could directly assess several aspects of the model's performance by inspecting the graphic output. Numerous errors were detected in this way that might not otherwise have been caught.

In developing the algorithms, it was found that the ability to program interactively gave greater flexibility in modifying the models and encouraged more experimentation. It was not necessary to submit a program and let the machine grind away. Execution could be interrupted at any time, intermediate output could be examined, and data or programs could even be modified before operation continued. Many ideas could be tested in the time needed for a single run of a conventional model. In addition, the power of APL enabled dealing with networks as matrices and vectors without having to program tedious intermediate steps and do-loops. The algebra of the problem could be dealt with almost directly rather than having to translate the mathematics into a computer language.

ACKNOWLEDGMENT

All model development work was accomplished on an IBM 370/158 computer at the Interactive Computer Graphics Laboratory (ICGL), Princeton University. All programming was done interactively by using VSAPL computer language under a virtual machine configuration that had the conversational monitor system. All figures were drawn by using assembler language drawing functions developed by the ICGL staff. Curve plots used functions of the LINPLOT package developed by Tom Hahn and Yehonathan Hazony of the ICGL. I wish to thank Granville Paules, Linda Moore, and Robert B. Dial of the Office of Planning Methods and Support, Urban Mass Transportation Administration, for their assistance in obtaining support for this research. This research was performed under a research, development, and demonstration grant from the Urban Mass Transportation Administration, U.S. Department of Transportation.

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Use of Computer Graphics to Analyze Navigational Performance and Jet-Route Separation

DALE LIVINGSTON, EDWARD J. KOBIALKA, AND NEIL W. POLHEMUS

Formulation of jet-route separation standards to achieve adequate levels of safety requires careful analysis of aircraft navigational performance. In the processing and analysis of extensive data obtained from the continental U.S. air traffic control (ATC) system, computer graphics techniques were used to develop a clean data base, to provide descriptive summaries of achieved navigational performance, and to portray the relationship between collision risk and track-system geometry. This paper describes these applications and their importance in ATC systems analysis.

As part of a general study of aircraft separation standards, the Federal Aviation Administration (FAA) has collected a large amount of radar data on aircraft navigational performance in the high-altitude continental U.S. jet-route system. These data were collected to serve as the empirical base for assessing the adequacy of current route-spacing criteria. In all, more than 10 000 flight records were collected along route segments in the Cleveland, Memphis, and Albuquerque air traffic control (ATC) centers.

The task of taking these data and using them to make recommendations regarding jet-route separation requires a careful step-by-step process of data verification, analysis, and interpretation. To assist in this process, FAA's National Aviation Facilities Experimental Center and the Department of Civil Engineering at Princeton University have relied heavily on the use of computer graphics. As described in this paper, the ability to portray interactively the recorded ATC environment and analytical results is essential to ensure a meaningful and useful analysis of methodologies for establishing separation standards.

Initially, the raw radar returns needed to be compiled into a data base representative of actual navigational performance along selected jet routes in the study area. To screen out aircraft that were not actually attempting to navigate along the routes--for example, those that had been given a direct clear, a holding pattern, or some other maneuver by ATC--visual inspection of the recorded tracks on an interactive graphics terminal proved to be invaluable. Summaries of daily traffic on selected routes were similarly generated, as will be described later.

It is of considerable interest to determine the likely explanation for the times when ATC did intervene in an aircraft's performance and the resulting consequences. To reconstruct the environment that surrounds a particular aircraft at a specified time, an interactive graphics technique was developed.

Several graphical procedures designed to provide descriptive summaries of observed navigational performance and also to refer aggregate performance to the current very-high-frequency omnidirectional radio-ranging (VOR) system-use accuracy standard are described. The important use of graphical display in guiding the estimation of lateral overlap probabilities is illustrated and, finally, a computer-generated movie that was developed to describe the modeling procedure for the case of intersecting jet routes is described. In each of these stages of the analysis, graphical display is crucial to ensure effective use of the mathematical results by those who eventually make the decisions.

QUALIFYING THE DATA

It is characteristic of any data collection that most of the data is useful and some is not. Of that which is useful, a portion requires special attention to render it acceptable. This data collection was no exception and certain graphical tools were designed and implemented in order to identify those data that required additional attention or deletion from the sample set. These tools proved to be valuable for indicating features of the data that may have been overlooked by summary processes or other attempts to estimate the character of the data through quantification. As used here, "qualification" of the data is a term that relates to the graphical methods used to examine data and determine suitability for the sample.

The raw radar returns used for estimation of aircraft position were collected from three separate radar sources. Given the error inherent in reporting radar position, the collation of these data required smoothing for accurate depiction of aircraft position. The smoothing technique chosen was a method of robust nonlinear smoothing tailored expressly for radar-derived data (1-4). Figure 1 shows both the raw and the smoothed radar data as plotted on a flat-bed plotter. The aircraft at the ends of the data trace indicate the direction of flight with respect to the route. The triangles represent the raw data, and the smoothed data points are connected by a solid line. Data traces such as these were produced in digital form for each of the 10 000 aircraft in the sample, but only those that reflected special circumstances were reviewed.

Figure 1 also provides an example of the robust performance of the smoother. This aircraft exhibits a standard delay tactic used by ATC; a linear smoother would not have been able to handle this situation but the smoothing technique used tracks the data well. Such a maneuver was not suitable for the description of aircraft navigational performance as considered in this study and would have been deleted from the sample after detection. Although it may have been possible to detect the tactic through other analytical techniques, it was easier to confirm the maneuver through this display.

Once a preliminary data base had been amassed, certain investigative techniques were used in order to delete from the sample those aircraft whose courses had been directly influenced by ATC. To provide the data used in this investigation, observers had been placed at each controller position during the data collection to provide a log of the aircraft sampled and voice recordings of the conversations between pilots and ATC. When initial screening of an aircraft's navigational performance indicated the possibility of direct intervention by ATC, another graphical aid was used. Figure 2 is a view of one such interrogation of the data base, copied directly from a cathode-ray tube (CRT) display. The information displayed on the screen shows the jet route and protected airspace, the position data trace, and the aircraft identification. The data block in the upper right corner identifies the aircraft and supplies additional information about the trace (from top to bottom): the aircraft identifier, jet route flown, VOR route segment displayed, beginning and ending trace times (in hours and minutes), aircraft beacon code, altitude (in hundreds of feet), and Julian date (the number of days elapsed in the year). The intended route of the aircraft and an area surrounding it known as the protected airspace relate the aircraft's track to the local control area.

After the data are presented on the screen, an analyst may use the terminal's crosshairs to identify portions of the smoothed aircraft trace for closer examination. By moving the crosshairs to a particular place on the data trace and pressing the return key, a small data block appears that contains the time at that position, the perpendicular distance to course (in nautical miles), and the distance to the nearest navigational aid (in nautical miles). Five such blocks are displayed in Figure 2. The ability to determine maximum excursion from course and the associated time, the point of initiation of a turn, or some other characteristic of the data trace and to compare the observed behavior with commands given by ATC proved to be a valuable supplement in the decision to retain an aircraft in the sample. Since the reduction of a voice-recorded tape (the next step in qualifying the data) meant many person hours of dedicated effort, the possibility of removing a candidate from the sample at this point saved a large amount of human resource for alternate analytical work.

As a further step in the analysis of the data, multiple aircraft traces were plotted on the same route to present a sample of aggregate navigation performance. Figure 3 is a presentation of multiple traces plotted on a single route in which the angular nature of signal propagation as well as other properties of navigational performance may be noted. This illustration presents a day's worth of aircraft traces plotted on the plan of the route and the protected airspace. The display presents a qualitative view of navigational performance as well as an idea of the proportion of aircraft that escape the protected airspace; this quantity is crucial to the evaluation of collision risk. General trends

Figure 1. Nonlinear smoothing of aircraft position data.

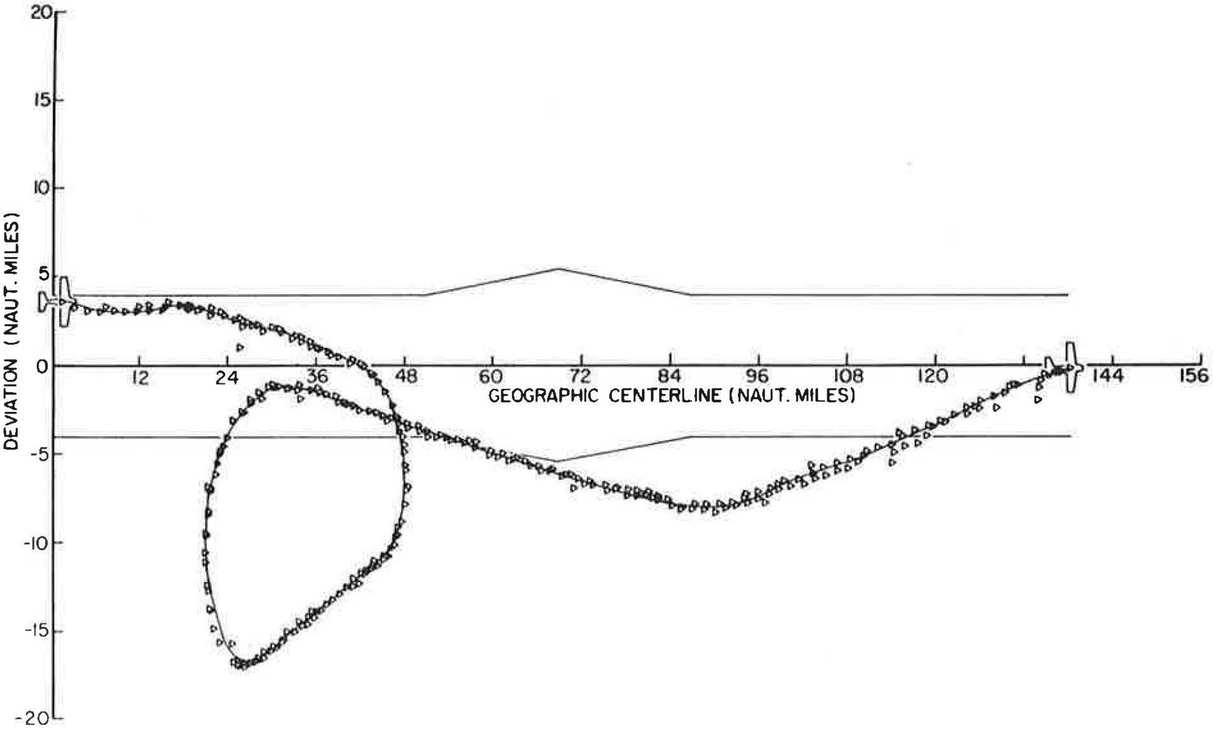
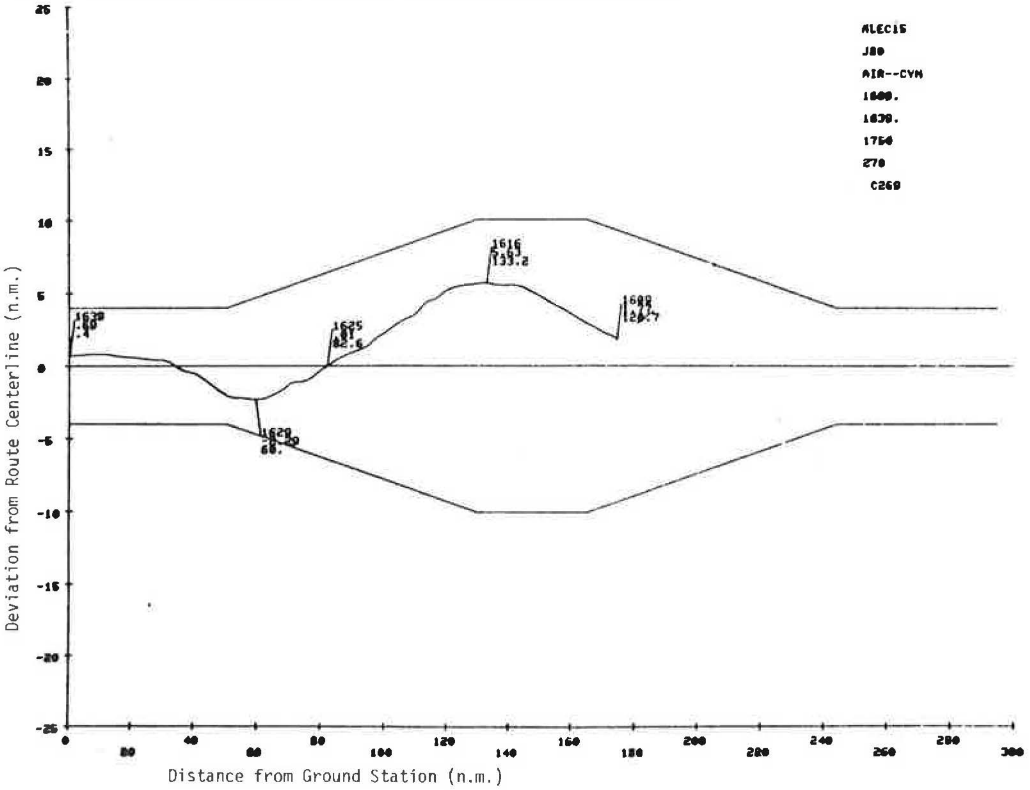


Figure 2. Trace of single aircraft that shows data blocks generated by interrogation.



and patterns associated with navigation performance in the aggregate become apparent after lengthy examination of multiple-trace plots for each route under consideration, which has allowed the study of daily trends in navigation performance and on occasion has uncovered meteorological conditions that affect other flights in the same time period.

Figure 4 shows an additional graphical tool

Figure 3. Multiple aircraft traces generated from fast-time data replay.

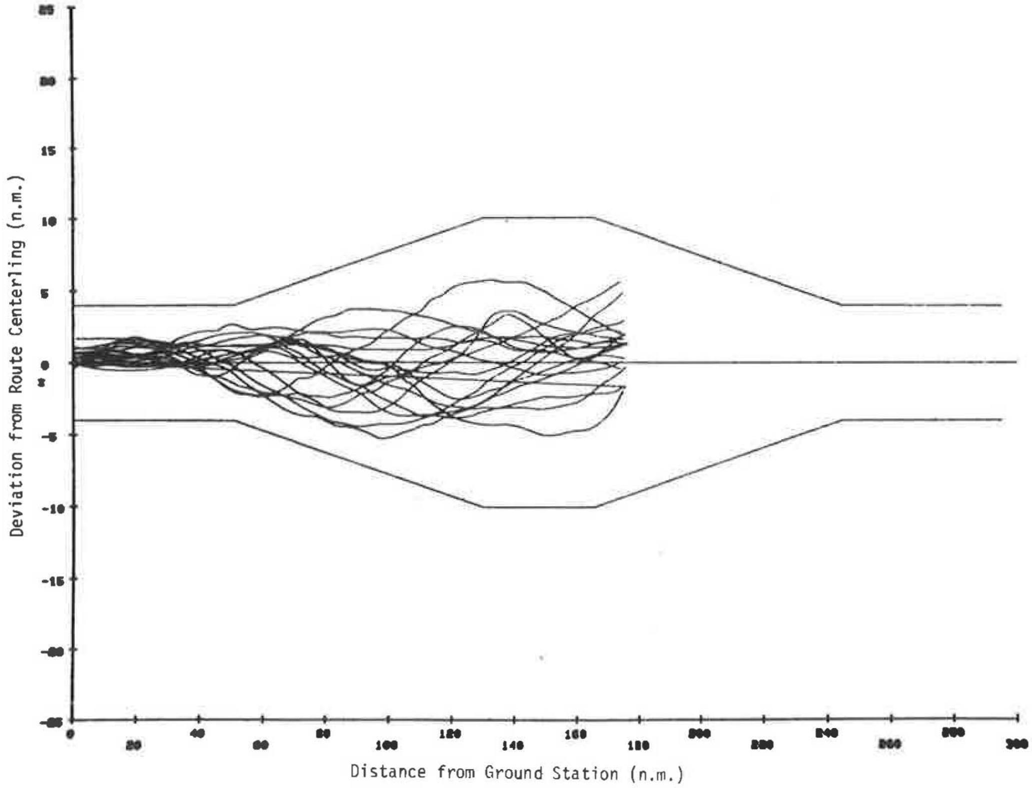
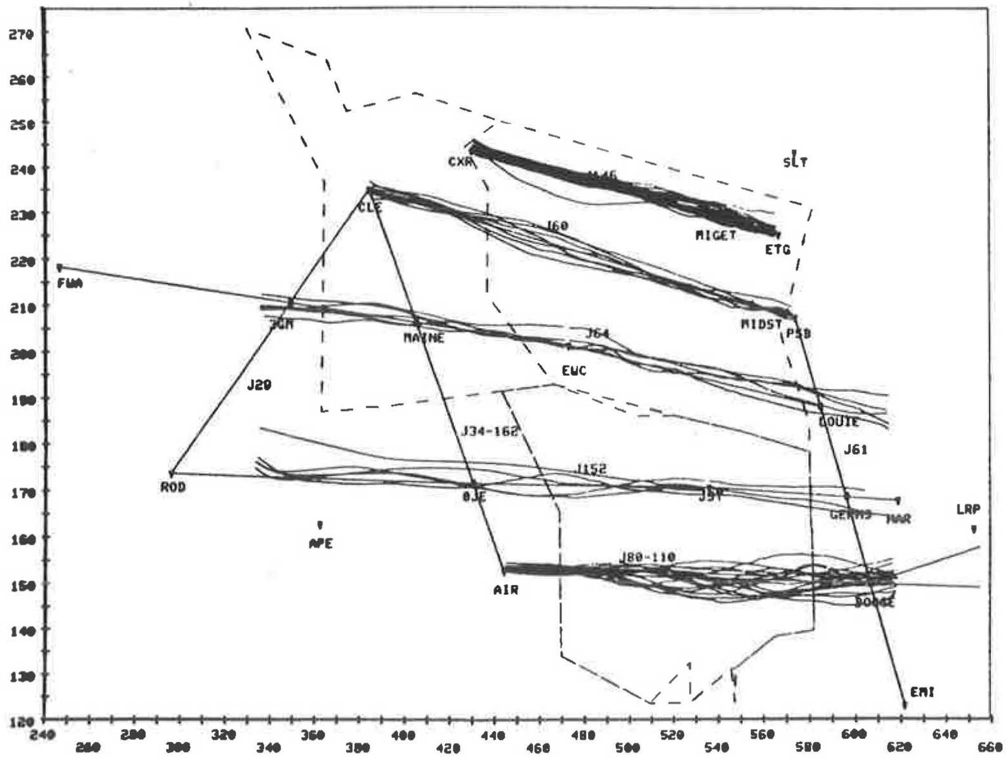


Figure 4. Representation of one day's sample plotted on the local control area.



designed to help relate aggregate performance on one route to that noted on adjacent routes in the same time period. The geometry of the local control area and the applicable routes is projected onto the screen and the analyst recalls an interval of time during which an event of interest occurred. The interaircraft dynamics of the situation may be observed to aid in determining those factors that may have influenced the aircraft's position with respect to the route. Again, a fast-time examination of the actual scenario that uses any number of aircraft may be portrayed. By allowing the field to be enlarged beyond the area of interest, certain anticipatory aspects of pilotage could be observed and analyzed. This analysis provided background for the explanation of observed behavior.

EXAMINING THE ATC ENVIRONMENT

Proximate trace plotter (PROXPLOT) is a FORTRAN program designed to examine the air traffic environment around a specified aircraft. Although previous data processing had proceeded with the goal of characterizing the navigation performance of selected aircraft with respect to their intended flight paths, a need to examine the traffic environment about an aircraft of interest was perceived. Satisfying this need would allow a more-thorough investigation of the possible impact of ATC or navigation errors on the safety of the system.

A graphical display of the ATC environment seemed to provide the most efficient way of transmitting this information. The initial concept called for software that would read a radar data record (RDR) tape and present radar position data on a CRT display; essentially it would play back the plan video display that had appeared at the controller's position. This concept was rejected as infeasible; hardware limitations prevented the presentation of such large amounts of data in a reasonable amount of time. These limitations lay not only in the graphic display, but also in processing time; an RDR tape contains raw radar data in an encoded format, and much processing must be done before the data can be effectively displayed.

These restrictions are circumvented by the design of PROXPLOT, which is in reality two separate programs. First, a file of data is collected by the program named PROXBOX, which operates under a batch monitor. The analyst specifies to PROXBOX a specific aircraft (the candidate) and a set of times that may be of interest. PROXBOX reads through the radar data and follows this particular aircraft as it flies through radar coverage. A proximity disk of specified radius and thickness is carried with the candidate aircraft; all other aircraft that enter this disk are noted along with the time and distance of their closest approach to the candidate. A hard-copy summary of these data is made available for analysis. Second, PROXBOX also acts as the data collector for the graphical display of PROXPLOT. At any set of times specified by the programmer, PROXBOX writes to disk file the current position of the candidate aircraft and any aircraft within its proximity disk as well as a short history (about 10 radar hits or approximately 1 min) of the preceding positions of all aircraft. It is this file that provides the data to be displayed by PROXPLOT.

Figure 5 is a copy of the display produced by PROXPLOT obtained from a xerographic copier connected to the CRT. The flight trace of the candidate aircraft is approximately in the center of the display area and is marked by a line of asterisks. The symbol ϕ next to the data point farthest on the right identifies the leading side of the trace (the most-recent data) and indexes the trace to the data block in the upper right-hand corner. This data block indicates the radar beacon code that identifies the aircraft, the last recorded flight level, the time of the last data point for that trace, and the x-coordinates and y-coordinates of the last point in that trace. The display area is automatically scaled so that the candidate trace is plotted in the center of the area and the diameter of its proximity disk fills about 75 percent of the screen. ATC environment data for that center are stored on line, automatically accessed, and plotted. These data include the location of the navigational aids (navaids, shown by triangles), jet routes defined by these navaids (solid lines), and the sector boundaries of the controlling center (dashed lines). The dashed-line circle (plotted at the discretion of the analyst) shows the extent of the proximity disk with reference to the last point of the candidate trace.

Once the basic information has been displayed, the analyst has the opportunity to obtain more information from the plot by using the display-screen crosshairs and single-letter commands. Examples of these are also shown in Figure 5. The operator may obtain the plot of the x-, y-, z-, and t-coordinates of any one radar data point by moving the crosshairs to the point and giving the appropriate command letter. The selected point is circled, and the operator moves the crosshairs a short distance away and enters a label. The program labels the point as shown and writes the appropriate information on the right-hand side of the screen. In Figure 5, the most-recent point of trace 1, labeled A, has x-coordinates and y-coordinates 337.38 and 245.61, respectively; records flight level 350; and was taken at 20:03:06.7.

Other functions are available that work in much the same manner. The operator locates the point of interest by using the crosshairs and chooses a label to index the event. Current program configuration includes the capability to locate in terms of x and y any point on the screen or to measure the distance between any two points, as is shown for the distance between the candidate aircraft and the navaid SSO (labeled B). The operator also has the option of replotting the current display without the entered labels, of listing all radar data points displayed on the screen, and of skipping over any of the plots recorded on the input file.

The PROXPLOT program has proved useful in processing navigation data in the aggregate. Each aircraft that exceeded a certain distance from route centerline during its flight was screened to ascertain the origin of the error; specifically, a deviation that occurred under ATC cognizance or direction was not included in the navigation performance data base. Normal methods for determining ATC intervention include scrutinizing data collection logs and recording pilot-controller communications. Since these sources are not infallible, use of the above display in determining the traffic environment around the perceived error can often be helpful in determining the controller's intent and the source of the deviation.

PRESENTING SUMMARIES OF OBSERVED LATERAL DEVIATIONS

Having limited the sample to those flights determined to be navigating without direct ATC intervention, it was then of interest to characterize the statistical properties of the data. One particular question centers around the effect of distance from ground station on the magnitude of lateral deviation from route centerline. In particular, the current VOR system-use accuracy standard requires 95 percent of all traffic to be within a protected airspace centered about the route; the width of that airspace depends on the distance from the nearest ground station.

To illustrate the effect of distance on the distribution of lateral deviations, a graphical tool

Figure 5. Interactive examination of proximate aircraft.

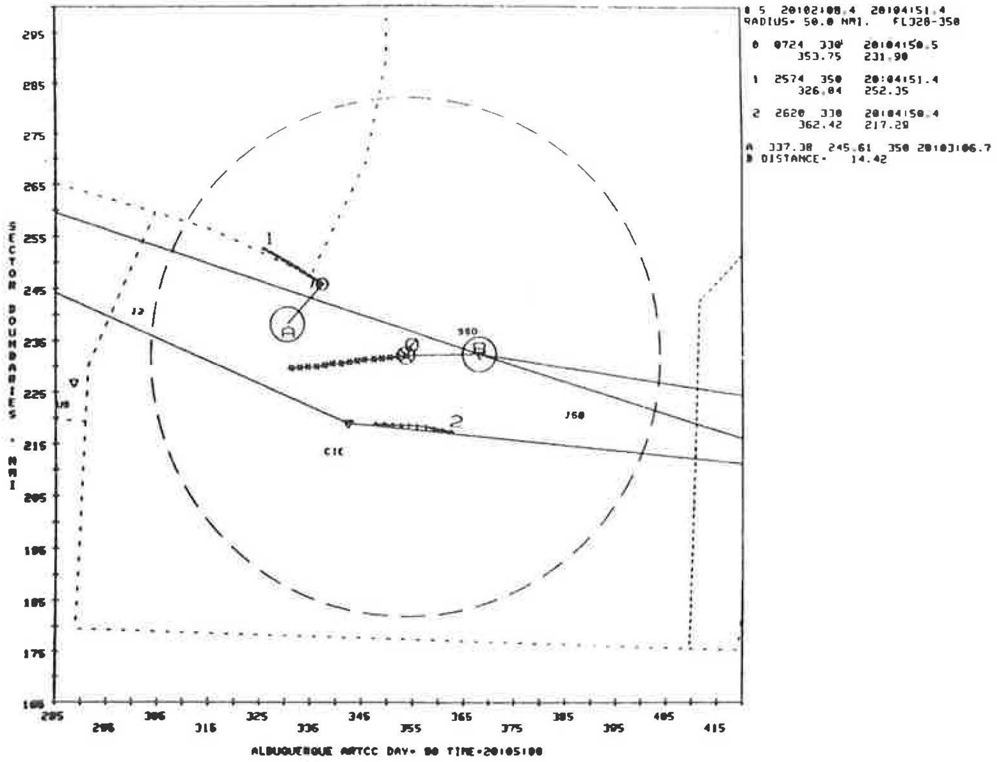
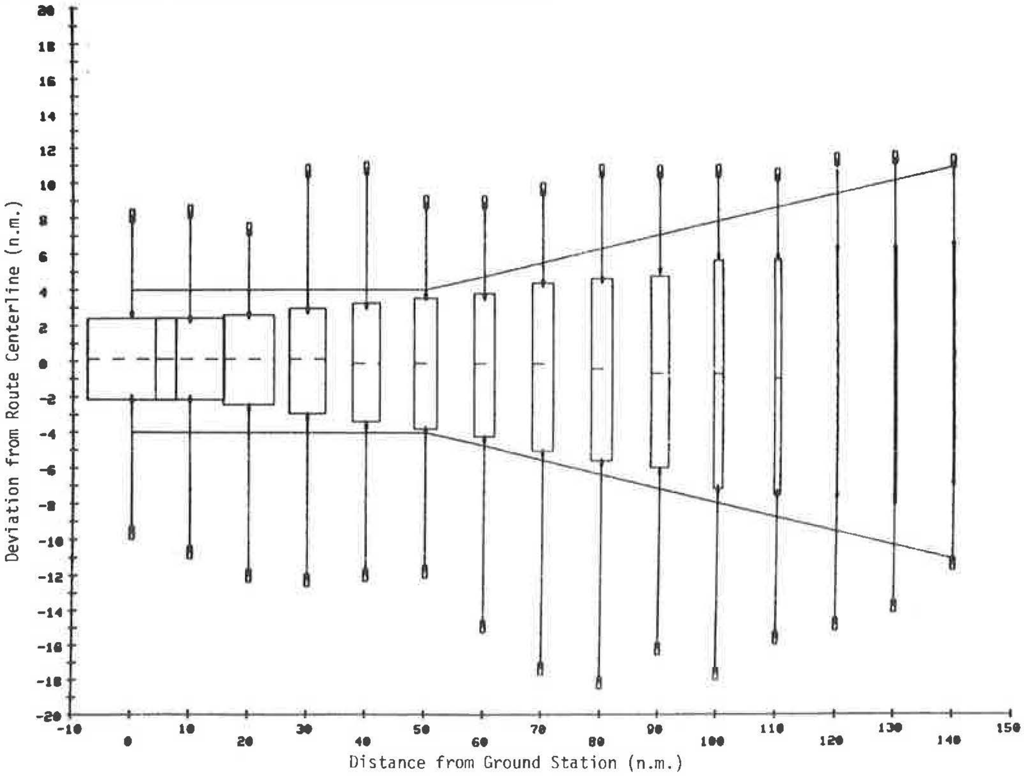


Figure 6. Summary characteristics of lateral-deviation distributions.



was developed similar to the box-and-whisker plot suggested by Tukey (5). This particular plot (Figure 6) shows both the protected airspace (funnel-shaped lines) and various summary statistics; it has the dual purpose of exhibiting the changing distributional form and determining whether the 95 percent containment was being achieved. At each milepost, the central rectangle is centered at the mean of the observed data, whereas its height is ±2 SD. If the distributional form is Gaussian, as postulated by the standard, then the box ought to enclose about 95 percent of the observations and be contained within the protected airspace.

The central dashed line in each box represents the median of the data and if not near the center could indicate excessive skewness. The kurtosis calculated from the observed data at each milepost is used to scale the width of the box. The narrowing of the boxes as the distance from the VOR increases indicates a flattening of the distribution; this is also illustrated in Figure 7, which shows a more-conventional illustration by using relative-frequency histograms.

Of particular interest during this study was the information in the tails of the distribution, which is a crucial input in later calculations of overlap probabilities. The tails of the distribution are defined by the outermost 2.5 percent of the recorded deviations on either side of the route centerline, indicated in Figure 7 by the "whiskers." To present this aspect of the data more clearly, Figure 6 was modified (not illustrated here) by removing the large rectangles that represent summary distribution statistics so that the relationship of the tails of the distribution to the protected airspace might be more easily perceived. This is an example of a type of graphics modification called "erasure," which allows selected information to be better assimilated by the viewer.

CHARACTERIZING THE DISTRIBUTION OF LATERAL DEVIATIONS

Many factors lead to the occurrence or avoidance of midair collisions. Some factors, such as escape maneuvers when two pilots judge that a collision is imminent, are difficult to model since the possible actions are so numerous. In contrast, for aircraft assigned to laterally adjacent routes, a factor directly related to the risk of collision that can be quantified is the magnitude of lateral deviations of the aircraft from their respective route centerlines. Determination of adequate lateral spacing between routes should be directly related to the resulting frequency with which aircraft will come close to each other laterally.

To state the problem formally, consider the task of determining an adequate spacing S_y between two parallel routes. If lateral overlap is defined to be the condition in which the centroids of a pair of aircraft are within a wingspan of each other in the direction perpendicular to the routes, then the probability of lateral overlap P_y is clearly a function of S_y. Determining the form of this functional relationship would allow for better specification of adequate separation between the routes.

In the absence of controller intervention, $P_y(S_y)$ could be determined by convolving the distributions of lateral deviations from route centerline for two aircraft on adjacent routes. If we let $f_1(Y)$ and $f_2(Y)$ denote the probability density functions for lateral deviations on the two routes, then

$$P_y(S_y) = 2\lambda_y \int_{\infty}^{\infty} f_1(Y) f_2(Y - S_y) dy \qquad (1)$$

where λ_y is the average wingspan of the aircraft.

Given the data base described in previous sections of this paper, the above convolution could be estimated either by observing lateral deviations directly or by fitting an appropriate density function initially and then performing the required integration. In either approach, the resulting estimate will be dominated by the tails of the lateral-deviation distributions (which represent very large deviations). Even given the extensive data base available, observed deviations in the extreme tails are very sparse. Consequently, if the data are used directly through a numerical convolution, values of $P_y(S_y)$ for large S_y must be obtained by smoothing and extrapolation (6). If density functions are fitted, the resulting estimates will depend greatly on how well these functions fit the tails of the observed data. In either case, graphical techniques have been found to be crucial in determining which mathematical models adequately describe the observed behavior.

Based on the current data collection, it was decided to take the second of the above approaches [reasons for this choice were documented by Polhemus (7)] and fit an appropriate density function to the lateral deviations from route centerline. To determine initially whether a simple distribution such as the normal or double exponential might be appropriate, graphical displays were generated that showed how the proportion of deviations greater than or equal to Y varied as a function of Y (equivalent to 1 minus the empirical cumulative distribution). Figure 8 shows such a plot for deviations at 50 nautical miles from the nearest VOR ground station; the equivalent curves for a normal distribution and a double-exponential distribution with standard deviation are equal to that implied by the current VOR system-use accuracy standard. With logarithmic vertical scaling, it is immediately apparent that the tail of the actual distribution is considerably heavier than implied by the normal. The double-exponential distribution, which does have heavier tails, is not supported by the data either. This simple graphical technique suggests immediately that a more-complicated distributional form is required; this conclusion was later substantiated by more-sophisticated goodness-of-fit tests.

Two natural extensions of the normal and double-exponential distributions, obtained by introducing additional parameters in the density function, are the exponential power distribution (8) and the generalized t-distribution (9). Both these distributions require numerical procedures in order to estimate the parameters. As is the case with all numerical procedures, it is essential that the analyst monitor the results carefully to ensure that the algorithm used behaves correctly.

Here graphical procedures were employed to assess the adequacy of the distributions as fit by the algorithm. Initially, the numerical algorithms were used to refit a normal distribution as a means of verifying the computer programs. The numerical fit was then compared graphically to the observed data by plotting the actual and predicted number of deviations in increments of 0.25 nautical mile. Figure 9a shows such a plot that uses logarithmic vertical scaling, from which it is evident that the data are more peaked in the center than a normal distribution would imply and that the observed tail is also much heavier than the normal fit. In contrast, Figure 9b shows the results of a fitted generalized t-distribution. Both the core and the tail of the fitted distribution correspond reasonably well to the observed data. Again, the graphical display is essential in allowing the analyst to judge the acceptability of the fit.

Once an acceptable fit has been obtained for the observed distribution of lateral deviations from route centerline, the resulting probability of lateral overlap can be obtained as a function of route separation S_y by convolving the distributions as indicated earlier. To summarize the results, one final graph is relevant--Figure 10, which shows how the probability of lateral overlap varies with route separation and assumed distribution. To convert the calculated probability into a measure of risk obviously requires many additional calculations and assumptions, which are outside the scope of this paper. Nevertheless, Figure 10 shows much about the relative relationship between route spacing and the potential for a collision, which, when combined with other factors, could be meaningfully employed to establish acceptable route-spacing criteria.

ANIMATED PRESENTATION OF THEORETICAL RISK MODEL FOR INTERSECTING ROUTES

Although the applications of collision-risk methodology to date have been solely for parallel routes, many route systems have nonparallel and intersecting routes. In explaining the derivation of overlap probabilities for such situations to nontechnical audiences, graphical procedures are again essential. Since the probability of overlap for a pair of aircraft that traverse an intersection

Figure 7. Relative-frequency histograms by milepost.

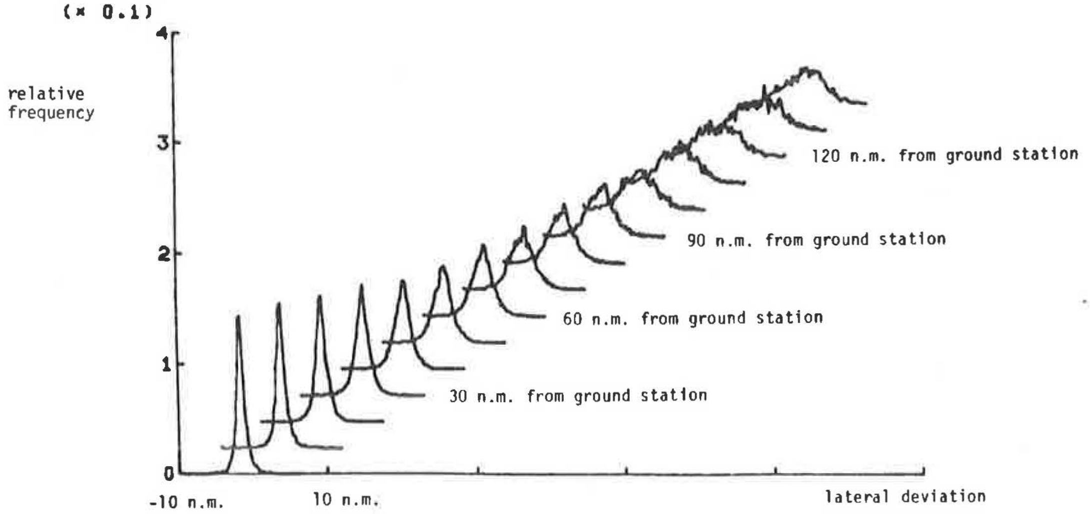


Figure 8. Comparison of observed and theoretical cumulative distributions (Cleveland).

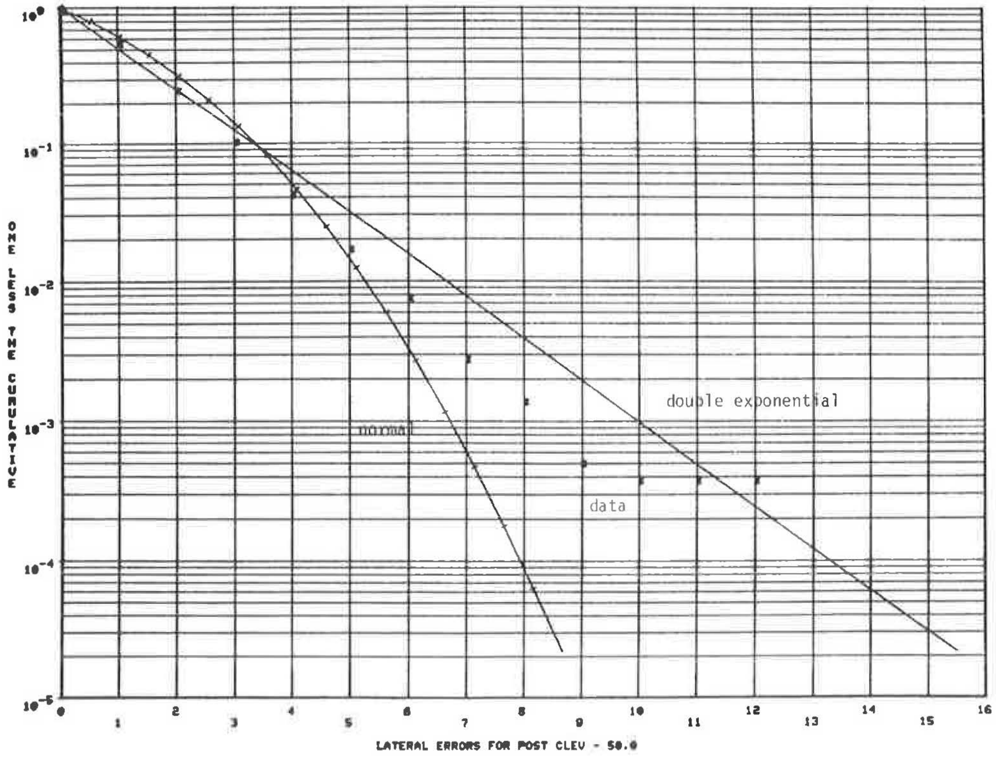


Figure 9. Normal and generalized fitted distribution at the 50th nautical milepost in Cleveland.

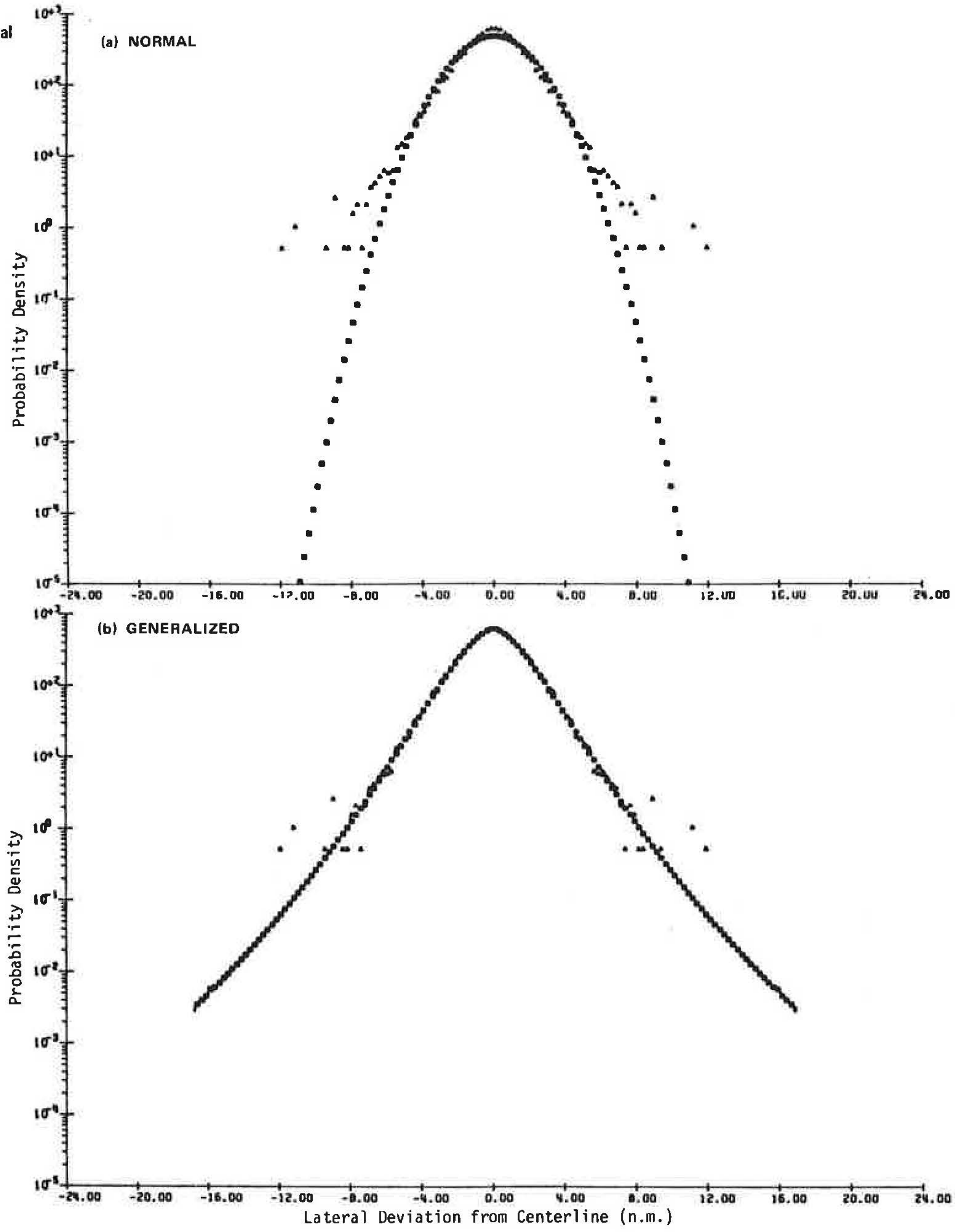


Figure 10. Probability of lateral overlap as function of route separation.

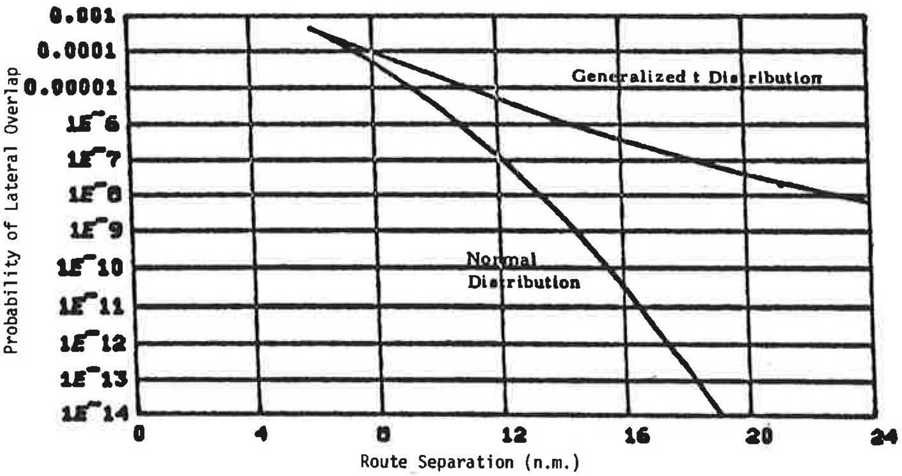
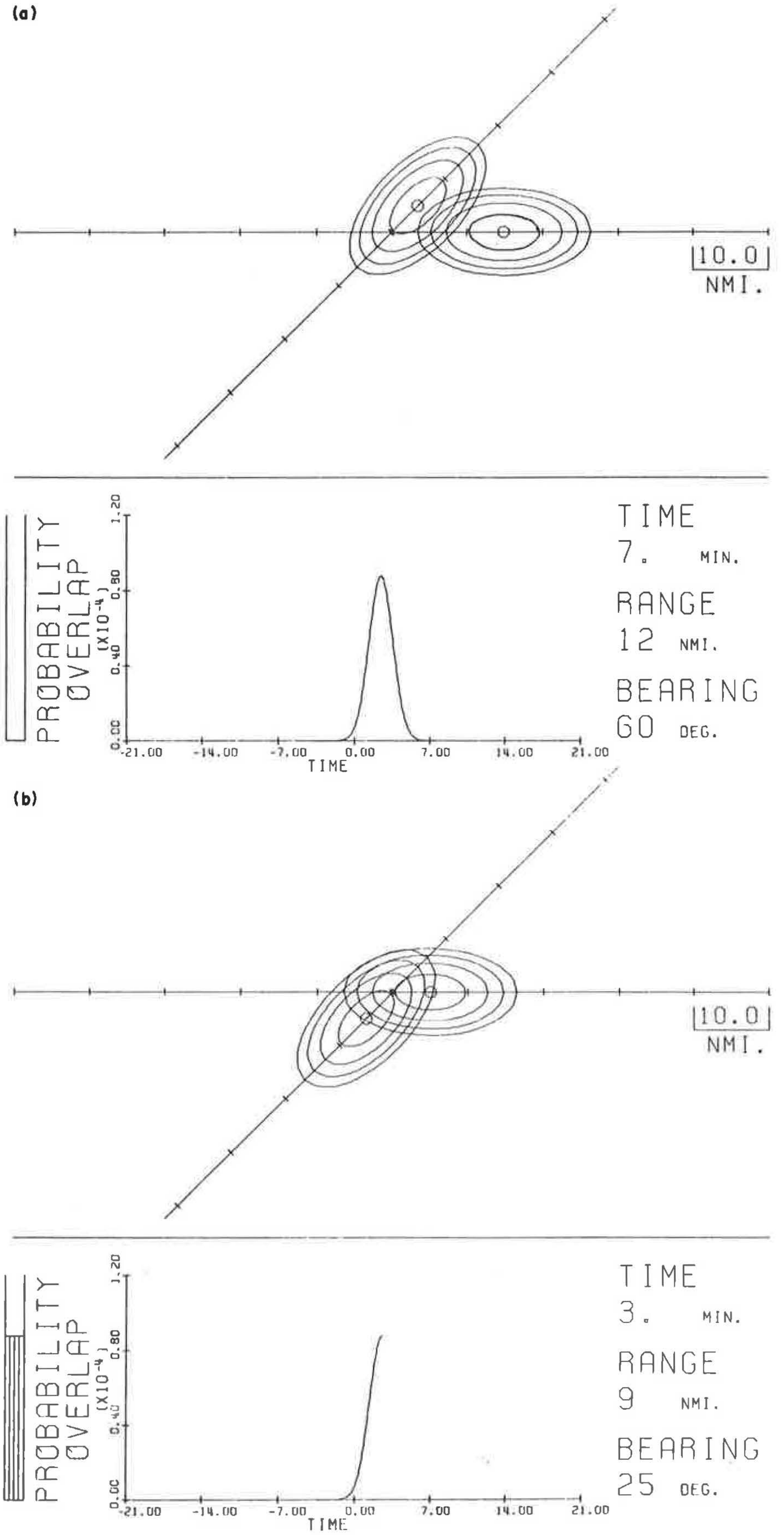


Figure 11. Selected frames from computer-generated movie that illustrate overlap probability for intersecting routes.



changes over time, a useful portrayal is through a computer-generated movie. Such a movie has been produced; two frames are shown in Figure 11. The example illustrated is a 45° intersection. The contours of the bivariate probability density function of along-track and cross-track errors are shown as ellipses about the planned position of each aircraft.

As the movie evolves, the ellipses move at a constant velocity through the intersection. As the first aircraft nears the center of the intersection the probability of overlap increases, as illustrated by the rising thermometer on the left. At the same time, a plot of probability versus time is created. The movie has been found to be particularly effective in explaining the general concepts of the model to a nontechnical audience, which is crucial if the analytical results are to be accepted.

CONCLUSIONS

Computer graphics has played a central role in the analysis of data and development of methodology for determining adequate jet-route separation standards. Development of a clean data base, summary description of navigational performance, estimation of lateral-overlap probability, and dissemination of the model have all been greatly enhanced by the availability of computer graphics. The use of graphical tools throughout the study resulted in substantial savings of analytical resources and an understanding of the problem that would otherwise have been very difficult to achieve.

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Applications of Interactive Graphics in Michigan's Statewide Transportation Modeling System

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Modern transportation agencies face increasing responsibilities and decreasing revenues. The only viable solution is increased productivity and efficiency. NETEDIT, an operational interactive method of updating, displaying, and interrogating networks, has allowed Michigan's Department of Transportation to increase its analysis capabilities without sacrificing production time. The utility of such a process is easily seen by contrasting manual coding and batch updating with the interactive update process. NETEDIT gives the user instant pictorial feedback, which enables correction of errors on the spot. This allows the average elapsed time for generation of alternatives to drop from two weeks to 4 h. In addition, the ability to vary the way a link is drawn—solid, dotted, dashed, crosshatched, even varying bandwidths—based on its attributes lends versatility. The addition of a digitizer tablet has allowed creation of 2000-node networks in two weeks. A tree-plotting subroutine eliminates much of the elapsed time in network calibration. Most importantly, NETEDIT, together with Michigan's Statewide Transportation Modeling System, has been used in more than 350 actual planning applications over the past two and one-half years. As a result, NETEDIT has become a valuable transportation planning technique in Michigan.

Governments face a challenge in meeting modern political realities. On the one hand, legislation and public expectations demand thorough planning and implementation of an expanding range of governmental responsibilities. On the other hand, the economic realities of the foreseeable future dictate a governmental belt-tightening; personnel and budgets will be maintained or cut back rather than increased.

Michigan's Department of Transportation (MDOT) is meeting just such a challenge in its Bureau of Transportation Planning. Although budget and personnel are not rapidly expanding, the demands on the planning process from federal legislation, MDOT's action plan, and concerned citizens have grown tremendously. MDOT must now consider many alternatives and modes and must examine an ever-widening range of impacts--travel, social, economic, and environmental--for every major transportation project it undertakes. Moreover, the people who live in the region of the proposed project and who will therefore be most affected by the final solution must be involved in each step. Based on the evaluation of the first set of alternatives, new alternatives may