REPORT NO. DOT - TSC - FAA - 71 - 3

A CONCEPTUAL NETWORK MODEL OF THE AIR TRANSPORTATION SYSTEM

THE BASIC, LEVEL 1 MODEL

AUREL N. de HOLLAN ARTHUR S. PRIVER

TRANSPORTATION SYSTEMS CENTER
55 BROADWAY CAMBRIDGE, MA 02142

APRIL 1971

TECHNICAL REPORT

Prepared for

FEDERAL AVIATION ADMINISTRATION
WASHINGTON, D. C. 20590

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Conceptual Network Model of the Air Transportation System. The Basic, Level 1 Model		5. Report Date April 1971
		6. Performing Organization Code
7. Author(s) Aurel N.de Hollan, Arthur S. Priver		8. Performing Organization Report No. DOT-TSC-FAA-71-3
9. Performing Organization Name and Address U.S. Department of Transportation, Transportation Systems Center, Cambridge, Massachusetts 02142		10. Work Unit No. R1034, R1102
		11. Contract or Grant No. FA-06
12. Sponsoring Agency Name and Address Federal Aviation Administration, Washington, D.C. 20590		13. Type of Report and Period Covered Technical Report
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A basic conceptual model of the entire Air Transportation System is being developed to serve as an analytical tool for studying the interactions among the System elements. The model is being designed to function in an interactive computer graphics environment which permits rapid alteration of rules and parameters, as well as continuous real-time graphical monitoring of system operations. The model described here is the first member in an evolving hierarchy of increasingly complex models, progressing in the direction of closer approximation to the real-world Air Transportation System.

17. Key Words	18. Distribution Statement
. Conceptual Transportation Systems Model .Flight Simulation .Input Package .Output Package	Unclassified-Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	44	

CONTENTS

LIST OF FIGURES

ACKNOWLEDGEMENTS

The authors are thankful for the many helpful comments on the original manuscript which the following individuals have so freely offered: from T.S.C., Mr. Calvin H. Perrine, Jr., and Mr. Laurence O. Higgins, both of S.A.; from the F.A.A., Mr. Simon Justman, RD-610. Virtually all of their comments are reflected in this report. The authors are further indebted to Messrs. Higgins and Justman for countless hours of patient instruction and indoctrination which they provided on all aspects of the Air Traffic Control System. Without this invaluable background information the model reported herein could never have been formulated. Finally, a special debt is acknowledged to Mr. Eugene M. Darling, Jr., T.C.D., T.S.C., who performed the laborious task of piecing together and editing the manuscript.

1.0 INTRODUCTION

An overall conceptual network model of the entire Air Transportation System is being developed for use in analyzing System performance in response to a variety of operating rules, control procedures, network configurations, and aircraft distributions. The model consists of: an Input Package for defining the data and parameters; a Flight Simulation Package to move planes through the system; an ATC (Air Traffic Control) Simulation Package to control the movements of the aircraft; and an Output Package to compute performance measures and to handle graphics displays. The model described here is the first (and most basic) member in an evolving heirarchy of increasingly complex models. We will refer to this first attempt as the Level 1 model.

Many features of the current real-world Air Transportation System have been incorporated in the Level 1 model. Those features which are not included would only serve to clutter this first model with unnecessary detail. However, these missing features can readily be included in Level 2 and future models as the need for them becomes apparent. There are many potential applications of the Level 1 model which are discussed below in detail.

In its present form, the model allows the user to analyze a problem quickly and easily. Experience with this first model will provide insight into both its strengths and weaknesses and, more importantly, will point the way to future upgrading of the model in the direction of a more meaningful analysis of the real world. Communication with the model occurs via interactive computer graphics which provides the user with a natural and easy means for setting up the problem, watching the system in action, changing parameters, and gathering performance statistics.

1.1 OPERATION OF THE MODEL

The model permits the user to define an arbitrary network configuration, consisting of a set of terminals and navigational aids with specified airway geometry connecting them. Various sectors may be defined for air traffic control purposes, and hand-offs of flights passing from one sector to another are included. All altitude levels may be used by aircraft flying in the system and standard vertical and horizontal separation criteria for low-level and high-level (or jet) routes are incorporated.

For simplicity, the Level 1 model is restricted to aircraft operating under Instrument Flight Rules (IFR). In addition, it is assumed that the positions of all aircraft in the system are displayed on air traffic controllers' radar scopes which are the controllers' primary information source. Furthermore, all flights in the system conform to schedules (which may be defined by the user for each terminal). Multiple flights may be scheduled for departure at the same time at one terminal. These flights are then sequenced according to the characteristics of the terminal being used, taking into consideration the number of incoming flights and the rules governing aircraft separation in the terminal area. Only Standard Instrument Departure (SID) routes are used by the aircraft. This restriction simplifies the problem of determining potential conflicts in the vicinity of terminals.

Upon arrival in a terminal area, aircraft are placed in arrival queues and must follow Standard Approach Routes (STAR's) when landing. Aircraft are handed off between terminal area controllers and enroute controllers at predetermined boundary crossing times.

Flights are continuously updated while in progress and search logic in the Air Traffic Control (ATC) simulation detects projected, or actual, violations of the separation rules. A timing control cycles through the simulated aircraft in either real time or event time. In real time mode the position of each aircraft is updated at every clock cycle. In the case of event time the clock is turned forward to the next event in a single step. Potential flight delays are considered and all aircraft are advanced. The need for special action is checked.

Some air traffic controller functions are incorporated into the model, including communications between aircraft and controllers during handoffs and conflict resolution. A priority list of situations requiring controller attention is generated.

Measures of system performance are calculated while the model is in operation. These include controller workload, average time in arrival queues, average departure delay, system response time etc. The system in action is portrayed on interactive graphics displays in a form which is both realistic and readily understandable. In particular, areas of congestion or potential hazard can be immediately seen. Moreover, the model is designed to be useable by people without computer programming experience.

1.2 APPLICATIONS OF THE MODEL

The model may be used to analyze many different Air Transportation System concepts and to examine their effects on all components of the system. The interactive nature of the system is especially useful in this context.

For instance, we could analyze problems associated with airway width. In particular, we can measure the number of potential conflicts encountered on airways of various widths. Techniques for predicting capacity limitations in sector operations can be evaluated. Also, we may wish to consider the lengths and number of messages received and transmitted by the sector controller as a factor limiting the number of aircraft in the sector.

The manner in which aircraft are advanced through the system, and the number and types of delays encountered in this process, can be analyzed. The major bottlenecks in the system could thus be pinpointed, as well as the capacities of various segments of the system. Congestion and sector workload problems could be studied.

A sensitivity analysis of the separation rules could be performed. For a given network configuration and aircraft schedule, the altitude separation rules could be altered, as well as the longitudinal separation rules, both enroute and in the terminal area. The performance of the system and the number of potential conflicts could be measured under various types of rules.

The model may be used to examine metering and sequencing in the Air Transportation System. The traffic levels can be analyzed in the various parts of the system.

The NAS Stage A enroute features could be studied in terms of improvement in system operations, increased capacity, and enhanced safety. System changes could be incorporated into the model and various performance measures obtained.

A conflict analysis might be performed in which various measures of actual and potential conflicts are examined. For our purposes a conflict is a violation of the separation rules. Several threshold levels for determining potential conflicts (i.e. situations that are not conflicts but might develop into conflicts) may be considered, as well as weighted measures reflecting how closely different aircraft approach one another.

Controller workload could be analyzed, albeit in a restricted sense. One might assume that workload is some function of the number of messages received and transmitted, the number of potential conflict situations handled, the number of hand-offs completed, the total traffic flow in a sector, etc.

An analysis of route structures could be made by changing the configuration of the network while keeping the same general schedule of aircraft. The effects on system congestion and controller efficiency of adding or removing different airway segments could be measured by analyzing the traffic flow and controller actions in the modified system.

The model also allows the user to analyze the impact on the system of new types of aircraft (such as the SST). This can be easily done by entering the characteristics of the aircraft into the model. With the new type of aircraft introduced, it would then be possible to measure conflict potential, traffic flow, and the other aspects of the system by exercising the model and comparing "before" and "after" results.

The above is not an exhaustive list of applications for the Level 1 model. It is, rather, a representative list of typical problems which could be solved. We expect that other similar applications will suggest themselves and that these can be handled either directly by the Level 1 model, or by making minor modifications thereto.

1.3 LIMITATIONS OF THE MODEL

The Level 1 model does not include all features of the current Air Transportation System. The missing features are omitted to reduce the complexity of the first level model. It is a simple matter to expand the model to add any desired feature.

Specifically, VFR flights are excluded from the model, initially, since they do not comprise a significant proportion of the scheduled air carrier traffic, nor does the ATC system exert as much influence on them as it does on IFR flights.

Non-radar areas are excluded from consideration because different separation rules apply in these regions. No non-scheduled flights are permitted in order that identical schedules may be used in different runs of the model.

Missed approaches are ignored, simply as a matter of convenience. They are also quite rare. Also, no special emergency situations are considered in the system.

Trans-oceanic flights are excluded because of the different separation rules for such traffic. No random direct route features are considered by the Level 1 model.

Sectorization is accomplished by drawing a straight line sector boundary. Thus the number of sectors into which the simulated enroute airspace can be divided is four; two high altitude and two low altitude sectors.

Flight tracking is not implemented. Instead, all aircraft are assumed to be following their assigned fixed routes which are limited to defined airways. There is no distinction made between low-level and high-level sectors. Also, no low-level/ high-level altitude handoffs are permitted in the system. Transponders are not modeled and flight strip generation is not considered in detail.

1.4 ORGANIZATION OF THIS REPORT

This report is divided into six sections: An introduction (section 1.0), a section for each major portion of the model, namely; 2.0 Input Package, 3.0 Flight Simulation, 4.0 ATC Simulation, 5.0 Output Package and a final section on Model Implementation (section 6.0). The model is depicted as a flow diagram in Figure 1, with the major portions surrounded by dashed lines. Each section begins with a detailed block diagram of the portion of the model treated therein. These diagrams show all inputs and outputs; the flow of data and control; and the logical functions performed.

All sections contain several subsections, each of which describes the functions performed by one of the boxes in Figure 1. Boxes are referred to by their numeric code. Extensive cross-referencing has been used to facilitate understanding of the relationship between model components.

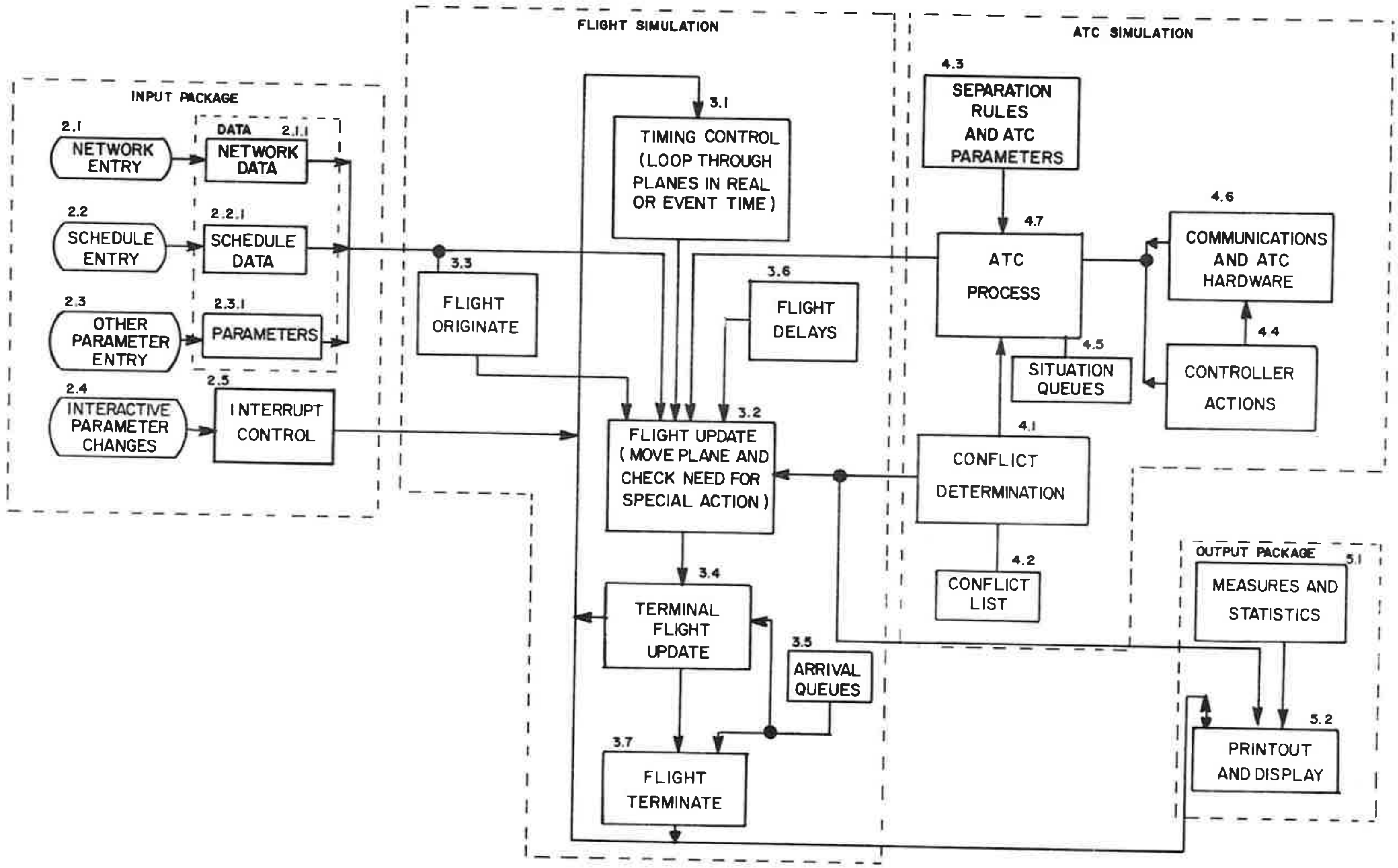

Figure 1.- Air Transportation System Network Model-Computer Program Outline

2.0 INPUT PACKAGE

The Input Package is invoked by means of a data tablet which is used to enter terminals, navigational aids, and sector boundaries at desired positions. The characteristics of different types of aircraft may also be entered as well as a schedule of flights in the network. For example, a variable traffic load of mixed aircraft types can be imposed on a variable network of multi-level airways interconnecting at least 20 terminal areas.

The Input Package consists of both functions and data as follows:

Functions	Data
2.1 Network Entry	2.1.1 Network Data
2.2 Schedule Entry	2.2.1 Schedule Data
2.3 Other Parameter Entry	2.3.1 Parameters
2.4 Interactive Parameter Changes	
2.5 Interrupt Control	

2.1 NETWORK ENTRY

The Network Entry Module permits the user to specify an air transportation network consisting of airways, navigational aids (Navaids), terminals in arbitrary combination and geometry, and ATC sectors. The network is entered by means of an input data tablet, a keyboard, and a graphical display. The capacity of the Level 1 model is 20 terminals, 20 Navaids and 64 airways.

A terminal is defined by a 3 character identifier, such as BOS, and its geographic position. A navigational aid is similarly specified, together with its channel frequency. An airway is defined by its identification code and its component segments connecting terminals and/or navigational aids. Since entry of a complex network involves a fair amount of labor, provisions exist for storing networks on disk and for recalling them when needed.

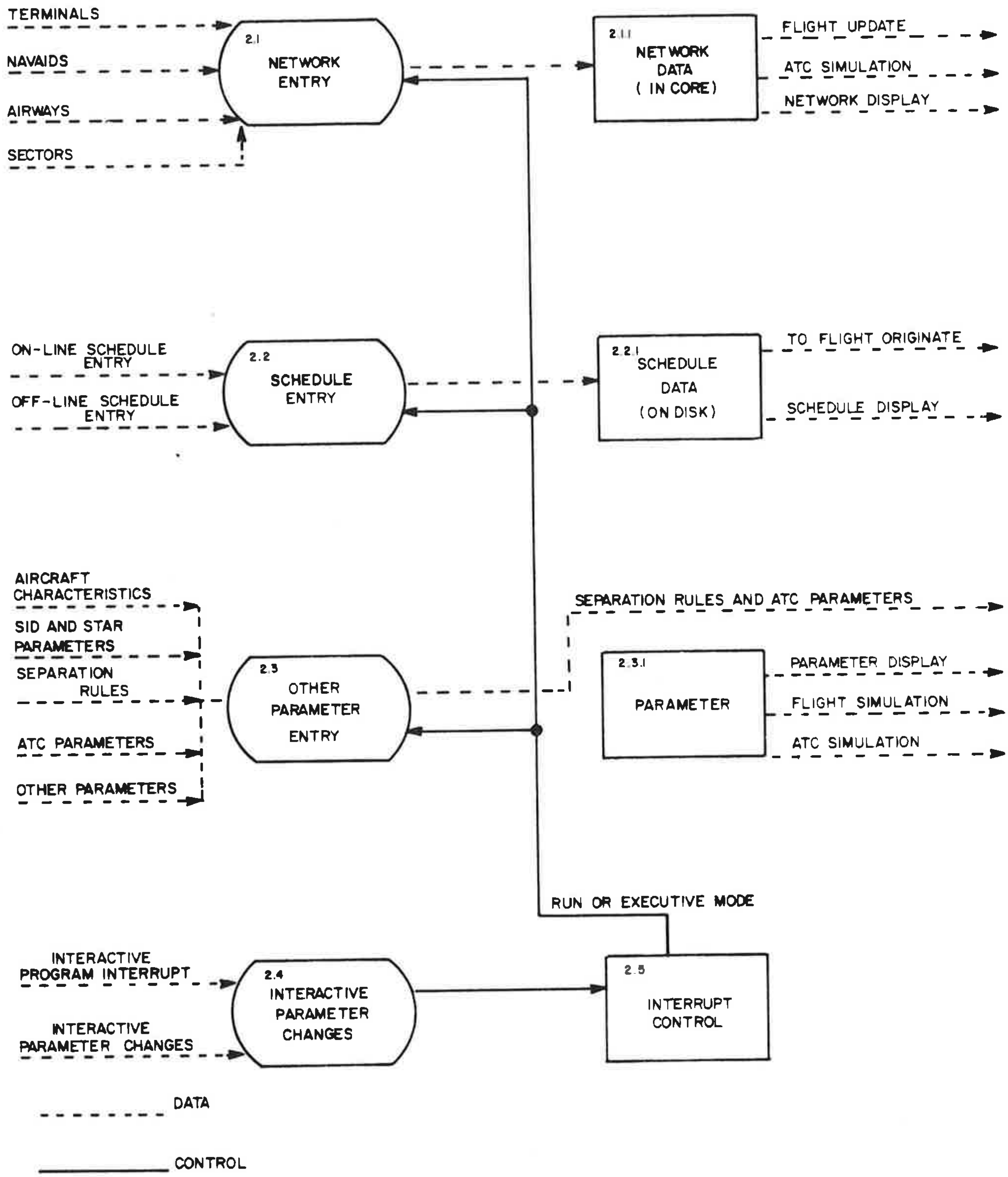

Figure 2.- Input Package

2.1.1 Network Data.- The Network Data Module consists of four parts: Terminal Data, Navaids Data, Airway Data, and Sectorization Data.

2.1.1.1 Terminal Data.- For each terminal there is an internal data block containing the following information:

(a) Name of the terminal (3 characters).

(b) Geographical x location with respect to some origin (nmi).

(c) Geographical y location with respect to the same origin (nmi).

(d) A pointer to the list of airways connecting with this terminal.

On the scopes, a terminal symbol and the ID code are displayed at the appropriate location.

2.1.1.2 Navigational Aid Data.- For each NAVAID there is a data block representing the following:

(a) Name of the Navaid (3 characters).

(b) Geographical x location in nmi from same origin.

(c) Geographical y location in nmi from the same origin.

(d) Frequency.

(e) A pointer to the list of airways passing over the Navaid.

A Navaid symbol and ID are displayed on the scopes at the appropriate location.

2.1.1.3 Airway Data.- For each airway there is a data block containing the following:

(a) Identifier (e.g. V94 or J3).

(b) Initial terminal or Navaid.

(c) Second terminal or Navaid.

(d) Length of the first segment of the airway (nmi).

(e) Angular (magnetic) leading of the first segment of the airway (degrees).

(f) Third terminal or Navaid.

(g) Length of the second segment.

(h) Angular heading of the second segment

. . .

m. Last terminal or Navaid.

m + 1. Length of the last segment.

m + 2. Angular heading of the last segment.

m + 3. End marker.

An airway is drawn as a sequence of line segments connecting terminals and/or Navaids, tagged with the identifier.

2.1.1.4 Sectorization Data.- It will be possible to draw a straight line dividing the network into two sectors. The parameters defining the sector boundary (end points of the line) are recorded.

2.2 SCHEDULE ENTRY

The Schedule Entry Module imposes a schedule of IFR flights upon the network. The schedule is composed of a series of flights. The basic elements of a flight plan are entered for each scheduled flight. Thus, a flight is represented by: an identifier (e.g. TW 538); the aircraft type (e.g. 4 engine jet transport); a takeoff time; a route representing the network airways to be travelled; and an arrival time at the destination point. Schedules may be entered interactively (using the keyboard and the tablet); prepared off-line and read in via paper tape; or saved and recalled from disk. Schedules may also be read from magnetic tapes (such as those in use at the ARTCC's) and converted into the proper format for saving on disk. All flights originate and terminate in the model. Up to 128 flights may be active (take off, land, or be airborne) at any one time.

2.2.1 Schedule Data.- The schedule data entered is immediately sorted with respect to scheduled departure time and put into a list of flights. Each flight entry contains the following data items:

(a) Identification number (e.g. TW 538)
(b) Type of aircraft.
(c) Point of departure.
(d) Proposed departure time (in Zebra time).
(e) Destination.
(f) Estimated arrival time.
(g) An arbitrary number of airway segments to be followed and desired altitudes on each segment.
(h) End marker.

A special routine will allow the display of scheduled flights originating from, or terminating at, any given airport.

2.3 OTHER PARAMETER ENTRY

2.3.1 Parameters.- The Other Parameter Entry Module is used to interactively enter those parameters which are required in addition to network, terminal, and schedule parameters.

The following parameter classes which are under consideration will be entered in the Parameter Module:

(a) Aircraft Characteristics: An aircraft characteristics table of the following form will be used in the model:

AIRCRAFT CHARACTERISTICS TABLE

Characteristic	4 Engine Jet	Short Haul	Jumbo Jet	SST	Gen. Av
Takeoff Speed (kts)	140	125	150	170	95
Landing Speed (kts)	120	110	130	160	85
Climb Rate (ft/min)	3500	2500	2200	5000	1000
Descent Rate (ft/min)	3000	2200	2200	4000	1000
Cruise Speed (kts)	470	410	500	1200	160
Approach Speed (kts)	150	140	160	190	100
Acceleration (kts/sec)	1	1	1	1.5	.75
Deceleration (kts/sec)	.75	.75	.75	1.0	.50
Turn Rate (deg/sec)	3	3	3	3	3

(b) Separation Rules: Typical separation rules are 3 nautical miles (nmi) separation between aircraft on the same altitude level within 40 miles of a radar center and 5 nmi separation beyond 40 miles. Altitude separation of 1000 ft. is required for low-level flights below 18,000 ft., and 2000 ft. for high-level flights above 18,000 ft. There are also terminal area separation rules such as no two aircraft may be on the same runway at the same time, and a departing aircraft may takeoff only if any approaching aircraft is at least 4 miles from the end of the runway.

(c) Delays: The intervals of time required for different types of controller functions, and message times of the communication system can be specified.

(d) Internal Simulation Parameters: The time increments τ for the simulation, the display frequencies, the frequency with which statistics are gathered, and a parameter to slow down the simulation may all be specified for the system.

2.4 INTERACTIVE PARAMETER CHANGES

The simulation model will have two modes of operation: run mode and executive mode. In run mode the model will be in full operation with aircraft being flown in the network simulation, controller actions occurring, statistics being gathered, etc. The run mode is the basic operating mode of the system.

The executive mode is a control mode in which all action in the model is frozen. At such a time the user may add to, update, or change parameters using the Interactive Parameter Changes Module. The following kinds of changes can be made:

(a) Networks may be altered - modes and links may be added and/or deleted.

(b) Terminals may be changed by deleting and/or adding runways.

(c) Schedule entries may be deleted or new flights may be added using the methods outlined in section 2.2 Schedule Entry. In executive mode the value of any parameter can be updated, be it an aircraft characteristic, a separation rule, or an internal simulation parameter.

The user has the ability to validate the input data before starting, or resuming, the running of the model. To switch from run mode to executive mode, or vice versa, a simple keyboard command is given by the user.

2.5 INTERRUPT CONTROL

The simulation will have two modes, run mode and executive mode, defined in section 2.4 Interactive Parameter Changes. In run mode, control is through the 3.1 Timing Control Routine which calls various other routines necessary for the simulation.

In executive mode the system waits for parameters, schedules, terminals, network entry, or output. To go from executive to run mode, a RUN command is typed which starts the simulation with current parameters and current (if previously interrupted) time.

3.0 FLIGHT SIMULATION

A timing control in the Flight Simulation Package cycles through the aircraft in either real time or event time. (In the case of event time the clock is stepped forward to the next event such as the beginning of the next leg of a flight or the entry into the terminal phase in a single step.) Flights due to depart are entered into the system and all flights are updated. Potential flight delays are considered and all aircraft are moved. The need for special action is checked. Aircraft due to land are placed in arrival queues under control of the terminal flight update procedure.

Functions performed by the Flight Simulation Package are:

3.1 Timing Control
3.2 Flight Update
3.3 Flight Originate
3.4 Terminal Flight Data
3.5 Arrival Queues
3.6 Flight Delays
3.7 Flight Terminate

3.1 TIMING CONTROL

This routine provides the time increments required for simulation. Its functions are as follows:

(a) Increment time by τ which is specified in section 2.3 Other Parameter Entry.

(b) Call 3.3 Flight Originate to see if it is time for a new flight to take off. If so, implement the takeoff procedures.

(c) Loop through all active flights and call the 3.2 Flight Update routine for each.

(d) Furnish the time of day to the ATC and Output Routines.

(e) At intervals specified by a parameter entered in

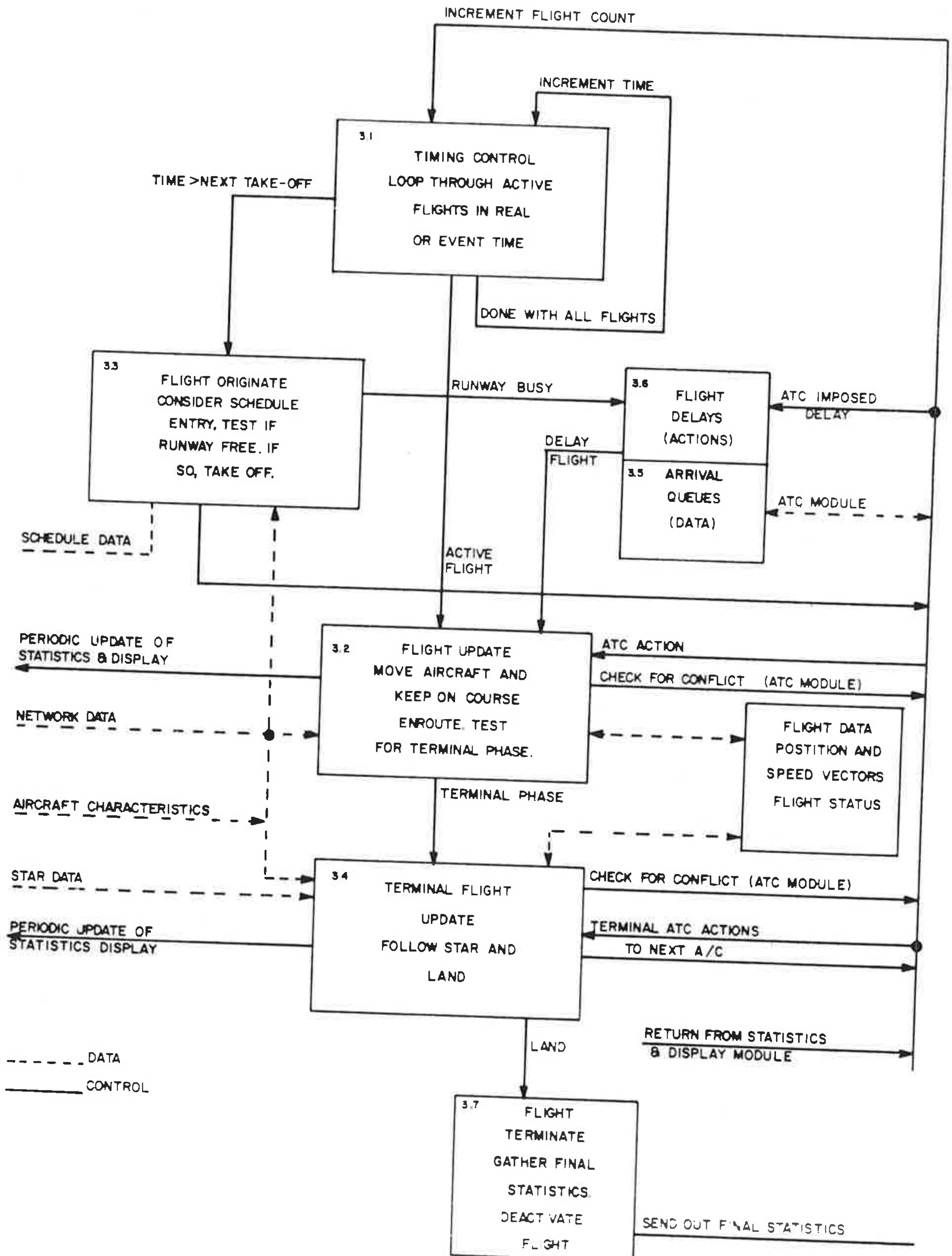

Figure 3.- Flight Simulation Module

2.3 Other Parameter Entry, call the printout and display routines to output the current status of the system.

The model may also be run in an "event time" mode in which step (a) is eliminated. In its place, the clock is turned forward in a single step to the next event (e.g. a scheduled departure or the arrival of an aircraft at the end of an airway segment). All aircraft are moved in the system to the positions they should occupy at the time corresponding to the event. Steps (b)-(e) are pre-scanned to establish the earliest next event. This mode of operation is faster from the point of view of gathering statistics, but would tend to produce jerky motion of the aircraft on a graphics display.

3.2 FLIGHT UPDATE

This routine is called to move the planes in the simulated network (enroute phase) and to check the need for special actions.

The following data block will be internally maintained for each active flight:

- (a) Identification.
- (b) Pointer to a schedule entry which contains route and scheduled times.
- (c) Pointer to the aircraft characteristics list, giving the aircraft type.
- (d) The current longitudinal x coordinate in the system.
- (e) The current longitudinal y coordinate in the system.
- (f) The current altitude level.
- (g) The ascent/descent rate.
- (h) Turn rate (degrees/sec).
- (i) Velocity (direction and magnitude).
- (j) The next node (terminal or Navaid identifier).
- (k) Actual departure time.

(l) Deviation from pre-computed schedule (delay).

(m) Desired altitude.

(n) Desired heading.

(o) Desired speed.

The routine will iterate the position of the aircraft assuming present velocity, turn rate, and climb rate. Instantaneous velocity changes are permitted. X, Y, and Z deviations from standard airways occur due to maneuvers made in entering airway segments and also due to Navaid errors. When the desired heading and altitude are reached, turn rate and climb rate are set to zero. After each iteration, the routine calls the 4.1 Conflict Determination Routine which checks whether the extrapolated flight path of the aircraft creates a conflict. If so, the ATC Simulation Module is invoked to resolve it.

If the iterated configuration indicates that the flight is ready to land (i.e. terminate), control is handed off to the 3.4 Terminal Flight Update Routine. If the aircraft is approaching the next check point of its flight path (end of an airway leg) a maneuver is set up if necessary to enter the next leg.

The normal exit of the 3.2 Flight Update Routine is back to the 3.1 Timing Control Routine.

3.3 FLIGHT ORIGINATE

The Flight Originate Routine shall perform the following functions:

(a) Take the time generated by the 3.1 Timing Control Routine and test it against the sorted schedule data to see if there is a departure scheduled.

(b) If there is a departure scheduled: specify the airport, check for runway availability at the airport. If there is no available runway, delay departure.

(c) If there is a free runway, put the aircraft at the end to the runway, after a fixed taxi delay, and initiate take off. Utilize the appropriate aircraft takeoff speed and climb rate.

(d) After takeoff, free the runway.

(e) Use the aircraft characteristics (i.e. takeoff speed, climb rate, turn rate, and acceleration) to determine the time required to negotiate the Standard Instrument Departure (SID) path which the aircraft is constrained to follow. Conflict prediction is performed during the departure phase.

(f) After the aircraft enters the first airway segment of its trip, its departure phase is terminated.

3.4 TERMINAL FLIGHT UPDATE

The Terminal Flight Update Routine is quite similar in structure to 3.2, the (enroute) Flight Update Routine, with the main difference being that more frequent controller actions are required, not so much for collision avoidance, as for vectoring. Thus, there is associated with each terminal approach a table of rules which specify actions to be executed at specific fixed points along the Standard Approach Routes (STAR's).

Thus a typical terminal flight update might proceed as follows:

(a) Iterate to a new aircraft position, considering x, y location, velocity, altitude, turn rate, and climb rate.

(b) Check the position of the aircraft against the STAR to determine if a maneuver is necessary. If so, execute the maneuver.

(c) As the aircraft nears the terminal area, see if a STAR and corresponding runway are available. If they are, have the aircraft follow the STAR, then call the

3.7 Flight Terminate Routine. If they are available, place the flight in an arrival queue until it is able to complete its landing.

(d) Go to 4.1 Conflict Determination to ascertain whether the extrapolated flight path of the aircraft would result in a situation requiring controller action (i.e. a potential conflict).

3.5 ARRIVAL QUEUES

For each terminal, an Arrival Queue is maintained containing entries for all flights that are arriving at that terminal. A flight is inserted in the appropriate arrival queue when it enters the terminal airspace of its destination terminal. This entry is maintained until the flight is terminated. An arrival queue entry will contain the identifier of the flight, a pointer to the flight data block (see 3.2 Flight Update), the status of the flight (proceeding, holding, final approach, etc.), and the estimated time of arrival. There is a sub-queue for each possible independent approach path (i.e. STAR). Flights are sorted in the queues, with the flight nearest to landing being entered at the top of the list. The characteristics of these queues will provide a primary measure of how well the ATC system can handle the traffic load imposed upon it.

3.6 FLIGHT DELAYS

If a delay is to be of at least two minutes duration, the aircraft is normally placed in a standard racetrack holding pattern. However, in this model delays are represented by stopping the aircraft in mid-air. This is done for programming convenience and is unlikely to affect the conclusions derived from running the model. In exiting from a delay in which an aircraft has been halted in this manner, the speed shall be instantaneously reset to the value it had immediately prior to stopping.

One delay list will be kept which records the time deviation of each flight from the scheduled time (i.e. the "trip" delays). A second list will contain all the controller imposed delays (i.e. the "individual" delays). Both lists will be regularly transmitted to the 5.1 Measures and Statistics Module. The sum of these two delays is stored in item (1) of the 3.2 Flight Update data block.

3.7 FLIGHT TERMINATE

Flights are terminated by going through a final approach routine followed by a landing routine, both of which require that the aircraft execute a rigid set of maneuvers defined by the STAR. After landing at a particular terminal, a delay factor (the "runway occupancy time") is imposed before releasing the runway and calling the flight "terminated".

The Flight Terminate Routine gathers the final measures and statistics for the flight and relays this information to the Output Package. The routine also frees that flight's data block in storage for use by a new flight.

4.0 ATC SIMULATION

The ATC Simulation Module imposes a simple air traffic control system upon the Flight Simulation Module. The purpose of this ATC Simulation Module is to ensure orderly and safe traffic in the simulated flight system. Orderliness is accomplished through the implicitly modeled flight tracking function and through the handoff procedures which take flights from takeoff through terminal airspace to enroute airspace to terminal airspace and landing. Safety considerations are introduced into the model by defining certain situations as inherently unsafe (as in the real ATC system). Procedures and control mechanisms are instituted to correct these unsafe (i.e., conflict) situations when they occur.

The ATC Simulation Module operates as follows: The 4.1 Conflict Determination routine interacts with the 3.2 Flight Update and 3.4 Terminal Flight Update routines to determine whether the extrapolated positions of active aircraft would result in conflicts. (Conflicts are precisely defined in section 4.3 Separation Rules and ATC Parameters.) These extrapolated (potential) conflicts, as well as actual conflicts, are kept in the 4.2 Conflict List. The 4.7 ATC Process Supervisor Routine picks up the potential conflicts (and handoffs as well), stores them in the 4.5 Situation Queues and hands them to the 4.4 Controller Functions Module, as action situations to be evaluated. Corrective measures are instituted, if required, by the 4.6 Communications and A.T.C. Hardware Module. This activity, in turn, alters the paths of aircraft in the Flight Simulation Module, thereby closing the ATC feedback loop.

4.1 CONFLICT DETERMINATION

The purpose of the conflict determination routine is to determine, for each simulated aircraft, whether the path of the

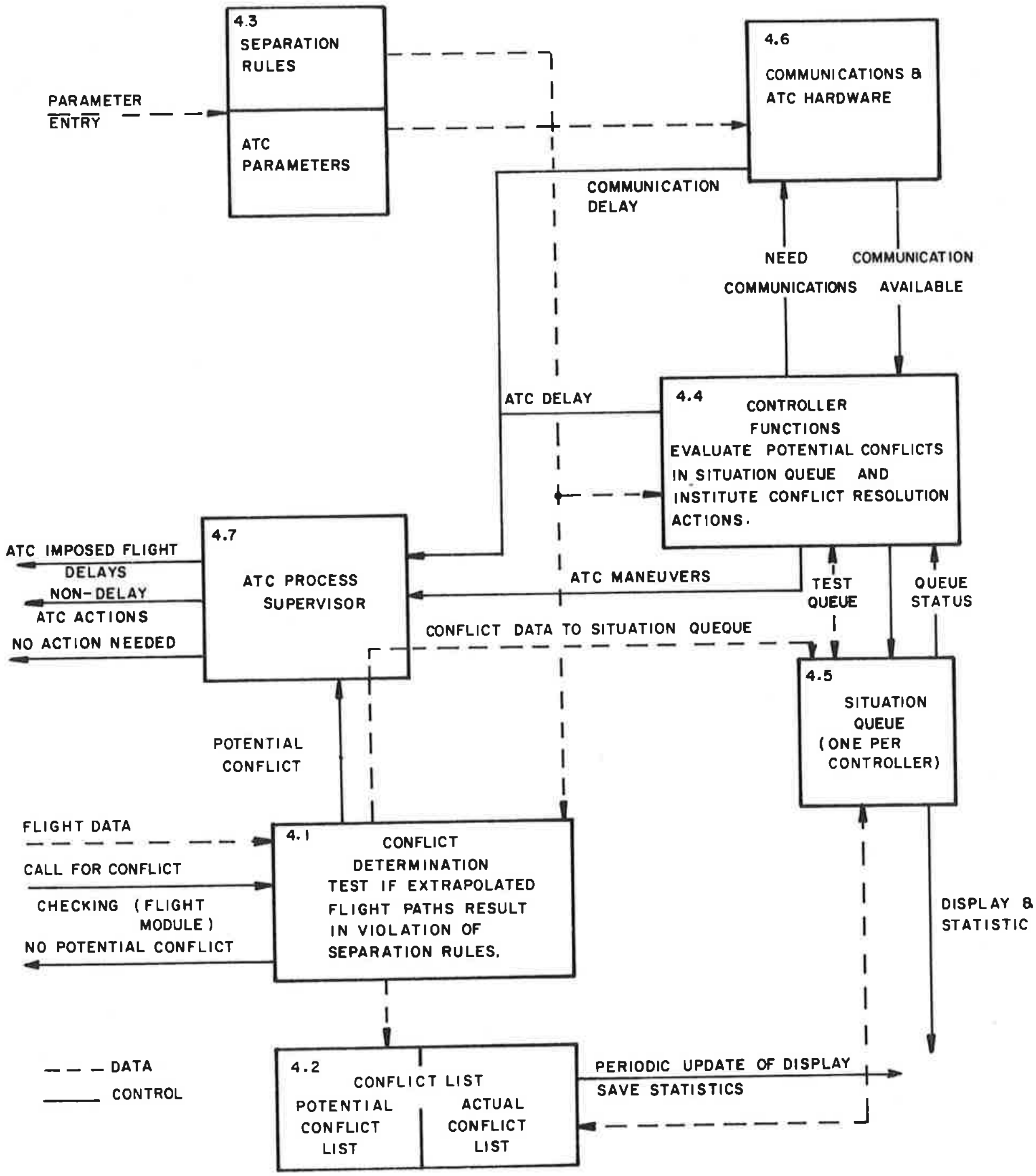

Figure 4.- Traffic Control Simulation Module

aircraft (as extrapolated by the system) results in a conflict situation. A conflict is defined as a violation of the 4.3 Separation Rules. Conflicts as recognized in the Level 1 model fall into 5 categories:

(a) Head On: two aircraft are converging head on at the same altitude level and on the same airway. The extrapolated paths meet in 10 minutes flying time or less.

(b) Overtaking: two aircraft are traveling in the same direction at the same level on the same airway, separated longitudinally by 10 minutes or less.

(c) Intersection: two aircraft are on the same altitude level and their extrapolated paths intersect in 10 minutes or less, or they are separated laterally by less than 5 nmi.

(d) Ups and Downs (or altitude crossing): an aircraft going from one altitude level of an airway to another (airway levels are separated by 1000 ft below 18,000 ft, 2000 ft above 18,000 ft) crosses a level on which there is another aircraft 10 minutes longitudinally or 5 nmi laterally separated from the crossover point. Also, two aircraft, one ascending and one descending, may come into conflict as described above.

(e) Terminal Area: conflicts of the above four types may occur in the terminal area, except that different separation rules apply within 40 nmi of the terminal.

Note that all the conflict types involve only two aircraft. Multi-aircraft conflicts are not defined per se, but will show up as several two-aircraft conflicts.

At each time slice in the simulation, the conflict determination routine checks whether any aircraft in flight

(e) SID's and STAR's: The minimum longitudinal separation of aircraft on SID's and STAR's shall be 2 minutes flying time beyond the outer marker, 30 seconds inside the outer marker.

The many exceptions and special rules used in normal ATC procedure are not considered.

4.3.2 ATC Parameters.- There are many parameters involved in the operation of this model. They are defined and discussed in the appropriate sections of this report. The analyst running the model shall have an opportunity to vary these parameters (e.g., controller response time or aircraft climb rates), as well as the separation rules, in performing sensitivity analysis. One important set of parameters, not discussed elsewhere, is the limits the analyst may impose on the maximum allowable number of planes in a sector, in the total simulation, or in a holding pattern. Such limits are roughly tantamount to the imposition of flow control on the system.

4.4 CONTROLLER FUNCTIONS

In this model ATC controller functions are simulated by a computer program requiring no intervention on the part of the analyst who is running and observing the simulation. The model addresses itself to the gross functional aspects of the controller's activity as he endeavors to ensure safe, orderly, and expeditious traffic flow. However, the model does not contain the many detailed controller actions. These actions are aggregated into delays for purposes of the Level 1 model. There are 3 enroute sector controllers and up to 20 terminal controllers in the model, so that several handoff functions can be handled in parallel with several conflict determinations if the need arises.

4.4.1 Types of Controller Functions.- The model specifically enacts the three* functions of handoff, conflict detection, and conflict resolution, which we consider to be the principal controller functions. The following is a detailed description of these functions and the situations causing them:

(a) Handoff

A handoff is defined as a change in controller jurisdiction over a flight. Five types of handoff situations are considered: enroute sector boundaries, enroute to terminal transition, terminal to tower control transition, tower control to terminal ATC transition, and terminal ATC to enroute transition. In the Level 1 model we do not consider low to high altitude handoff situations.

The model will represent a handoff by introducing a work interval during which the controller will be considered busy, and hence not available for any other functions. The model will try to make the controller free, and thus able to pay attention to the handoff early enough to avoid holding of a flight. However, for various reasons, flight holding may still occur. Whenever this happens the holding situation will be recorded and later incorporated in the holding statistics. These holding statistics will be one of the important measures of system performance.

Handoffs will also involve communications and attendant delays which are discussed in the communications section.

---

*The flight following function is not explicitly modeled because it is assumed that an aircraft normally maintains its flight plan. However, delays in controller performance have been introduced to take into account, implicitly, those functions (such as flight following) which are not modeled explicitly.

The following table shows an example of delays to be encountered as a function of the situation queue of the controller:

Work Interval and Delay
Handoff Table

Handoff Type	Number of Situations in the Queue 1	2	>2
Enroute Sector	10 sec	20 sec	40 sec
Enroute-Terminal	20 sec	30 sec	50 sec
Terminal-Tower	5 sec	10 sec	15 sec
Tower-Terminal	5 sec	10 sec	15 sec
Terminal-Enroute	20 sec	30 sec	50 sec

Notice that the handoff times increase with the situation queue size which is a measure of controller workload.

(b) Detection of Potential Conflicts

The algorithm which detects potential conflicts is the 4.1 Conflict Determination Routine. Here we discuss what the simulated controller does when it detects one of the four basic types of conflict (overtaking, head-on, crossing, or ups and downs).

(1) The potential conflict is added to the end of the controller's situation queue which is a table (one for each controller) containing all the current tasks the controller has to perform. The simulated performance of each task entails a delay (including human factors) which may be different for the enroute and terminal phases - e.g., typical delays would be 6 seconds enroute, 10 seconds terminal.

(2) If the controller is busy with other tasks he may not be alerted to the potential conflict in time to prevent an actual conflict from occurring.

(3) Once the simulated controller is alerted to a potential conflict it then assesses (i.e., this step corresponds to the human controller taking a sharp look and interpreting what he sees) whether the situation will actually result in a conflict. If not, that situation is deleted from the list of current action situations. If there is a threat of conflict the situation must be resolved, hence a request for immediate conflict resolution (see the next section) is placed on the top of the controller's situation queue. The delay for situation assessment is a variable parameter (perhaps 15 sec in the terminal phase and 30 sec enroute might be appropriate).

(c) Coordinated Resolution of Potential Conflicts
Requests for resolution of threatening conflict situations will always occur at the top of the situation queue, thus the controller must immediately pay attention to them. A logic menu is constructed, listing each type of conflict, the conditions in the conflict region (i.e., whether or not adjacent levels or airways are occupied), the resolution, and the delay due to controller action in making and executing the decision. Communication delays associated with such actions are considered in section 4.6 Communications and ATC Hardware.

The algorithms for diverting aircraft in conflict are described below. The resolution of each conflict requires a certain time interval which must be specified.

A. Head-On (2 aircraft at the same altitude):

A-1 Next airway below is free: divert the aircraft heading north or east down to the nearest level below.

A-2 Airway level below is busy, next airway above is free: divert the aircraft heading south or west up to the free airway level.

A-3 Both airway levels directly above and below are busy: divert one aircraft off course until the two aircraft pass one another, then resume navigation.

B. Overtaking (2 aircraft at the same altitude): Situations B-1 and B-2 are the same as A-1 and A-2, respectively, and have the same conflict resolution procedures.

B-3 Slow down the overtaking aircraft.

B-4 Divert the overtaking aircraft and vector it around the slower one.

C. Crossing (aircraft at the same level, paths cross):

C-1 One of the two airway levels directly above or directly below any of the aircraft is free. Move the appropriate aircraft to the free airway level. If there is more than 1 free level choose by lot.

C-2 If there are no free levels, turn one aircraft until it is no longer converging. Five minutes later turn it back on course. If the above action causes another conflict, divert the second aircraft.

C-3 One aircraft may be placed into a holding pattern for the duration of an even number of minutes greater than 4. For the purposes of modeling ease, aircraft in holding patterns are stopped.

C-4 If actions C-1, C-2, C-3 would all result in another conflict we assume that controller saturation has been reached.

D. Overtaking Conflicts Near a Terminal: To resolve overtaking conflicts on the standard instrument approach and departure paths in the terminal area, slow down the overtaking aircraft to 10 kts below the speed of the overtaken one if the conflict occurs more than 20 nmi from the terminal; or to the speed of the overtaken aircraft if less than 20 nmi from the terminal.

E. Ups and Downs: If an aircraft is scheduled to cross an altitude level on which another is flying and also to cross, overtake, or meet the other aircraft head-on, a so called "ups and downs" conflict occurs. Resolution is as follows:

E-1 Cause the aircraft(s) changing altitude to stop ascending or descending (but otherwise proceed on course) for a period of 2 minutes, after which test again for a potential conflict.

E-2 If one aircraft must cross the level of another in order to land, place it into a holding pattern until the other aircraft is out of range. Test every 2 minutes (a variable parameter) for a potential conflict.

4.5 SITUATION QUEUES

A Situation Queue (one per controller) is an ordered data list containing an entry for each situation (handoff or potential conflict) which requires the attention and possible intervention of the controller. An entry contains the following information: the identifier(s) of the aircraft involved; current position, altitude, and velocity in system coordinates; the projected time and system coordinates of the handoff or expected conflict; and the situation type.

When a new action situation arises, it is placed at the bottom of the situation queue and must wait in the queue until

5.0 OUTPUT PACKAGE

Measures of system performance are calculated by the Output Package. These include controller workload, average time in arrival queues, average departure delay, etc.

Functions of the Output Package are:

5.1 Measures and Statistics

5.2 Printout and Display

5.1 MEASURES AND STATISTICS

This routine compiles the values of certain model variables that are required to analyze system performance. These variables fall into two categories: instantaneous values or measures that present the status of the model at a given time; and statistics which include integrated and averaged values and distributions. Statistics are continually generated. They may be obtained at any time by interrupting the simulation and calling for a printout of statistics or results in the executive mode (see section 2.4 Interactive Parameter Changes). This action generates output for the period from the beginning of the simulation run to the point of interruption. After the printing of statistics, the simulation run may be continued. It should be noted that, while the model is stochastic in nature, runs are nonetheless *exactly* repeatable. This is achieved by resetting the initial random number (controlling the random number generator) to the value it had at the beginning of the run which one wishes to repeat.

The following is a list of instantaneous measures constantly monitored in the Level 1 model.

5.1.1 Flight Simulation Load

(a) The number of aircraft (total) in flight.

(b) The number of aircraft in each sector.

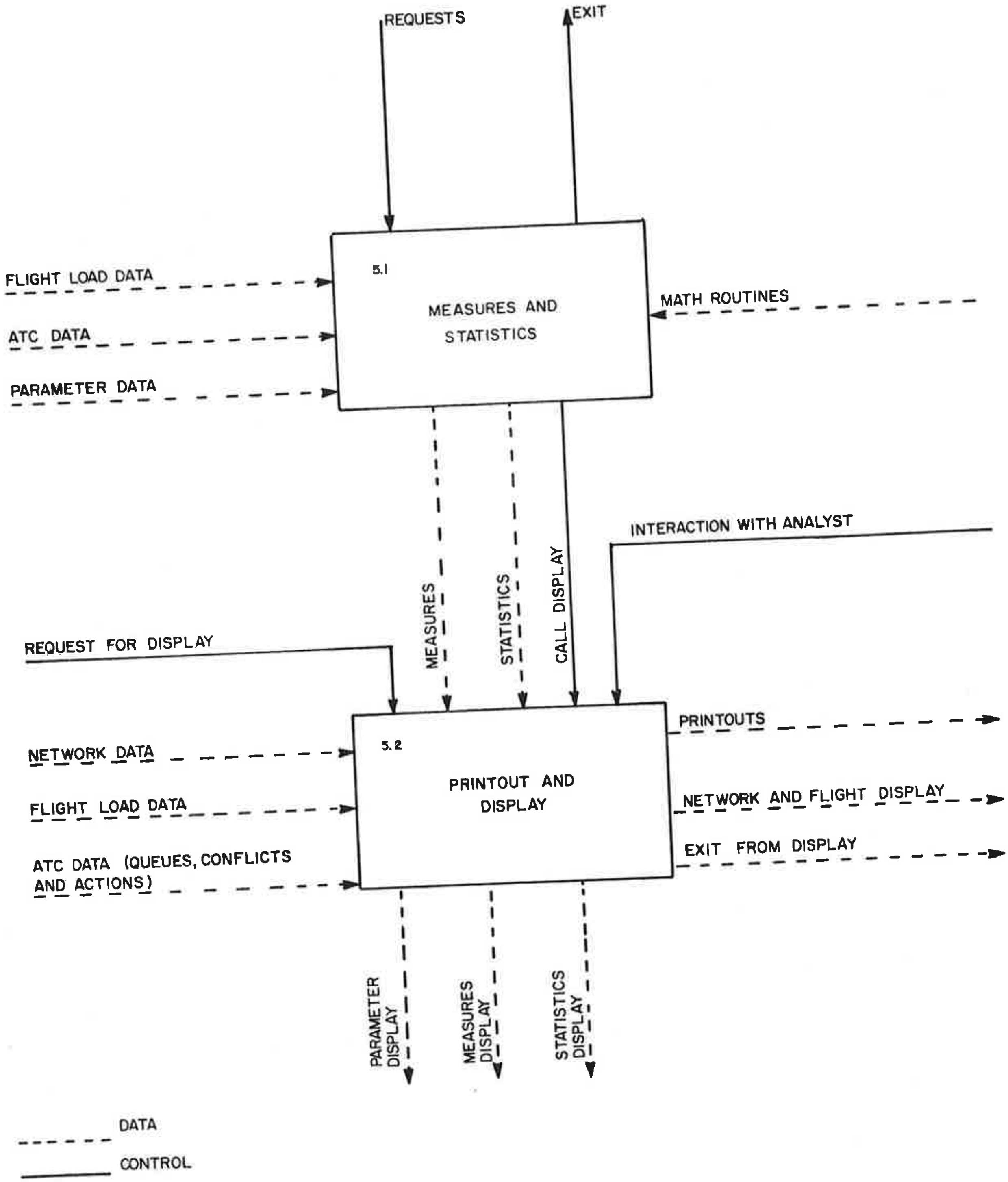

Figure 5.- Output Package

6.0 MODEL IMPLEMENTATION

The model is being implemented on a Honeywell DDP-516 computer. The installation is described in detail in the following write-up of the Transportation Animated Graphics (TAG) System. Briefly, the system has a memory of 16,000 16-bit words, a teletype, a 10-head disk drive, a magnetic tape unit, a 300 line per minute lineprinter, two Vector General graphics display consoles, a Rand Tablet, and a switchbox. The model is written in macro assembly language and it occupies 24,000 bytes of core storage.

6.1 THE TAG SYSTEM

The TAG (Transportation Animated Graphics) System is an interactive man-machine computer-driven assemblage of displays and peripheral input/output devices capable of dynamically representing transportation system models and simulations in action. This System is located in the Data Technology Branch where it is used to dynamically display simulations of traffic flow in the air, on the ground, or at sea. The TAG System (shown in the attached block diagram) consists of the computer (in red), the display controller and consoles (in blue), and the peripheral input/output devices (in orange).

The computer system is a Honeywell DDP-516 which drives both TAG and TRIM (TRansportation IMagery), a computer controlled flying-spot scanner used to automatically identify traffic in aerial photographs. In the TAG System the display controller interfaces both consoles and peripherals to the computer. The primary TAG output devices are the display consoles which are high quality CRT's on which both text and complicated moving images can be drawn. The CRT's are not of the storage type, but rather are refreshed from display files so that dynamic displays can be readily generated. A multi-console system is used to simultaneously display several aspects of a model. For instance, one scope might show cars moving along a network of

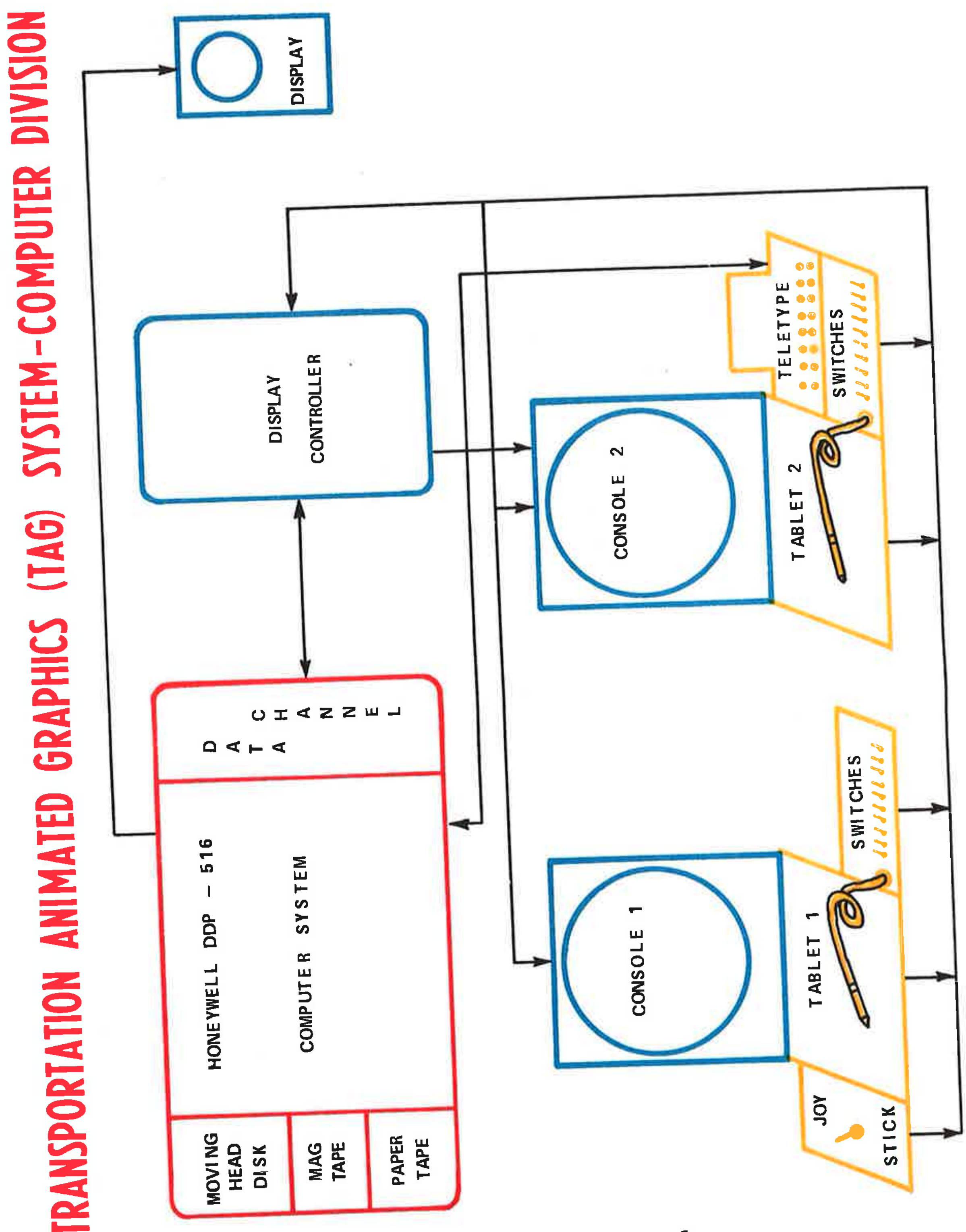
TRANSPORTATION ANIMATED GRAPHICS (TAG) SYSTEM-COMPUTER DIVISION
DISPLAY
DISPLAY CONTROLLER
HONEYWELL DDP - 516
COMPUTER SYSTEM
DATA CHANNEL
MOVING HEAD DISK
MAG TAPE
PAPER TAPE
CONSOLE 2
TABLET 2
TELETYPE
SWITCHES
CONSOLE 1
TABLET 1
SWITCHES
JOY STICK

Figure 6

roads while the second scope could list traffic parameters and statistics in alphanumeric form. In another simulation, the two consoles may display the air traffic which controllers in adjacent sectors see. The goal of such a simulation might be to develop novel manual, semi-automated, or fully automated handoff strategies, and to analyze the effect of each on airway capacity or collision probability.

The TAG System incorporates a variety of peripheral input/output gear which facilitates on-line human interaction with the simulation. The teletypewriter is used both for input to the computer and for hard-copy output. A light pen will be available to enter inputs directly on the CRT face. The operator will also have a data tablet for use in entering or selecting information to be displayed. A joy stick will provide the capability to simulate driving a car or flying a plane. Switch boxes will be available for use in simulating control functions. The TAG System will eventually be upgraded by adding: (1) Two or more display consoles which will be interfaced to the original display controller, (2) a graphical hard-copy system for pictorial output.

The TAG System design permits rapid reconfiguration of the user station to suit many different applications. For instance, in highway traffic modeling the user station may consist of two display scopes and a tablet placed in a well lit office. Such a station might appeal to highway designers and urban planners. For an air traffic simulation, all devices could be grouped close together in the laboratory where, initially, the scopes might show what a traffic controller sees, but at the flick of a function switch one of the displays could show what a particular pilot sees, and the joy stick would be brought into action. To summarize, the TAG system provides a highly versatile input-output capability, appropriate for almost every conceivable transportation simulation task.