIRCS
THRST COMPUTATION: (MACH VARIATION HERE, ALTITUDE IN ATMOS) 
THRST = IDLE + (MAX-IDLE)(DELTA THROTTLE NORMALIZED SQURED)

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<th>[1/2<em>S</em>C B16R</th>
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<td>NOOP</td>
<td>QSC</td>
<td>TIMES V SQRED B26</td>
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<td>QSB</td>
<td>1/2 * S + B B18R</td>
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<td>BRRF</td>
<td>SSPAN</td>
<td>1/2 <em>S</em>B*VSQR B28</td>
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<td>MPPYI</td>
<td>SAREA</td>
<td>1/2 * S B11R</td>
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<tr>
<td>ARMD</td>
<td>QS</td>
<td>1/2 * S * VSQR B21</td>
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THRST:  

MDAR'H ITHVM [IDLE VS. MACH B12  
MPYU MACH  
MDAR ITHMO [IDLE(M=0) B12  
BRA'E F  
ANAR ZERO [ZERO IF NEGATIVE  
ARPS 3  
ARMD IDTHR [STORE IDLE B15  

MDAR'H MTHVM [MAX VS. MACH B13  
MPYU MACH  
MDAR MTHMO [MAX(M=0) B15  
ARPS 2  
BRAW'E F  
MDAE N IDTHR  

MDAR'H DTHRO [NORMALIZED THROTTLE  
MPYU DTHRO [SQUARED B0  
BRMD MXTHR  
ARAR H' F  
MPYU MXTHR  
MDAR IDTHR  
BRAW'E F  
ARPS 5 [SHIFT TO B20  
ARMD THRST [USE AS B22 (FOUR ENGINES)
[FOllowing variation with mach is applied to c sub l-alpha
[CLaLP = 4.584 - 2.22 MACH + 5.378 MACH SQRED (IN RADIANS)
[ALPHA HERE IS FOR X BODY AXIS PLUS 1.9 DEG. INCIDENCE ANGLE
[ALSO FOR DFLAP G.T. 6 DEG. ADD INCREMENT OF 1.081 / RAdIAN

LCORR: MDAR'H  MACH
MPYU  MACH
NOOP
ARAR'H'F
MPYI  25430  [5.387 B3R
NOOP
ARBR'F
MDAR'N'F  10703  [2.22 B3R
MPYU  MACH
NOOP
BRAE'F
MDAE  CL0  [4.584 B3
ARMD  CLALP  [LIFT SLOPE VS. ALPHA B3

LFT: MDAR  DFLAP
MDAE'H'N'F  DFLP6
JAPAN  NOFLP  [IF FLAPS G.T. 6 DEG
ARBR'H'F  [THEN ADD INCREMENT
MDAR'H'F  4246  [OF 1.081 TO CLALP B3
MDAE  CLALP
ARMD  CLALP  [AND (FLAPS - 6) B0
BRAR'F
MPYI  CLFLA  [TIMES C SUB L-FLAPS B2R
NOOP  [ANSWER SHOULD BE POS.
ANOAR  ZERO  [UNLESS JUMP FROM ABOVE
ARMD  CLFLP  [THEN ZERO CLFLP B2
MDAR  ALPHA
MDAE'H'F  2076  [ADD 1.9 DEG INCIDENCE
ARBR'F  [IN RADIANS B-1
MDAE'H'N'F  23774  [SUBTRACT 17.9 DEG. STALL
JAPAN  . 5  [IF STALLED DECREASE
ARLS  1
ARAR'H'N'F  [ALPHA BY AMOUNT ABOVE
BRAS'H'F  [CRITICAL THUS DECREASING
JUMP  . 2  [CLIFT LINEARLY
BRAR'H'F
MPYU  CLALP  [FROM ABOVE B3
MDBR  CLFLP  [FLAP CONTRIBUTION B2
BRAE'F
ARBR'F
MDAR'F  CLELE  [C SUB L-DELTA E B-1R
MPYL  DELEV  [DELTA ELEVATOR B0R
NOOP
ARRS  3
BRAE'F
ARBR'F
ARAR'H'F
MPYU  GS  [DYNAMIC FORCE B21
BRMD  CLIFT  [TOTAL C SUB L B2
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THE FOLLOWING SUBROUTINE COMPUTES THE AIRCRAFT MOMENTS FROM AERODYNAMIC FORCES

| ROTAT:          | RLL:          | MVAR 'H   | BETA   | [SIDE SLIP ANGLE TO B-1R] |
|                |              | MPYI     | CBETA   | [ROLL COEF. DUE TO BETA B-2R] |
| NOOP           |              | NOOP     | 1       |                          |
| ARBR 'F        |              | ARBR 'F  | CRUDD   | [COEF. DUE TO RUDDER B-5R] |
| MVAR 'F        |              | MPYL     | DRUDD   | [DELTA RUDDER FROM YCDI BOR] |
| NOOP           |              | NOOP     | 3       |                          |
| BRAE 'F        |              | BRAE 'F  | CAILE   | [COEF. DUE TO AILERONS TO B-2R] |
| ARAR 'H 'F     |              | MVAR 'F  | QSB     | [IFROM TRNSL B26] |
| MPYU NOOP      |              | ARAR 'H 'F| QSB50   | [IPROD TO B-1R] |
|                |              | NOOP     | 1       | [IFROM TRNSL B26] |
| BRAE 'F        |              | BRAE 'F  | LXX     | [TOTAL ROLL MOMENT B26] |
| DIVI           |              | MVAR 'H  | CMALP   | [DIVIDED BY INERTIA B22R] |
| NOOP NOOP      |              | BRAE 'F  | 2       | [STORE AS B2 FOR EQMM] |
| ARMD 'H        |              | ARMD 'H  | LMOM    |                          |

<p>| PTCH:          |              | BRAE 'F  | ALPHA   | [C SUB M-ALPHA TO B1R] |
| MVAR 'H        |              | MVAR 'H  | CMO     | [ANGLE OF ATTACK B-1R] |
| MVAR 'H        |              | MVAR 'H  | CMALP   | [COEF. DUE TO ELEV. BOR] |
| MVAR 'H        |              | NOOP     | 3       | [DELTA ELEVATOR BOR] |
| BRAE 'F        |              | MVAR 'H  | DELEV   |                          |
| ARGF           |              | MVAR 'H  | DFLAP   |                          |
| BRAE 'F        |              | MVAR 'H  | DF14    | [IF FLAPS G.T. 14 DEG] |
| JPAI           |              | MVAR 'H  | NFLP    | [THE FLAPS -14] |
| NOOP NOOP      |              | MVAR 'H  | CMFLP   | [TIMES C SUB M-FLAP BOR] |
| BRAE 'F        |              | NOOP     |         |                          |</p>
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**TOTAL: 151**

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**QSC**
- **151**
- **DYNAMIC FORCE B26**
- **IC SUB M-Q B5R**
- **[B0**
- **[B21**
- **PRODUCT B26**
- **[SUM AS B26**
- **[INERTIA B23R**
- **STORE AS B1 FOR EQMM**
- **SIDESLIP ANGLE TO B-1R**
- **[YAW COEF. DUE TO BETA B-3R**
- **[YAW COEF. DUE RUDDER B-3R**
- **[DELTA RUDDER B0R**
- **[SUM TO B-3R**
- **[YAW RATE TO B-1R**
- **[COEF. DUE TO YAW RATE B-2R**
- **FOR EQMM B0**
[FOLLOWING SUBROUTINES COMPUTES ATMOSPHERIC VARIABLES.
COMPUTATION PROCEEDS ON THE ASSUMPTION THAT QUANTITIES VARY SLOWLY WITH ALTITUDE.

ATMOS:

MDAR'X  CLK2  [COUNT 15X'S /SEC
MDAR'S'N'F  15  [IF FIFTEENTH
JPAN  ACONT
ARMD  CLK2
MDAR'X  TTIME  [INCREMENT CLOCK SECS
MDAR  %CLKKF
JPAN  ACONT
JPFR  $TMDSPL FORM CLOCK DISPLAY
JUMP'I  ATMOS

ACONT:

MDAR'X  ATCNT  [CREATE JUMP
MDAE'L  [NEXT ROUTINE
JUMP'I  ATLS1-1
ARIF'F  [JUMP THERE
MDAR  $R  [IF ALTITUDE L.T. 5000
MDAE'L;  -5000.1K
JSAN  $MKLTS  [DO MKLTS
JUMP'I  ATMOS

ATLS1:  ATM01:ATM02:ATM03:ATM04:ATM05
[RHO/RHO0 = 1 - 1.835(R/65536) + 1 (R/2**16)**2
ATM01:

MDAR'H  RB16  [DIVIDE BY 65536
MPYU  RB16  [I.E. NOW NORMALIZED B0
MDBR'H'N  RB16  [SQUARED IS B0
ARRS  1
ARMD  RSQR  [STORE SQUARE AS B1
BRAR'F  [RECALL RB16 AS B16R
MPYI  35270  [1.835 AS B1
MDBR'H  FS  [+1 TO BR AS B0
MDAE  RSQR
ARLS  1  [SHIFT SUM TO B0
BRAE'F  [ADD +1
ARAR'H'F
MPYI  RH00  [RHO ZERO B-8R
NOOP
ARMD  RHO  [STORE RHO B-8R
JUMP'I  ATMOS

IFOLLOWING SUBROUTINE IS USED HERE AND IN 4D COMPUTATIONS
[A/A0 = 1 - (3.6825*10**-6)(ALTITUDE IN FEET) BELOW 36.089 FT
[A/A0 = .867 ABOVE 36.089

SOUND:

ARBR'F  [COMP. SPEED OF SOUND
[hold altitude
MDAE'H'N'F  21476  [SUBTRACT 36.089 FT B16
JPAN  . 3  [SPEED OF SOUND ABOVE
MDAR'H'F  17074  [36.089 IS CONSTANT
JUMP'I  SOUND  [USE 967.6 FT/SEC B11
BRAR'N'F  [LAPSE RATE FOR A/A0 IS
MPYI  7562  [3.6826*10**-6 PER FT AS B-16
MDBR'H  FS  [PRODUCT IS B0
BRAE'F  [ADD +1 AS B0
ARAR'H'F
MPYI  21343  [TIMES 1116.4 FT/SEC B11
NOOP
JUMP'1 SOUND
[ALTITUDE B16
JUMP'1 ATMOS
[FOLLOWING COMPUTES A LINEARIZED CONVERSION FACTOR FOR
CONVERTING MACH TO INDICATED AIRSPEED
WHERE KIAS = M2IAS * MACH (KIAS IN KNOTS B10)
AND M2IAS = 656 - (.0091)(ALTITUDE IN FEET)
[ALSO THE ANGULAR DIFFERENCE BETWEEN .7 MACH AND 300 KNOTS
[FOR ROTATION OF THE MACH INDICATOR
ATM03: MDAR RB16 [ALTITUDE AS B16
MPYI 22506 [TIMES .0086 AS B-6R
NOOP
MDAE'H'F 24400 [CONVERSION IN KNOTS B10
ARM D M2IAS
ARAR'H'F
MPYI 1205 [.9 DEGREES PER KNOT
NOOP [.7 MACH = .63
AS B4
MDAE'N'H'F 416 [.9 * 300 KNOTS AS B14
ARM D'H $MHANG [ANGLE FOR MACH SCALE
JUMP'1 ATMOS
[FOR ROTATION OF THE MACH INDICATOR
ATM04: JPSR $MACHC [SET UP MACH SCALE
JUMP'1 ATMOS [IN "FNST2"
[FOLLOWING CORRECTIONS ARE APPLIED TO THRUST/ ENGINE VS. ALTITUDE
[MAX CONTINUOUS (M=0) =13800 -.28125 (ALT IN FT)
[MAX THRUST DEC. WITH MACH = -7800 .3117(ALT IN FT) ALT L.T. 15000
[ -3125 +.185(ALT - 15000) ALT G.T. 15000
[IDLE THRUST(M=0) = 1000 LBS. ALL ALTITUDES
[IDLE THRUST DEC. WITH MACH = -2000 ALT L.T 15000
[ = -2000+.07(H-15000) G.T.15000
ATM05: MDAR RB16
JUMP'1 ATMOS
[15000 FT B16
JPSR BLW15
MDAE'H'N'F 7246 [.185 B-2R
ARBR'F
ARAR'H'F
MPYI 27534
NOOP
MDAE'H'F 71712 [.3117 B14
ARM D'B MTHVM [MAX THRUST VS MACH B15
BRAR'H'F
MPYI 21727 [.07 B-3R
NOOP
MDAE'H'F 70137 [.2000 B13
ARM D'B ITHVM [IDLE THRUST VS MACH B12
JUMP
MDAR B R816
BLW15
ARAR'H'F
MPYI 23745 [.3117 B-1R
MDBR'LJ 602771H [.2000 B12
MDAE'H'F 60607 [.7800 B14
BRMD ITHVM
ARM D'B MTHVM
FOLLOWING SUBROUTINE INTEGRATES VEHICLE FRAME VELOCITIES TO OBTAIN EARTH FRAME POSITION. NOTE THE CHANGE OF COORDINATE AS DISPLAY +Y AXIS POINTS NORTH AND +X EAST WHILE THE OPPOSITE IS TRUE IN VEHICLE FRAME.

INTEGRATION RULE: \(x(n) = x(n-1) + \frac{h}{2} (2v_x(n))\)

- **MTCOM:**
  - MDAR 'F 55777 [-.28125 B-1R]
  - MPYU RB16
  - NOOP
  - MDAE 'H 'F 15364 [13800 B15]
  - ARMD MTHW0 [MAX (M=0) B15]
  - ARXD 'F
  - ARMD ATCNT
  - JUMP 'I

- **ATCNT:** 0
- **RB16:** 0
- **RSQR:** 0

**INTGV:**

- MDAR 'B VX [2X'S VEHICLE Y VEL. B11]
- MDAE 'B WYX [PLUS X WIND VELOCITY]
- ARAR 'H 'F
- MPYI DT15 [DELTA T/2 B-4R]
- NOOP
- ARR5 16. [SHIFT TO B23]
- MDBR 'B VY
- ARMD GVX
- MDAE Q
- ARMD 0 [EARTH Y POSITION B23]
- ARMD $YF [IY POSITION FOR "MMAP2"]
- BRAR 'F
- MDAE 'B WYV [IY WIND VELOCITY]
- ARAR 'H 'F
- MPYI DT15
- NOOP
- ARR5 16. [EARTH X POSITION B23]
- MDBR 'N 'B VZ
- ARMD GYV
- MDAE P
- ARMD $XP [IX POSITION FOR "MMAP2"]

- BRAR 'F 'H
- MPYI DT15 [2X'S NEG VZ B9]
- NOOP
- ARR5 18. [ALTITUDE B23]
- MUBR R
- BREA 'F
- ANAR ZERO [PREVENT ALTITUDE FROM GOING NEGATIVE]
- ARMD R
- ARLS 7
- NOOP
- ARMD RB16 [STORE AS B16 ALSO]
- MDAR GVX [CALCULATE GND SPEED]
- MPYL GVX [FT PER UPDATE B6R]
- NOOP

**ATCME:**
- MTHMO
- ATMOS

**INTGV:**

- MDAR 'B VX [2X'S VEHICLE Y VEL. B11]
- MDAE 'B WYX [PLUS X WIND VELOCITY]
- ARAR 'H 'F
- MPYI DT15 [DELTA T/2 B-4R]
- NOOP
- ARR5 16. [SHIFT TO B23]
- MDBR 'B VY
- ARMD GVX
- MDAE Q
- ARMD 0 [EARTH Y POSITION B23]
- ARMD $YF [IY POSITION FOR "MMAP2"]
- BRAR 'F
- MDAE 'B WYV [IY WIND VELOCITY]
- ARAR 'H 'F
- MPYI DT15
- NOOP
- ARR5 16. [EARTH X POSITION B23]
- MDBR 'N 'B VZ
- ARMD GYV
- MDAE P
- ARMD $XP [IX POSITION FOR "MMAP2"]

- BRAR 'F 'H
- MPYI DT15 [2X'S NEG VZ B9]
- NOOP
- ARR5 18. [ALTITUDE B23]
- MUBR R
- BREA 'F
- ANAR ZERO [PREVENT ALTITUDE FROM GOING NEGATIVE]
- ARMD R
- ARLS 7
- NOOP
- ARMD RB16 [STORE AS B16 ALSO]
- MDAR GVX [CALCULATE GND SPEED]
- MPYL GVX [FT PER UPDATE B6R]
- NOOP
ARBR'F
MDAR
MPYL
NOOP
BRAE'F
JPSR
MPYI
NOOP
MDAR'H'A
ARRS
ARMD'H
JUMP'1
FRINC: 100.1K
FHINC: 3038.1K
RLIM: 50000.1K
QS: 0; QSB: 0; OSC: 0
RHO: 233601H
SPDSN: 212271H
MACH: 0
KIAS: 0
M2IAS: 236101H
THRT: 5442000
IDTHR: 0; MXTHR: 0
MTHVM: 606071H
MTHW: 153641H
ITHVM: 602771H
ITHW: 76401H
WVEL: 0; GVX: 0; GY: 0
GSPD: 0; VX: 0; VY: 0; VZ: 0
P: 0; Q: 0; R: 500.1K
ALPHA: 0; SIN: 0; COSA: 0
BETA: 0; SINB: 0; COSB: 200001H
LIFT: 0; DRAG: 0; YAERO: 0
XTM: 0; YTM: 0; ZTM: 0
UBN: 0
UB: 0
VSQ: 0; VS: 0
VTS: 122401H
PRATE: QRATE: 0
PDOT: GDOT: 0
LMM: MION: 0
UDOT: WDOT: 0
XBM: YBM: 0
DELEV: DAILE: 0
DSPOL: 0
DFLAP: 0
FRATE: 151H
DTHRO: 0

[DELTA DIST SQRED B16
[ALTITUDE INCREMENT
[ALTITUDE LIMIT
[DYNAMIC FORCE TERMS
[FROM TRANSL
[ATMOSPHERIC DENSITY B-9R
[SPEED OF SOUND B11
[MACH NUMBER
[INDICATED AIRSPEED B10
[CONVERSION FACTOR B10
[THRUST
[THRT]
[HANDLE VS. MACH B13
[MAX VS. MACH B15
[IDLE VS. MACH B12
[IDLE(M=0) B12
[IDLE AND MAX
[GROUND SPEED AND COMPS
[VEHICLE VELOCITY
[

[WINDED COMPS
[ANGLE OF ATTACK
[SIDESLIP ANGLE
[USED IN DIRCS
[ITEM STORAG IN FORCE
[ITEM STORAG IN EQMM
[ITEM STORAG IN WTB
[ITEM STORAG IN EULER
[BODY AXIS VELOCITIES
[TOTAL VELOCITY
[ANGULAR RATES
[ANGULAR ACCELERATIONS
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<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>CLALP</td>
<td>222541H</td>
<td>Slope of lift coef. B3</td>
</tr>
<tr>
<td>CLLP</td>
<td>222541H</td>
<td>Min slope of lift coef. B3</td>
</tr>
<tr>
<td>KDRAG</td>
<td>153241H</td>
<td>Lift curve coef. B-3</td>
</tr>
<tr>
<td>CDGER</td>
<td>126</td>
<td>Drag coef. due to gear B1</td>
</tr>
<tr>
<td>CAILE</td>
<td>137021H</td>
<td>Roll coef. due ailerons B-2</td>
</tr>
<tr>
<td>CMO</td>
<td>14221H</td>
<td>Min pitch coef. B0</td>
</tr>
<tr>
<td>CMALP</td>
<td>605601H</td>
<td>Pitch coef. due to alpha B1</td>
</tr>
<tr>
<td>SSIX0:0; SSIX1:0; SSIX2:0</td>
<td>0; 0; 0</td>
<td>Shared source six</td>
</tr>
<tr>
<td>SSIX3:0; SSIX4:0</td>
<td></td>
<td>Register storage</td>
</tr>
<tr>
<td>NZERO</td>
<td>0</td>
<td>Gear flap -0=down</td>
</tr>
<tr>
<td>GFLG</td>
<td>0</td>
<td>Moving map scale</td>
</tr>
<tr>
<td>SCALE</td>
<td>2</td>
<td>Mask</td>
</tr>
<tr>
<td>MSK</td>
<td>77777</td>
<td>Freeze flag</td>
</tr>
<tr>
<td>MK1</td>
<td>77776</td>
<td>15 counts/sec</td>
</tr>
<tr>
<td>ZERO</td>
<td>0</td>
<td>Program clock time</td>
</tr>
<tr>
<td>SEVEN</td>
<td>7</td>
<td>Neg full scale</td>
</tr>
<tr>
<td>READY</td>
<td>0</td>
<td>Pos full scale</td>
</tr>
<tr>
<td>FNSWS</td>
<td>0</td>
<td>Instruction to change</td>
</tr>
<tr>
<td>CLK2</td>
<td>0</td>
<td>Sign of AR and BR</td>
</tr>
<tr>
<td>TTIME</td>
<td>0</td>
<td></td>
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<td>NFS</td>
<td>40000</td>
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<tr>
<td>FS</td>
<td>37777</td>
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<tr>
<td>NEGAT</td>
<td>ARR'N'F</td>
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</tr>
<tr>
<td>NEGB</td>
<td>BRB'N'F</td>
<td></td>
</tr>
<tr>
<td>ONEB2=10000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TERMINATE</td>
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A portion of the assembly language program which solves the time-controlled navigation equations is included here. The logic of the various subroutines is shown in the associated comments. The omitted portions of the program are uniquely associated with the Adage computer's graphic display or the moving map used in this simulation.
THIS PROGRAM DISPLAYS ASSIGNED TIME, ALTITUDE, AND SPEED FOR FOUR DIMENSIONAL WAYPOINTS. THE DISPLAY AND MOVEMENT OF WAYPOINT DATA HAS BEEN ADAPTED FROM ANDERSON'S TRAFFIC ROUTINES FOR TRAFFIC MOVEMENT. C.J. CORLEY 9/74

IT ALSO CONTAINS THE COMPLETE MIN TIME - MAX TIME CONTROLLER COMPUTATION FOR MEETING ASSIGNED TIMES AND FOLLOWING A FOUR DIMENSIONAL ROUTE. C.J.C. 11/74

ENTRY WDRAW,UMOVE,SIDL,FORDI,MXDRW,MNDRW
ENTRY TOP,TDA,TAP,TDS,TSP,TDT,TTP,TD2,TX
ENTRY TY,TTDRW,STDRW,TIMEI,TIME2,SDISF
ENTRY S60WP,S62WP,S63WP,STRBF,CLKF,TMDSP
ENTRY SPSET,VERGR,SBUGD,DBUGD,CMSPC,SVLST
ENTRY WPSL,SELST,WPIDO,STGSL,MXTIM,MNTIM
ENTRY ACCEL,DECEL,PROFL,MXASP,MNASP,PTAFL
ENTRY STAGE,WPMX,MXTA,MNTR,FINZ,FINAS
ENTRY FINTH,SMU

FORDI:

MDAR'L
JPSR'I FDLST-1 [EACH CALL DO NEXT IN FDLST
MDAS'X FDPTR
ARIR'F
JUMP'I FORDI

FDPTR:

16
FDLST:

PROFL [VERTICAL GRADIENT AND SEGMENT
MXASP [TIME TO DESCEND AT MAX SPEED
MNASP [TIME TO DESCEND AT MIN SPEED
CMSPC [COMMAND SPEED BUG
PROFL
MXASP
MNASP
CMSPC
MXDSP [CREATE EARLIEST ETA DISPLAY LIST
MNDSP [CREATE LATEST ETA DISPLAY LIST
PROFL
MXASP
MNASP
CMSPC
FDESR [INITIALIZE SUBROUTINE LIST

FDESR:

MDAR SELST [SELECT NEG
JPAN FDESI [STORE POSITIVE
MDAR'F 16 [COME HERE ON NEXT PASS
MDAR'H SPSET [IN STORE MOVE SPEED
MPYI 3462 [BUG WITH COCKPIT KNOB
BPMO FDPTR
ARBR'F
MDAR 8RB16 [IF ALTITUDE B16
MDAE'H'F 63625 [C.T. 25000
[FOLLOWING CODING FORMS TWO ROUTINES MXASP AND MNASP WHICH COMPUTE
TIMES OF ARRIVAL BASED ON MAX SPEED AND MIN SPEED]

AA=MXAS0
BB=AS0
CC=ACCEL
DD=DECEL
EE=MXAS3
FF=FINAS
GG=AS0
HH=FINAS

IREPEAT NN,(MX,MN)

NN\ASP:

MDAR'F 6 [COUNTER TO LIMIT]
ARMD'N ITERC [NO. OF ITERATIONS]
ARMD'O ITERF [ITERATION FLAG]

NN\L1:

MDAR STG3 [INITIALIZE ASP CHANGE]
ARMD DCDST [DISTANCE FROM PROFL]
MDAR AA
MDAE'N BB [AIRSPEED DIFFERENCE B10]
ARBR'F
ARRS 6 [TO B16]
ANAR ZERO [PREVENT GOING NEG]
DIVU CC [RATE OF CHANGE B3]
NOOP
ARMD NN\TM0 [TIME REQ. IN SECS B13R]
BRAR'F [COMPUTE AVE ASP]
ARRS 1 [DURING CHANGE (FT/SEC) B10]
MDAE BB
ARAR'H'F
MPYL NN\TM0 [TIMES TIME B13R]
MDBR STG1
ARMN NN\D0 [DIST TO CHANGE B23]
BRAE'N'F [MINUS DIST AT INIT ALT]
JPAN NN\L2 [NEG IF STG 1 GREATER]
ARRS 10. [USE AS B18]
MDBR ZERO
MPYU'N TANSI [DIST TO ALT BY TAN B-2]
BRMD NN\TM1 [ZERO TIME IN LEV FLT]
[JUMP HERE WITH HIBND (IN AR, DIVIDE BY 2)]

[CHANGE EACH ASP BY (HIBND - LOBND) / 2]

[SUM ALL TIMES]

[TIME BEFORE CHANGE B16?]

[IS ITERATION IN PROGRESS?]

[IS CURRENT AIRSPEED GREATER THAN FINAL?]

[SHIFT TO B16]

[FINAL G.T. CURRENT JUMP ELSE DECEL TIME]

[COMPUTE AVE ASP DURING DECEL]

[COMPUTE DIST TO DECEL]

[REMAINING DIST TO W.P. ISUM B23]

[NOT ENOUGH DIST JUMP]
ARBR'F
DIVU
NOOP
ARMD
MDAR
ARMD
MDAR'N
BRAE'F
JPAN
JUMP
[REMAINING DIST AT FAST
OR SLOW GIVES TIME B13R
LIMIT EXTREME TO
FAST OR SLOW
IS DIST REMAINING
L.T. REACTION DIST

NN\L9:
DIVU'N
NOOP
ARMD
BRAR'N'F
ARRS
MDAE
ARAR'H'N'F
NPYL
MDBR
BRAE'F
JPAN
ARBR'F
DIVU
NOOP
ARMD
MDAR
ARMD
MDAR'N
BRAE'F
JPAN
JUMP
[ACCEL TIME
COMPUTE DIST TO ACCEL
NOT ENOUGH DIST JUMP
REMAINING DIST AT FAST
LIMIT EXTREME TO FAST
OR SLOW
IS DIST REMAINING
L.T. REACTION DIST

NN\L10:
ARXO'F
ARMD
NN\L11:
MDAR
FINAS
ARMD
NN\ASO
ARMD'O
NN\ASF
NN\L12:
MDAR
NN\TM4
MDAS
NN\TM4
MDAR'A
MSK
ARRS
1
ARMD
NN\TIM
JUMP'I
[NOT ENOUGH TIME
FOR INSIDE REACTION
DISTANCE
SET FLAG FOR CMSPC
SUM TIMES B13R
TO B14R

AA=ASO
BB=MNASO
CC=DECEL
DD=ACCEL
EE=FINAS
FF=MNAS3
GG=FINAS
HH=AS0
ENDI
RUDIMENTARY LINEARIZED AVERAGE AIRSPEED DURING DESCENT

**MNAVR:**

- **MDAR**
- **MDAE'N**
- **ARRS**
- **MDE**
- **ARMD**
- **JUMP'1**

**ISIMPLE AVE AIRSPEED IDURING DESCENT**

**MXAVR:**

- **MDAR**
- **MDAE'N**
- **ARRS**
- **MDE**
- **ARMD**
- **JUMP'1**

**ENTRY ALTITUDE B16**

- **MDAR**

**SUBTRACT 25000 FT B16**

- **MDAE'N**

**JPAN**

**BELOW 25000 SIMPLE AVE**

**MDAR**

**-2**

**OR IF FINAL ALT B16**

- **MDAE'N**

**JPAN**

**ABOVE 25000, SIMPLE AVE**

- **ARMD**

**DF2**

**ELSE 25000-FINZ=DF2**

- **BRAE'F**

**MXSLZ-FINZ =DFT (TOTAL)**

- **ARMD**

**DFT**

- **MDAR**

**MXAVS2**

- **MDAE'N**

**MXAVS3**

**ARRS**

**1**

- **MDE**

**MXAVS3**

**ARAR'H'F**

**CAVE BELOW 25K TO B10R**

- **MPYU**

**DF2**

**TIMES DF2 B16**

- **BRMD**

**DF1**

**IMXSLZ-25000 = DF1**

- **ARBR'F**

**HOLD B26**

- **MDAR**

**MXAVS0**

- **MDAE'N**

**MXAVS2**

**ARRS**

**1**

- **MDE**

**MXAVS2**

**ARAR'H'F**

**CAVE ABOVE 25K TO B10R**

- **MPYU**

**DF1**

- **NOOP**

- **BRAE'F**

**SUM B26**

- **DIVU**

**DFT**

**TOTAL DIFF B16**

- **NOOP**

- **ARMD'H**

**CAVE AIRSPEED B10**

**MXAVS1:**

- **MDAR**

**MXAVS0**

- **MDAE'N**

**MXAVS3**

**ARRS**

**1**

- **MDE**

**MXAVS3**

- **ARMD**

**MXAVE**

- **JUMP'1**

**MXAVR**

**COMPUTE SIMPLE AVE B10**
SET UP WAYPOINT AND ASSIGNED TIME FOR DISPLAY AND COMPUTATION CENTER WITH SOURCE SIX REGISTER TWO IN AR

S62WP:

ARMD  WPTEM
MDAR'H'A  MSK17
ABR'R'H'F
MDAE'H'N'F  WPNUM  [NO OF WAYPOINTS]
JPN  2  [INVALID WAYPOINT ID]
JUMP'I  S62WP  [SELECT/STORE IN SELECT]
MDAR  SELST
JPAH'I  S62WP  [SELECT/STORE IN SELECT]
MDAR  WPSEL  [0,4,8,...]
MDAS'F  WPID0
ARMD  WPTR1  [1ST & 2ND POINTER]
ARMD  WPTR2  [TO TOP OF VALUE LIST]
BRAR'F
MPYI
BRMD'I  WPTR1  [1ST LABEL LIST LOCATION]
ARRS 1  [CONTAINS ID NUMBER]
MDAS'F  DLST
ARMD  WPTR3
MDAR'F'  17  [CONTAINS ASSOCIATED]
MDAR  WPTEM  [W.P. ID]
ARBR'A'F
ARRS 4
BRMD  ATA3
MDBR'F  17
ARBR'A'F
ARRS 4
BRMD  ATA2
MDBR'F  17
ARBR'A'F
MDAR'F  6  [6 SECONDS B14R]
MPYL  ATA3  [THIRD DIGIT B14R]
BRMD  ATA1
ARBR'H'F  [BR HOLDS SECONDS B13]
MDAR'F  10.
MPYL  ATA1  [10'S OF MINS. B14R]
NOOP
ARRS 1
MDAS  ATA2  [ADD UNIT MINUTES]
ARBR'O'F  [HOLD SECS L.H. B13]
MDAR  WPATA  [MINS R.H. B14R]
BRXO'F
ARRH'O'F  [RETURN IF SAME ATA]
JPLS  2
JUMP'I  S62WP  [MINNS. B14R]
BRAR'F  [60 SECS B14R]
MPYI  60.
BRMD  WPATA  [UPDATE ATA]
BRAS'H'F  [ADD SECS B28]
ARRS 1  [SHIFT SUM TO B29]
ARMD'I'X  WPTR1  [STORE IN VALUE LIST]
SET UP WAYPOINT ALTITUDE AND AIRSPEED FOR DISPLAY AND COMPUTATION CENTER WITH SOURCE SIX REGISTER THREE IN AR

S621:

JUMP 'I S62WP

S63WP:

ARMD WPTEM
ARRS 8
MDBR MSK3
ARBR'A'H'F
MDAR'A' MSK3
ARMD ASP1
ARMD WPAS
BRMD ALT2
BRMD WPALT
MDAR WPALT
ARBR'H'F
MDAR'A' MSK17
ARMD ASP3
MDAR'O'K WPAS
ARMD WPAS
BRMD ALT3
BRMD WPALT
MDAR WPALT
MDAR WPSEL
MDAS 'F WPID0
ARMD WPTR2
MDAS 'F 2
ARMD WPTR1

LIMIT ALTITUDE TO 39,900 FT
LIMIT AIRSPEED TO 399 KNOTS
1ST AIRSPEED DIGIT
1ST ALTITUDE DIGIT
SELECT/STORE IN SELECT

SKIP ID AND ATA
OLD ALTITUDE LABEL

NEW ALTITUDE LABEL

OLD AIRSPEED LABEL

NEW AIRSPEED

MOAR

BRXO'F

JPLS

MDAR

MDXO

JPLS

JUMP'I

OLD ALTITUDE

NEW ALTITUDE

OLD AIRSPEED

NEW AIRSPEED

NWALT: MDAR'F 100.

MPYL ALTD3

BRMD LDALT

ARBR'F MDAR'F 1000.

MPYL ALTD2

NOOP

BRAE'F ARBR'F

MDAR'F 10000.

MPYL ALTD1

NOOP

BRAE'F ARLS

NOOP

ARM1 I WPTR1

ARM1 MDAR'F 10.

MPYL ASP2

BRMD LDASP

ARBR'F MDAR'F 100.

MPYL ASP1

NOOP

BRAE'F ARRLS

MDAR MDAE ASP3

ARLS 19.

MDAR WPR16

ARM1 WPR16

BRAE'F HN'F

MPYI 21471

NOOP

MDAE'F HN'F 24340

STORE TEST ALT LABEL

STORE ALT IN FT B16

STORE ALT B16

STORE TEST AIRSPEED LABEL

AIRSPEED IN KNOTS B29

SHIFT TO B10

ALT TO B16R

IAS TO MACH CONVERSION

SEE "ACSM2"
ARMD  WPI2M  IIAS IN KNOTS B10
MDAR  WPTEM  ICONVERSION B10
DIVU  WPI2M
NOOP  WPTEM  IMACH B0R
ARMD  WPTEM
BRAR'F  $SOUND
JPSR  $SOUND
ARAR'H'F  WPTEM
MPYL  WPTEM
NOOP  WPTEM
ARMD'B'I'X  WPTR1
MDAR  WPTR3
MDAS'F  4
ARMD  POINT
MDAR'I  POINT
ARMD  S632
MDAR  LDASP
MDBR  SPDXY
JPSR  $LABRT
S632:
JUMP'I  S63WP

POINT:
0
READ DISCRETE 4/D INPUTS FROM "ACSM2"

S60WP:
MDAR  $S6IX0
ARBR'H'F  4
ARRS  [S6(15) 1ST IN BR
BRBR'B'F  [S6(25) LAST IN AR
MDAR' A  [S6(16) 1ST IN BR
ARLS  MSK3
ARMD  WPSel
[MULTIPLY BY 4
BRAR'K'F  [0,4,8,...
ARMD  SELST
ANAR  [STORE = +GARAGE,
JPSAN  SELECT = -. 1ST PASS?
MDAR'N  SELEC
MDAR'N  [YES, COMPUTE
MDAR  SELST
[NO, THEN FLAG = NEG
ARMD  FLAG
ARMD  S60WP
ARMD  S60WP
FOR STORING.POS FOR
JUMP'I  NEXT SELECT

SELEC:
ARMD'N  FLAG
ARMD  WPSel
MDAR  WPID0
MDAS'F  SLPTR
MDAR'I  [SELECTED STORED WAYPOINT
JPSAN'I  S60WP
ARAR'B'F  RETURN IF NONE STORED
MDAS'F  SELST
MDAS'F  ELSE 2X'S WAYPOINT
VLST  PLUS VLST
MDAR  POINT
MDAR'I  [GIVES POINTER TO
MDAR  WAYPOINT X,Y VALUES
ARMD  WFX
MDAR'I'X  POINT
ARMD  WPY
<table>
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<tr>
<th>Instruction</th>
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[FOLLOWING S/R DOES ENTIRE VERTICAL SLOPE CONTROL AND SETS VALUES INTO BE USED IN MXASP AND MNASP]

PROFL:

<table>
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<th>Instruction</th>
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</table>
PRO1: ARMD $PPP [WAYPOINT Y VALUE
MDAR =P Y
ARMD $QQQ
JPSR $DISTC [IN "FNST2"
ARMD STAGE [DISTANCE TO W.P. B23
MDAE' L [SUBTRACT DECELERATION
STG3L: -91940.1K [DISTANCE
JPN SEC3 [LENGTH OF DESCENT PATH
MDPN SEC2
JPN SEC2
SEG1: ARMD STG1 [DIST TO GO IN LEVEL FLT
ARMD'O SEGIF
JUMP'I PROFL
[IN SEG 2 COMPUTE THE DESCENT REQUIRED TO PLACE AIRCRAFT ON SLOPE (AFTER 32 SECONDS OF TRAVEL (NO WIND)

SEG2: MDAE SLOPE [SLOPE DISTANCE B23
ARLS 3 [TO B20R
ARBR'F [COMPUTE REQUIRED ALTITUDE
MDAR'N $VT [32X'S VEL.B10 = B15
ARRS 5 [SHIFT TO B20
BRAE'F [SLOPE DIST REMAINING
ANAR ZERO [OR ZERO IF NONE
ARAR'H'N'F [AFTER 32 SECS
MPYU TANSL [COMPUTE ALT REQ AT THAT TIME
MDER $RB16
ARLS 2 [SHIFT TO B16
BRMD INITZ [CHANGE INITIAL ALTITUDE
MDAE'N FINZ [+(-FINAL) = -REQ IN 32 SEC
BRAE'F [ADD CURRENT =ALT TO LOSE
ARLS 2 [IN 32 SECS TO B14/32 = B9
ANAR ZERO [PREVENT CLIMB INDICATION
ARM'D VERGR [COMMAND DESCENT FT/SEC B9
ARM'D'O SEG2F
JPSR VBUGC
JUMP'I PROFL
SEG3: MDAR STAGE [REMAINING DISTANCE IN
ARMD STG3 [WHICH TO CHANGE SPEED
ARM'D'O SEG3F
MDAR FINZ
ARM'D INITZ [FIX INITIAL ALTITUDE
JUMP'I PROFL

LINEARIZED MINIMUM AND MAXIMUM AIRSPEED CALCULATION
FOR ANY ALTITUDE IN AR (B16)
MAX = 517 - .1124 H H ABOVE 25K  MIN = 155 + .0055 H  ALL H
H = 517 + .0084 (H-25K) BELOW 25K

MIMAS:
ARMH MMALT [ALTITUDE IN AR B16]
MIMAP:       63625 [-25000 FT B16]
ARMH MIMA1
MIMA1:       67551 [-.0024 KTS = -.004 FT/SEC]
MIMA1:       36700 [.0089 KTS = .015 FT/SEC B-6R]
MIMA2:       33243 [MAX KTS = 874 FT/SEC B10]
MIMA2:       22712 [RETURN MAXIMUM IN BR]
MIMA2:       10137 [155 KTS = 262 FT/SEC B10]
MIMA2:       155 [RETURN MINIMUM IN AR]

MIMA3:
MIMA4:       2052 [COMMAND DESCENT]
MIMA4:       4125 [LESS THAN 2000 FT/MIN?]
MIMA4:       10.0 [L.T. 2000+4000 FT/MIN]
MIMA4:       180. [ELSE LIMIT ROTATION]
MIMA4:       2.7 [TO 100 (METER PEGGED)]
MIMA4:       90 [DEG]

MIMA5:
MIMA6:       2546 [PER FT/SEC]
MIMA6:       1263 [ADD OR SUBTRACT]
MIMA6:       90 [33.3 FT/SEC]
MIMA6:       90 [DEPENDING ON SIGN]
MIMA6:       1.35 [OF V2]
MIMA6:       90 [LIKEWISE ADD OR SUB.]
MIMA6:       180 [90 DEGREES]

MIMA7:
MIMA8:       1263 [LIKEWISE ADD OR SUB.]
MIMA8:       90 [90 DEGREES]
MIMA8:       1263 [LIKEWISE ADD OR SUB.]
MIMA8:       90 [90 DEGREES]

MIMA9:
MIMA10:      1263 [LIKEWISE ADD OR SUB.]
MIMA10:      90 [90 DEGREES]
MIMA10:      1263 [LIKEWISE ADD OR SUB.]
MIMA10:      90 [90 DEGREES]

MIMA11:
MIMA12:      1263 [LIKEWISE ADD OR SUB.]
MIMA12:      90 [90 DEGREES]
MIMA12:      1263 [LIKEWISE ADD OR SUB.]
MIMA12:      90 [90 DEGREES]

MIMA13:
MIMA14:      1263 [LIKEWISE ADD OR SUB.]
MIMA14:      90 [90 DEGREES]
MIMA14:      1263 [LIKEWISE ADD OR SUB.]
MIMA14:      90 [90 DEGREES]

MIMA15:
MIMA16:      1263 [LIKEWISE ADD OR SUB.]
MIMA16:      90 [90 DEGREES]
MIMA16:      1263 [LIKEWISE ADD OR SUB.]
MIMA16:      90 [90 DEGREES]
171

NEGBR:  BRBR'N'F
NEGAR:  ARAR'N'F
ZERO:   0
NZERO:  -0
FLAG:   0
PTAFL:  -0
ITERF:  -0
ITERC:  0
SEGIF:  0
SEG2F:  0
SEG3F:  0
PROTT:  0
STRBF:  -0
CLKF:   -0
SDISF:  -0
MINS:   0
WPTEM:  0
WPTR1:  0
WPTR2:  0
WPTR3:  0
WPTR4:  0
WPASP:  0
WPALT:  0
WPATA:  0
ASP1:   0
ASP2:   0
ASP3:   0
ALTD1:  0
ALTD2:  0
ALTD3:  0
ATA1:   0
ATA2:   a
ATA3:   0
WPR16:  0
WPI2M:  0
LDALT:  0
LDASP:  0
WPSEL:  0
SELST:  0
TANSL:  65521H
COTSL:  46121H
INITZ:  0
FINZ:   0
FINTM:  0
FINAL:  0
FINAS:  0
WPIX:   0
WPIX:   0
STAGE:  0
STG1:   0
STG2:   0
STG3:   0
SLOPE:  0
DCDST:  0
TOLER:  800.1K
REACT:  2000.1K
ACCEL:  70001H
DECEL:  70001H
SPSET:  0
CNDSP:  0
ASD:    0

BRBR'N'F
ARAR'N'F
-0
-0
-0
-0
-0
-0
-0
0
0
0
0
0
0
0
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0
65521H
46121H
0
0
0
0
0
0
0
800.1K
2000.1K
70001H
70001H
0
0
0
VERGR: 0
VERRT: 401H
CHNGR: 11H 25252
ERROR: 0
90DEG: 90.1H
DF1: 0; DF2: 0; DFT: 0
MMALT: 0
SUM: 0
TAU1: 0; TAU1S: 0
TAU2: 0; TAU2S: 0
SIZE: 0
IREPEAT
IREPEAT
NN\TM\MM: 0
ENDI
IREPEAT
MM\(0,3)\]
NN\AS\MM: 0
NN\AS2: 0
ENDI
NN\AVE: 0
NN\SLZ: 0
NN\TIM: 0
NN\TA: 0
NN\ASF: 0
FIN\NN: 0
ENDI
HIBND: 0
LOBND: 0
DATA BLOCKS
VLST:
-195520.1K [X LOCATION (GARDNER)]
180140.1K [Y LOCATION]
-110908.1K [(PROVIDENCE)]
-153054.1K
-25344.1K [(ACTON)]
114816.1K
40000.1K [(WHITMAN)]
-62345.1K
DLST: IREPEAT
NN\(0,1)\]
-0 [X OFFSET (151H XXXXX)]
161H 0 [Y OFFSET
MD05 ID\NN
MD05 ALT\NN
MD05 SP\NN
MD05 TIM\NN
MD05 TRNGL
ENDI
REFERENCES


