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Statistical Study of the Closest Approach of Aircraft to Ground-Based Emitters: Results for Seattle and Comparison With Denver

March 1999

Final Report

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16. Abstract

A Technical Program was initiated by the Federal Aviation Administration (FAA) William J. Hughes Technical Center to measure the distances that aircraft fly within high-intensity radiation emitters. This program was launched as the FAA and the High-Intensity Radiated Fields (HIRF) advisory committees were defining HIRF regulatory rulemaking requirements. This study was a follow-on of the work conducted at the Denver International Airport to determine the actual distances that aircraft flew within emitters. This study focused on a similar effort at Seattle International Airport. This program presented the data gathered from the Seattle Airport along with a detailed comparison of the data between the two airports. Any observable patterns and similarities between the two airports were recorded. Information on emitter location, frequency, power, etc., was obtained from the Government Master File. Aircraft flight information was obtained from the System Analysis Recordings (SAR) tapes at the Seattle En Route Center. This program was used in conjunction with a research effort which located all high-powered emitters in the U.S. and Europe and established the actual HIRF environment.

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EXECUTIVE SUMMARY

The flight safety issues associated with the exposure of aircraft to High-Intensity Radiated Fields (HIRF) are being addressed by the Federal Aviation Administration (FAA). The current HIRF environment for aircraft is based on a worst-case evaluation of exposure leading to a concern that the required test levels may be excessive and unnecessarily burdensome. A clearer understanding of the interaction of HIRF with aircraft is desirable in order to understand both the likelihood of occurrences and the intensity of encounters. This report examines one of the main determinants of interaction, the closest approach of an aircraft to a HIRF emitter in the course of normal flight and takes a preliminary look at the electric field incident on an aircraft at that location.

Following the procedure established in the previous study of the Denver, Colorado, area, "Statistical Study of the Distance of Closest Approach of Aircraft to Ground-Based Emitters," DOT/FAA/AR-98/75 [1], a square area (120 nautical miles on a side) surrounding Seattle, Washington, was chosen as a study site. Information on emitter location, frequency, power, etc., was obtained from the Government Master File. Information on aircraft flight positions was obtained from the SAR (System Analysis Recordings) tapes at the Seattle En Route Center. Whereas for the Denver study the National Traffic Analysis Program (NTAP) was used to extract the flight information. Approximately 7000 flights over a three-day period were examined for proximity to emitters and electric field levels at inflight positions.

Based on the data collected, distributions of closest approach to any emitter and maximum aircraft electric field were generated for 7000 flights over a three-day period. Beacon codes were used to categorize different types of flight operations which were then examined for differences in the distributions. Local flight operations were treated separately to determine if different characteristics were observed as compared to other types of flights. It was also observed that the smallest values of closest approach to emitters and the largest electric field values often occurred either at or very near airports.

Comparison of the Seattle area results with those from the Denver area showed the consistency of the approach and many similarities in the distributions.[1] However, the importance of multiple data samples was revealed as, depending upon the figure of merit used, differences in the Seattle and Denver results as large as a factor of two were observed.

Such information and others like it contained in this report are essential in understanding the distributions of aircraft-emitter separation distances as they occur in normal flight. Only after an informed selection of separation distances is made can a well founded HIRF environment be derived.

INTRODUCTION

BACKGROUND.

The flight safety hazards associated with the exposure of aircraft to High-Intensity Radiated Fields (HIRF) are constantly being assessed and addressed by the Federal Aviation Administration (FAA). The actual HIRF environment for aircraft is still not fully defined, thus hampering the development of required testing levels for certification. A clearer understanding is needed of the interaction of HIRF with aircraft.

The HIRF levels currently used for certification of aircraft and avionics systems are based on a worst-case exposure. There is a real concern within the aviation community that these present test levels may be excessive and necessitate overtesting. In fact, the interaction of HIRF can be broken down into a number of components, each of which have a distribution of variables which determine both the likelihood and the strength of the HIRF-aircraft interactions. When distributions of variables associated with aircraft in actual use are examined, the likelihood of exposure as a function of the variables can be evaluated. The consideration of this additional detailed information permits better informed and better directed decisions about HIRF certification testing levels than does generic worst-case analysis.

A previous report undertook an examination of one of the distributions involved in the interaction of HIRF and aircraft, the distance of closest approach of aircraft to ground-based transmitters in the Denver, CO, area.[1] The present project objective is to obtain closest approach information for the Seattle, WA, area and to compare it to the Denver results.

APPROACH.

Some of the components of the interaction of HIRF with aircraft include

- emitter characteristics.

  - frequency
  - location
  - power
  - maximum antenna gain
  - antenna direction
  - antenna pattern
  - time dependence (on/off or pulse repetition pattern)

- aircraft characteristics.

  - type of aircraft (certification requirements)
  - shielding effectiveness of airframe
  - shielding effectiveness of cables and equipment
  - operating frequencies of equipment

- susceptibility levels of equipment
- time dependence of equipment use (takeoff/landing, cruising, etc.)

- aircraft flight characteristics.

  - class of aircraft
  - destination/flight purpose
  - altitude
  - location
  - time dependence of position (time of day/year, takeoff/landing/cruising, etc.)

Unfortunately, many of these variables are correlated in ways which are not easy to isolate. It is obvious that variables within one of the three categories listed might be correlated, but there also can be correlations between categories. For example, a radar devoted to tracking specific targets in a certain air space may adapt power level, antenna characteristics, and dwell time on target based on the location and motion of a specific aircraft. Especially in cases such as this, but also more generally, caution must be exercised in trying to build up a general distribution from a product of individual distributions which are assumed to be independent.

After some consideration of the possibilities, the effort in this investigation focused on the distance of closest approach of aircraft to ground-based transmitters in a specified area. In essence, this makes use of the locations of emitters and the positions of aircraft while in flight. It is also possible to estimate the maximum electric field experienced by an aircraft at its distance of closest approach to a given emitter. The geographical region used in the study is the Seattle, Washington, metropolitan area located roughly within 60 nm of the Seattle-Tacoma International Airport (SEA). Emitters were limited to those in the U.S. Government Master File (GMF) with frequency > 400 MHz with a nonnegligible electric field. The in-flight aircraft position information was obtained from the radar data recorded by the FAA for air traffic control purposes. Additional attention was given to types of flights and to the proximity of airport boundaries as they impact the observed closest approach distances.

EMITTERS

SOURCE OF EMITTER INFORMATION.

The emitter information from the FAA Washington Headquarters Government Master File database of electromagnetic emitters was supplied by Spectrum Engineering. The initial selection criteria for emitters were

- within approximately 60 nm of Seattle-Tacoma International Airport, and
- had a power to transmitter > 10 Watts <u>or</u> antenna gain > 10 dB.

Over 6800 emitter entries met these requirements. It should be noted that some emitters had multiple entries, one for each of several operating frequencies. An ASCII record for included emitter entry provided:

- GMF identification
- city of location
- state of location
- emitter latitude to 1 second
- emitter longitude to 1 second
- frequency
- power
- antenna gain
- site elevation
- antenna height above ground
- pulse information
- system descriptor

PROCESSING OF EMITTER INFORMATION.

The information obtained from the Government Master File is not without errors or omissions. Some of the observed problems and the way these problems were solved are

- latitude/longitude information only to nearest minute, used 00 for seconds value.
- antenna gain missing, used 6 dB.
- site elevation missing or obviously in error, used information from U.S. Geological Survey Digital Elevation Model.
- antenna height missing, used 0 ft.

U.S. GEOLOGICAL SURVEY DIGITAL ELEVATION MODEL. Site elevation problems were resolved by making use of U.S. Geological Survey Digital Elevation Model (DEM) information. This standard resource is openly available and contains elevation information to the nearest meter at 3 arc-second spacing in the United States. The information is available in separate files, each of which span one degree of latitude and longitude. For this project, sixteen files covering 4 degrees in both longitude and latitude were used. When the DEM was used to calculate the site elevation for emitters with known values, the agreement was generally good to 50 ft or better with only a handful of discrepancies greater than 100 ft. This cross-check procedure also helped to identify GMF site elevation errors.

SELECTION OF CANDIDATE EMITTERS. The list of emitter entries was pared down to 1962 by requiring frequencies > 400 MHz. The final selection cut was made on electric field level. For each emitter, an electric field, E, at 100-ft distance was calculated using

$$E = \sqrt{\frac{377 P F_g}{4\pi R^2}} \tag{1}$$

where
P = emitter power
F_g = antenna gain factor
R = 30.48 m (100 ft)

For frequencies > 400 MHz and at a distance of 100 ft, one is in the far field of each element of a transmitting antenna, but lack of phase coherence over the entire antenna may prevent the 1/R behavior assumed in equation 1. However, this effect on E is expected to be less than a factor of two. With this in mind, a relatively low level, E > 33-V/m, was used to select emitters for the final group to be used in further calculations; 278 GMF entries satisfied this cut. This final group of emitters is meant to represent the set of all emitters in the Seattle area which could possibly be responsible for the largest E field which any aircraft may experience. In fact, the 33-V/m cut is fairly conservative and the selected group is surely a worst case. Figure 1 shows the geographical distribution of these emitters. Clearly, it is not difficult to extend this procedure to calculate the largest field that may be experienced for each frequency, modulo, the uncertainty factors in the E field calculation of equation 1. Preliminary results from such a calculation are also presented later.

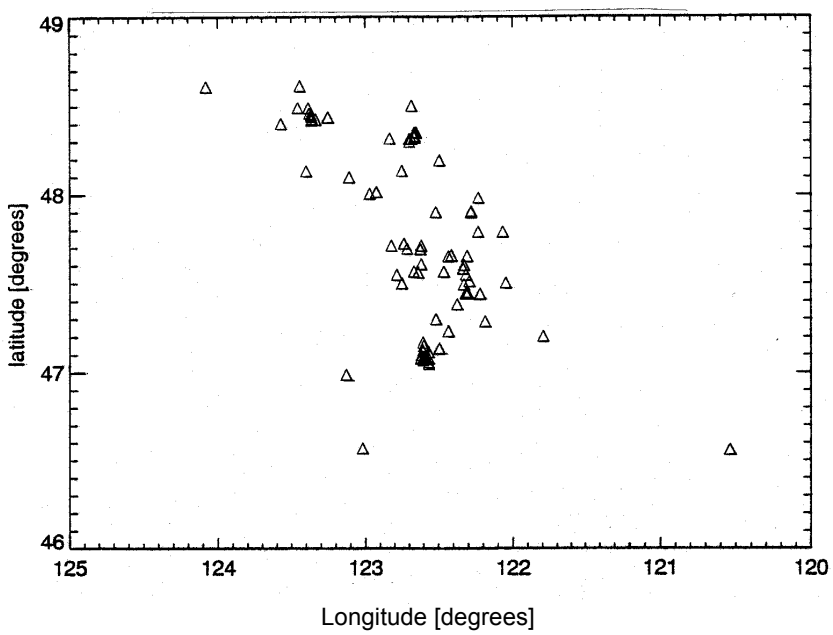


FIGURE 1. LOCATION OF EMITTERS CONSIDERED FOR CLOSEST APPROACH OF AIRCRAFT

AIRCRAFT FLIGHT POSITIONS

SOURCE OF AIRCRAFT FLIGHT DATA.

The aircraft flight positions were obtained from the FAA's Seattle En Route Air Traffic Control Center. The data were extracted from three days of Systems Analysis Recordings (SAR) tapes recorded March 31, 1992 through April 2, 1997. In a Denver study, "Statistical Study of the Distance of Closest Approach of Aircraft to Ground-Based Emitters," DOT/FAA/AR-98/75, the National Traffic Analysis Program (NTAP) was run by FAA personnel to select the aircraft position information as a function of time. The use of NTAP output to generate the desired information was outside the original design of the program and required intensive effort by FAA personnel. Although many voluminous data files were generated, it appeared that there were still

gaps in SAR information obtained by this method. The basic set of radar information extracted for an aircraft at a given time included

- beacon code identifier number reported by the aircraft transponder,
- latitude to the nearest second from radar processing,
- longitude to the nearest second from radar processing,
- time of the radar report to the nearest second, and
- adjusted altitude reported by the aircraft to the nearest 100 ft with respect to mean sea level.

For the present study of the Seattle area, copies of 45 SAR tapes were obtained and processed to obtain similar information. The NTAP records on the SAR tapes were processed to extract the limited data block (LDB) information. This included a report from each system radar of all of its radar responses for each of its sweeps. The data differed from the NTAP report only in the use of system coordinates for the en route center in the place of latitude and longitude. Other reference information from each SAR tape was used to immediately convert the system coordinates to the previously used latitude and longitude format. It should be noted this procedure was similar to that carried out by NTAP and was limited to the same accuracy by the 1/16-nm resolution of the SAR recorded system coordinates. The effect of this resolution limit will be examined later.

GENERAL PROCESSING OF AIRCRAFT POSITION INFORMATION.

The first step in processing the SAR records was to remove all but the information just listed. The result was an unordered group of sets of flight information data, for about 710,000 space-time points. A preliminary operation calculated aircraft altitude above ground level (AGL) at each point. This was done using the altitude reported with respect to sea level and the same Digital Elevation Model described in the emitter section. This new information was added to the existing information set for each point. The next processing step ordered the information sets first by beacon code and then by time. Inspection of this data structure revealed that some beacon codes were used and reused several times throughout the day. In fact, data for beacon 1200 code (used by aircraft not filing a flight plan) sometimes had multiple aircraft and their positions associated with the same time value. This additional ambiguity in the 1200 code data made it desirable to treat it separately from the non-1200 code data.

NON-1200 CODE DATA.

SEPARATION INTO FLIGHT TRACKS. Since one of the aims was to differentiate by flight, it was essential to identify the beginning and end of data segments associated with distinct flight operations. These will subsequently be referred to as flight tracks. Several data characteristics were examined to aid in distinguishing the individual tracks; they include

- time interval between radar reports,

- distance between aircraft positions on successive radar reports,
- difference in aircraft altitude on successive radar reports,
- aircraft speed calculated using position and time differences on successive radar reports,
- aircraft ascent/descent rate using successive radar reports,
- accumulated observation time for a beacon code with respect to some defined beginning time,
- accumulated distance for a beacon code with respect to some defined beginning position, and
- total number of points accumulated for a beacon code with respect to some defined beginning.

Figure 2 shows a relative frequency histogram versus aircraft speed. There is a clear separation in the data representing a region associated with points belonging to the same flight from a region associated with noise points or points belonging to different flights. An acceptance cut at < 0.5 miles/second is thus imposed. This value allows for some radar measurement jitter, but rejects clearly unphysical speed values.

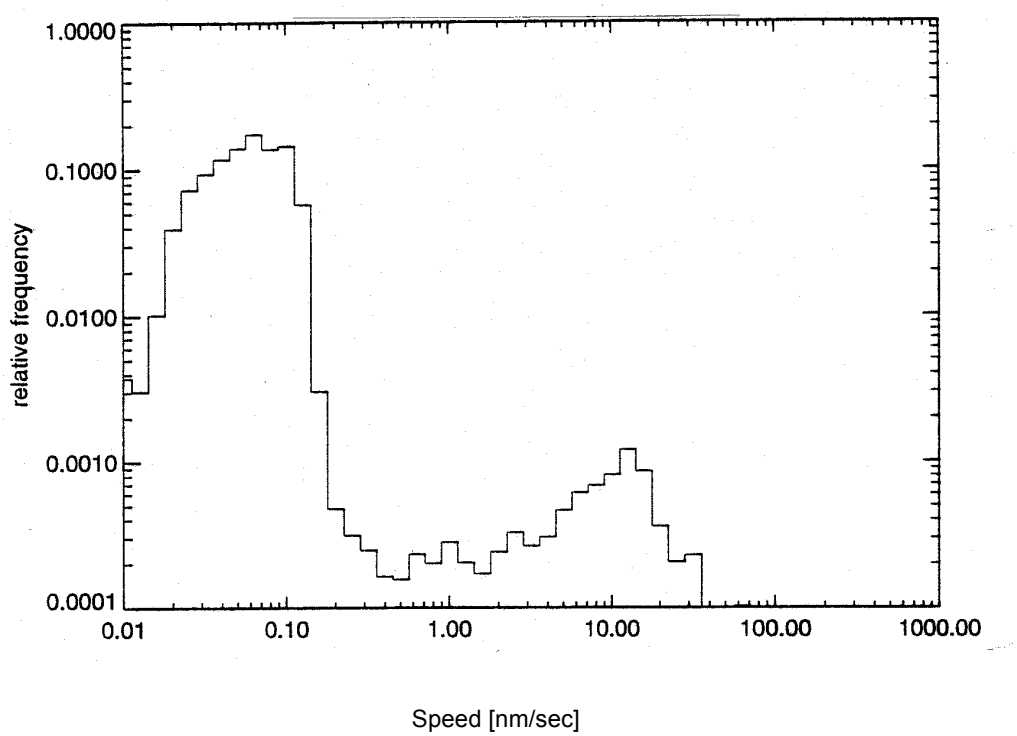


FIGURE 2. RELATIVE FREQUENCY OF SPEED BETWEEN SUCCESSIVE POINTS RECORDED FOR NON-1200 CODE FLIGHTS

A similar consideration of altitude leads to the relative frequency histogram versus the absolute value of ascent/descent rate displayed in figure 3. From this plot, a cut on maximum rate (200 ft/sec) is derived.

The third cut made required that there be 300 seconds or less separation between successive radar reports. This seems rather generous, but it was required for the Denver data and was imposed here for consistency of data processing.

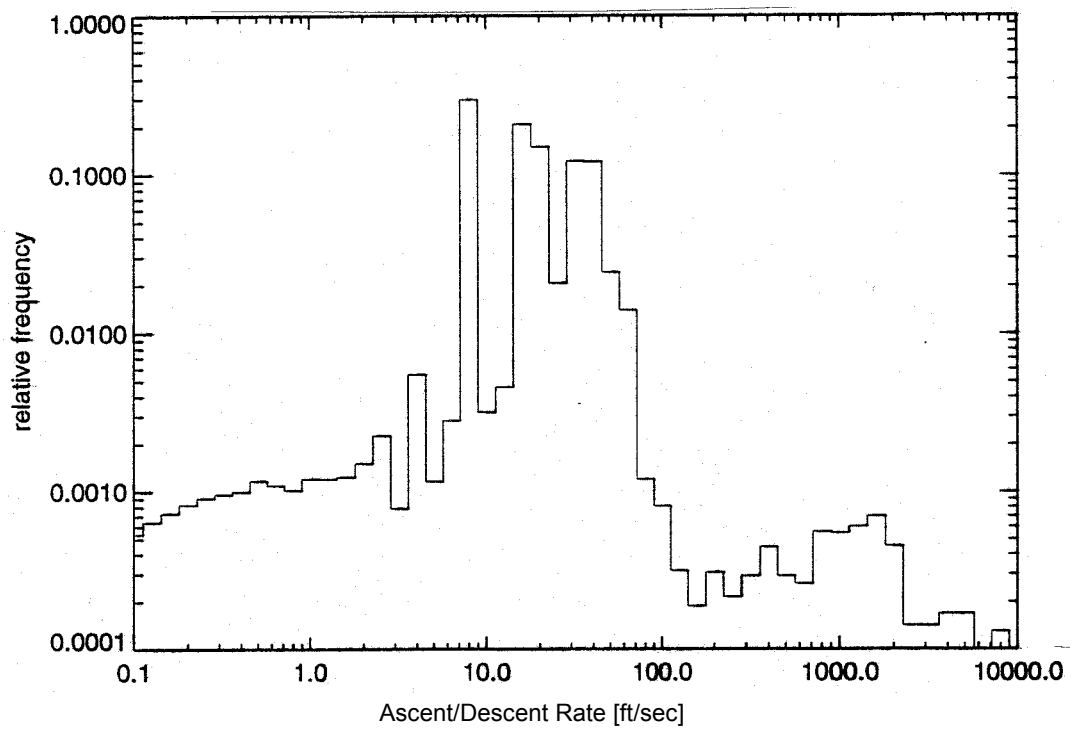


FIGURE 3. RELATIVE FREQUENCY FOR ASCENT/DESCENT RATE BETWEEN SUCCESSIVE POINTS RECORDED FOR NON-1200 CODE FLIGHTS

QUALITY CONTROL AND ACCEPTANCE OF FLIGHT TRACKS. The resulting flight track selections were examined for reasonableness and to understand their general characteristics. Figure 4 shows the relative frequency histogram versus the entire time accumulated for a flight track. As for the Denver data, it was decided that tracks of duration less than 5 minutes were not useful for the study and probably represented incomplete or unreliable data.

A similar consideration of the number of points recorded in the flight track leads to figure 5. This plot shows the relative frequency distribution for the total number of radar reported points in the track. A cut level of 20 points is imposed. Making this cut excludes a few percent of the tracks but eliminates many of those with marginal information. If a radar scan period of 10 seconds is assumed, a 20-point minimum for a 5-minute minimum duration track corresponds to a data loss rate of no more than 25%.

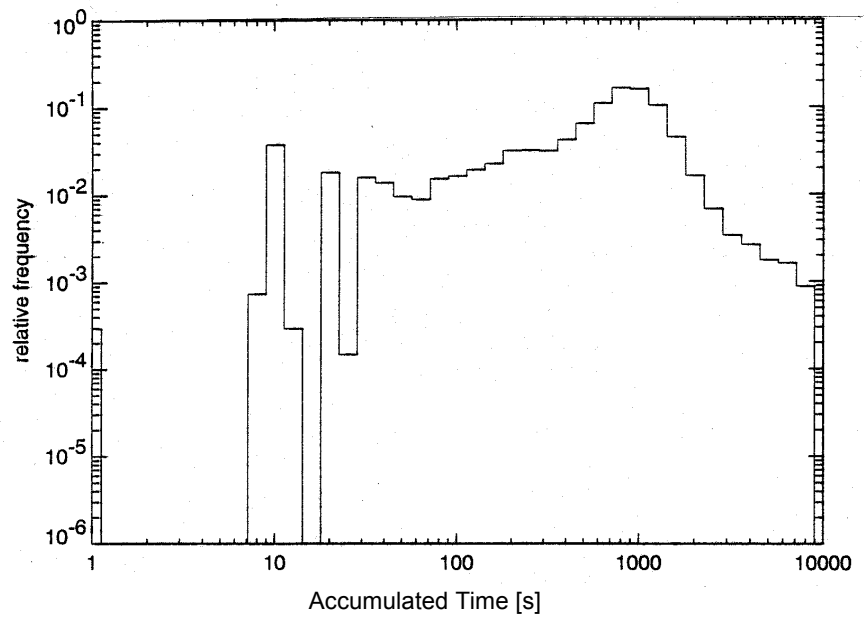


FIGURE 4. RELATIVE FREQUENCY OF HISTOGRAM ENTIRE FLIGHT TIME FOR TRACKS SELECTED FOR NON-1200 CODE FLIGHTS

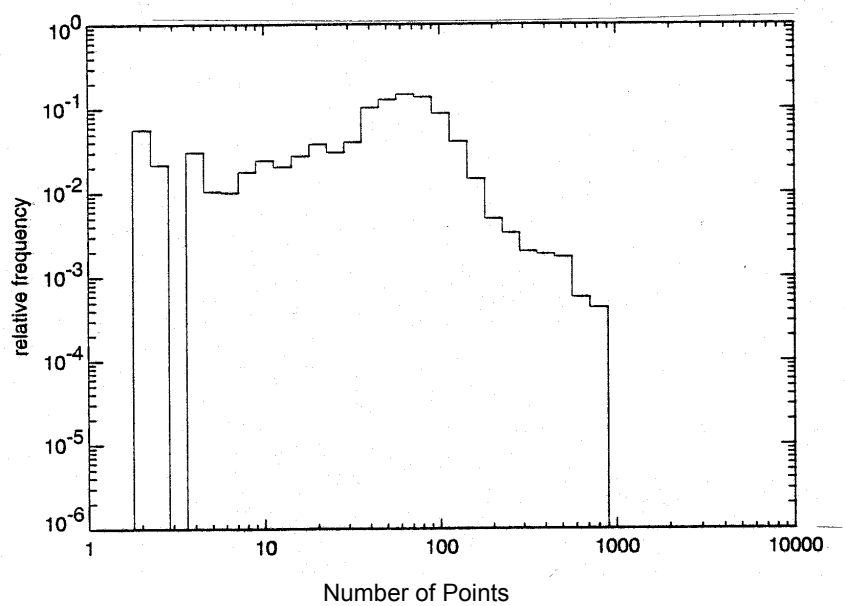


FIGURE 5. RELATIVE FREQUENCY OF TOTAL NUMBER OF POINTS IN TRACKS SELECTED FOR NON-1200 CODE FLIGHTS

With these additional requirements, processing yields ~ 5100 tracks averaging ~ 80 points/track for non-1200 beacon codes. By checking the location and altitude of the first and last points of the flight tracks, the track data can be associated with takeoffs or landings at Seattle-Tacoma International Airport (SEA). Approximately 1459 tracks fit this category, less than half as many

takeoffs/landings observed at Denver International Airport in the Denver study. Figures 6 and 7 show sample SEA tracks. Takeoffs and landings at other Seattle area airports as well as higher altitude overflights can be found in the remaining tracks.

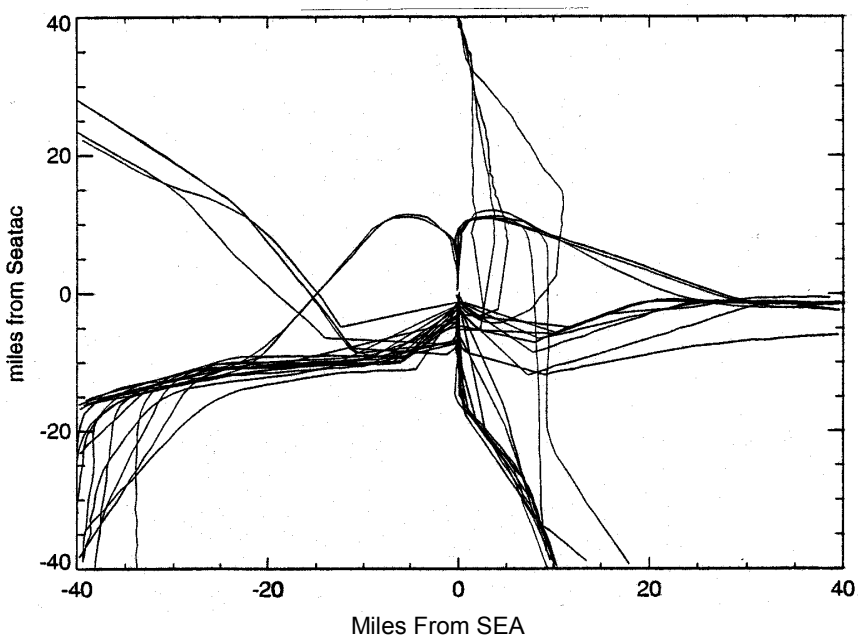


FIGURE 6. SAMPLE OF 50 TRACKS FOR FLIGHTS TAKING OFF FROM SEATTLE-TACOMA INTERNATIONAL AIRPORT

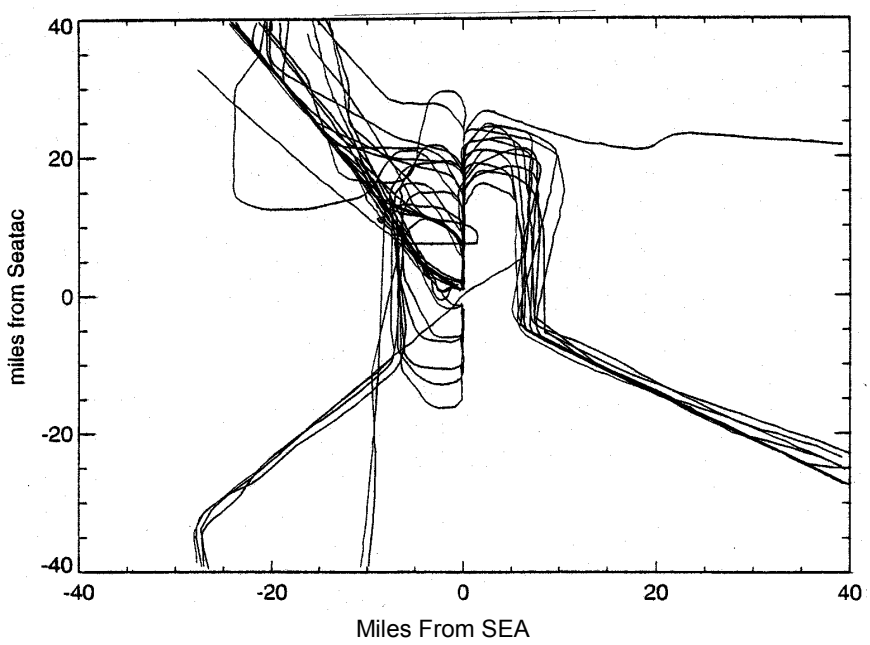


FIGURE 7. SAMPLE OF 50 TRACKS FOR FLIGHTS LANDING AT SEATTLE-TACOMA INTERNATIONAL AIRPORT

1200 CODE DATA.

SEPARATION INTO FLIGHT TRACKS. These non-1200 code data were at least well ordered and unique for a given flight track, requiring mainly the identification of start and stop points. However, the 1200 code data were much more entangled, requiring a different processing approach. It should first be noted that there were approximately 262,000 points with beacon 1200 code (~ 35% of all the data). These flights are mainly of interest because they represent a different category of aircraft operation.

Most of the same quantities used in studying the non-1200 code data were also used for the 1200 code data but a different approach in track selection was necessary. For illustration of the problem, figure 8 shows all the 1200 code points found within a particular three-hour time interval. Several features are immediately evident. The eye can pick out several apparently well formed and lengthy tracks, as well as a few shorter fragments. Furthermore, there are other points which do not seem to be associated with any tracks, indicating that caution is required in trying to link points up into tracks.

In general, the 1200 code data obtained by direct extraction from the SAR tapes is much different from that obtained via NTAP for the Denver study. The fraction of 1200 code points is nearly an order of magnitude greater, the point density on tracks seems higher and there appears to be a smaller fraction of unassociated points. It is tempting to speculate that this is due to direct access to all the data on the SAR tapes rather than the use of NTAP for a task for which it was not designed.

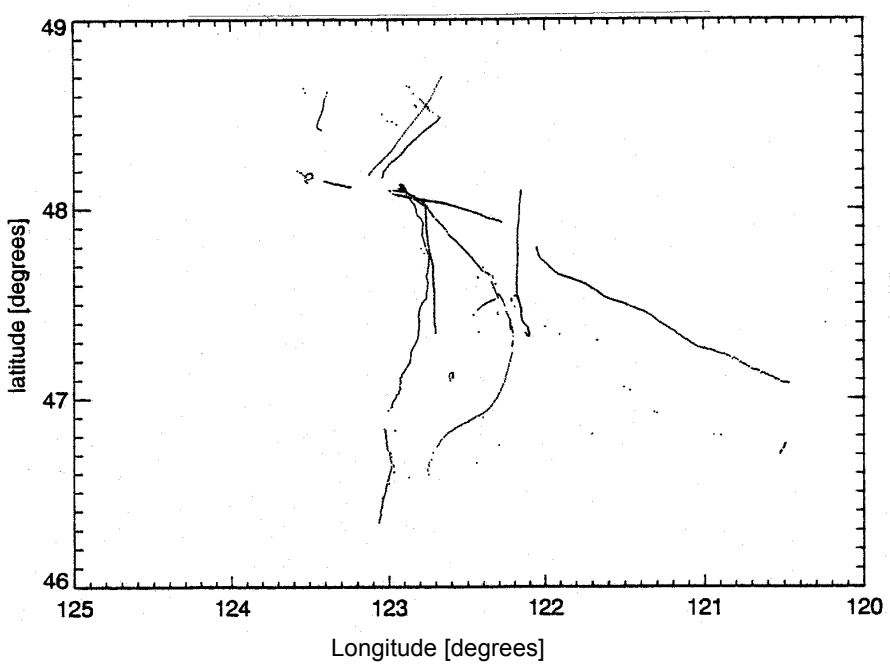


FIGURE 8. POSITIONS OF ALL 1200 CODE POINTS RECORDED IN A SAMPLE THREE-HOUR TIME PERIOD

Figure 9 is a scattergram of the distance between successive points as a function of time over three days. It can be seen that at certain times of the day (early morning and late night, local time) there is a lower density of points and the distance is usually less than 1 mile. It is tempting to identify these as times when there is only a single 1200 code aircraft operating in the Seattle area. Later in the day, there are many more points and while some of them have a character similar to the early/late day points, many more of them have separation distances of up to 100 miles. It is enticing to interpret this as the intermingling of points associated with different 1200 code aircraft operating simultaneously but at considerable distance from each other. Histograms of the number of 1200 code points per minute versus time support this analysis, going from 5-10 points/minute early in the morning to 40-50 points/minute at midday and to ~ 200 points/minute in late afternoon.

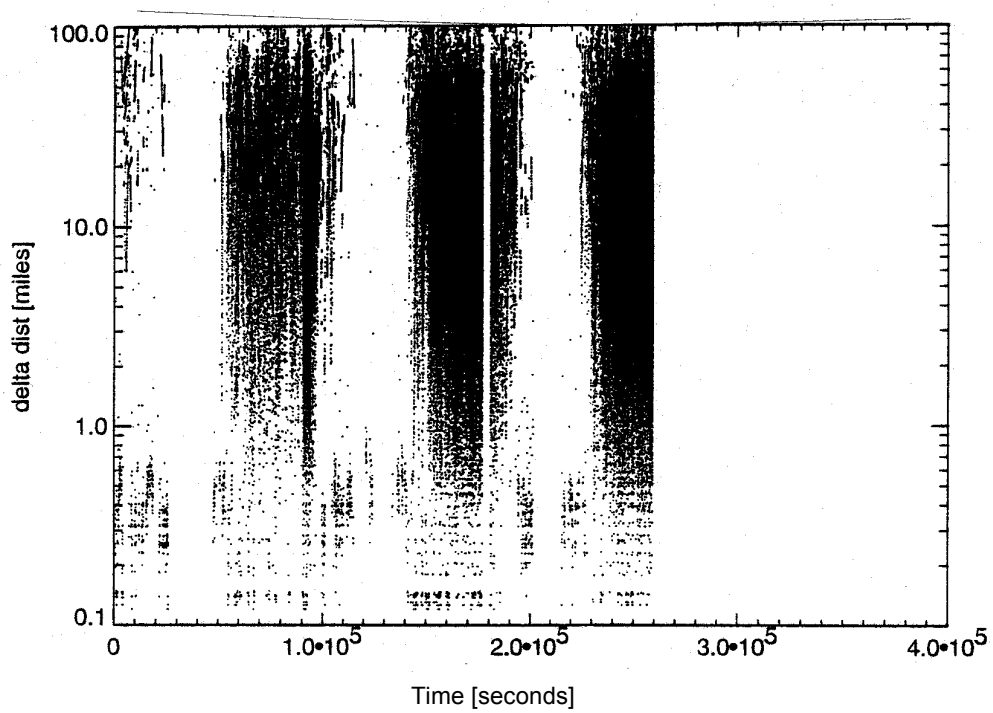


FIGURE 9. TIME INTERVAL BETWEEN SUCCESSIVE POINTS RECORDED FOR SEATTLE 1200 CODE TRACKS VERSUS TIME FOR THE ENTIRE THREE-DAY PERIOD

Figure 10 examines the distance difference between successive time-ordered points. Also on this plot is the cut value; the region below the line is the acceptance region used for assigning points to the same aircraft track. In addition to these data, it was necessary to include associated points having time values within 60 seconds of each other.

The track identification procedure is serial in nature using the time ordering of the points:

1. The first unused point is selected as an initial reference point and marked as used.

2. The next unused point in time is evaluated for satisfying the cut criteria with respect to the previous selected point.

3. Either the criteria are satisfied or not satisfied.

- If the criteria are satisfied, the point is added to the track, marked as used, and becomes the reference point used for the next comparison. One then returns to step 2.

- If the criteria are not satisfied, the track is terminated and stored. One then returns to step 1 to begin a new track.

The parameters used for track identification for the Seattle data are similar to those used for the Denver data but there appear to be many more tracks of higher quality.

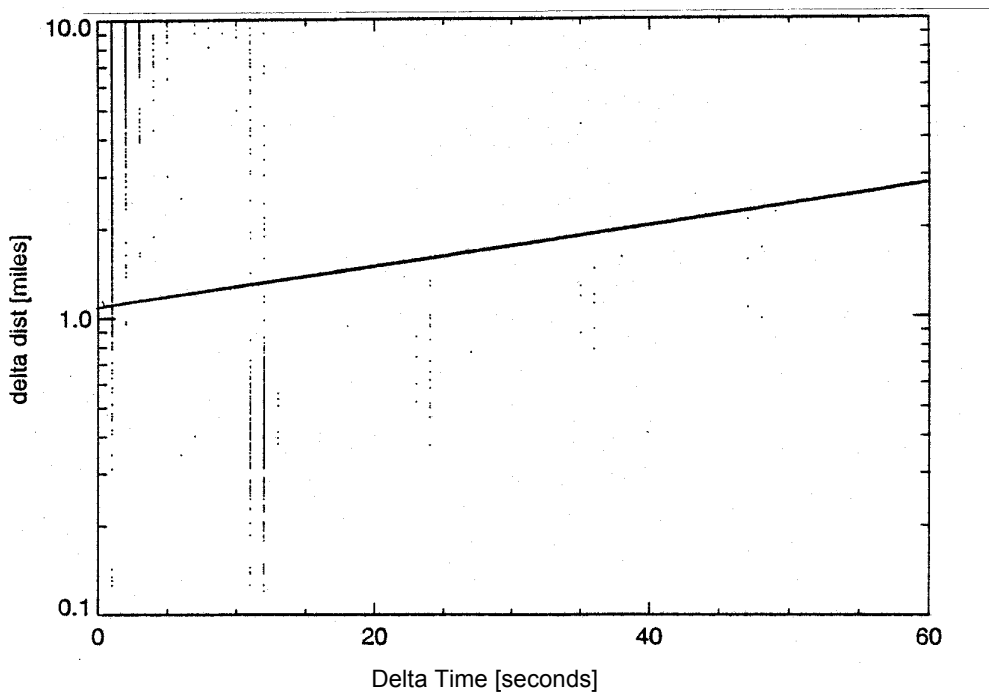


FIGURE 10. DISTANCE BETWEEN SUCCESSIVE POINTS RECORDED FOR SEATTLE 1200 CODE TRACKS VERSUS THE TIME INTERVAL BETWEEN THE SAME TWO POINTS

QUALITY CONTROL AND ACCEPTANCE OF FLIGHT TRACKS. Quality control requirements may be imposed on the ~ 6000 tracks found. When 5-minute track duration and 20-point minimum are required, the number of tracks decreases to ~ 2250 with an average of ~ 96 points/track. Figure 11 shows the points associated with accepted tracks for a three-hour period, and figure 12 shows the remaining unassociated points for the same time interval. These compare to the plot of all points in figure 8. Even though the minimum number of points for track acceptance was doubled to 20, the result is an order of magnitude more tracks with an average number of points three times greater than that found in the Denver study. Indeed, more than 1/4 of all the identified Seattle flight operations are associated with beacon 1200 code.

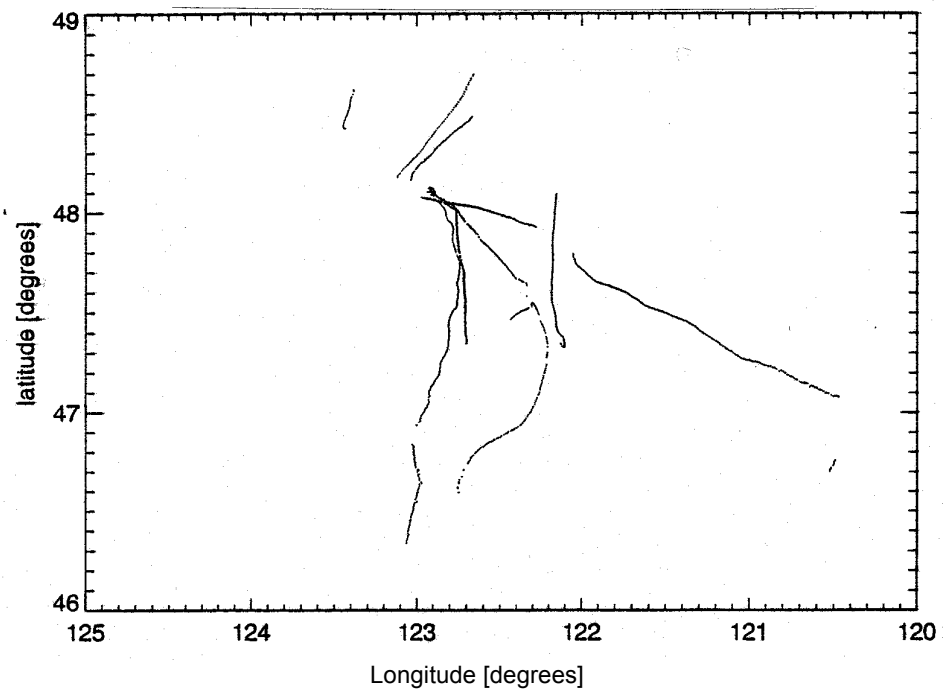


FIGURE 11. FINAL ACCEPTED SEATTLE 1200 CODE TRACKS IN THE SAME SAMPLE THREE-HOUR TIME PERIOD AS DISPLAYED IN FIGURE 8

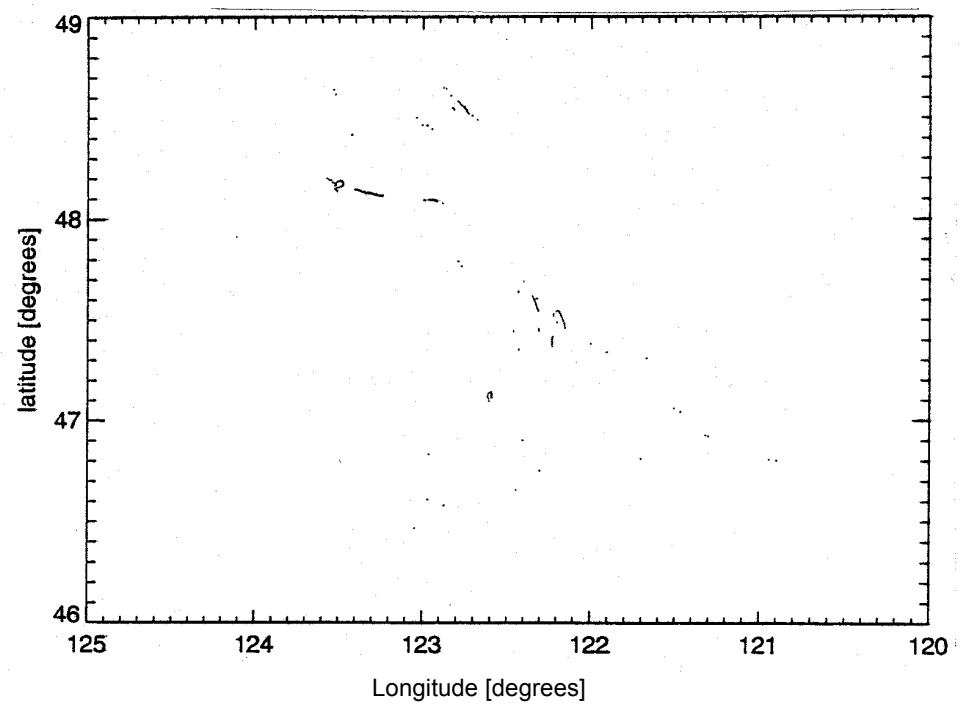


FIGURE 12. REMAINING SEATTLE 1200 CODE ORPHAN POINTS IN THE SAME SAMPLE THREE-HOUR TIME PERIOD AS DISPLAYED IN FIGURE 8

CORRELATIONS OF EMITTERS AND FLIGHT POSITIONS

GENERAL PROCEDURE.

With both the emitter positions and the aircraft flight positions known, it is fairly straightforward to calculate the closest approach of each flight track to each emitter. From this the overall closest approach of a given aircraft track to any emitter is easily found. Two items in this procedure should be noted:

- Straight line interpolation between successive points on the track is used to find the closest approach for the entire trajectory, not just at the recorded points.
- No extrapolation is done. Often the radar does not track the aircraft on the ground in some positions. This means that tracks for takeoff and landing may be truncated slightly short of the ground. Some extrapolation was tried, but the quality of altitude (above ground level) data required for extrapolation did not appear to justify extensive effort in this area.

NON-1200 CODE FLIGHTS.

For all non-1200 beacon code flight tracks, the correlation of emitters and aircraft flight positions through closest approach is shown in figure 13. For each aircraft track a line is drawn from the point of closest approach to the appropriate emitter, marked by a triangle. A variety of emitters and flight paths are represented. Figure 14 displays some of the geometric characteristics associated with the closest approach to an emitter in a scattergram of aircraft altitude (with respect to emitter height) versus horizontal distance from the emitter at the point of closest approach. From this plot, one may infer the elevation angle from the emitter to the aircraft. It is

operating at ~ 10,000 ft. There are also some higher altitude flights above 20,000 ft. Of the two lower altitude clumps, one set of operations occurs in the 1500- to 4500-ft range. Finally, there is a group with closest approach occurring at altitudes of < 1000 ft which must correspond to takeoffs and landings.

Figure 15 represents the relative frequency of closest approach (or slant range). A single occurrence on this plot has a value of ~ 0.0002 corresponding to the approximately 5100 flight tracks considered. Note the log-log scale of the plot. Integration of the curve in figure 15 yields figure 16. This plot shows that a 1% level of closest approach occurs at a distance of approximately 200 ft, not unlike the Denver results.

AIRPORT ZONES.

The behavior of an aircraft in the immediate vicinity of an aircraft is somewhat less variable than elsewhere, being governed more tightly by both general land/takeoff procedures and by the airport traffic control. Furthermore, a separate HIRF operating environment is under consideration for use in an airport neighborhood. It was, therefore, decided to investigate the

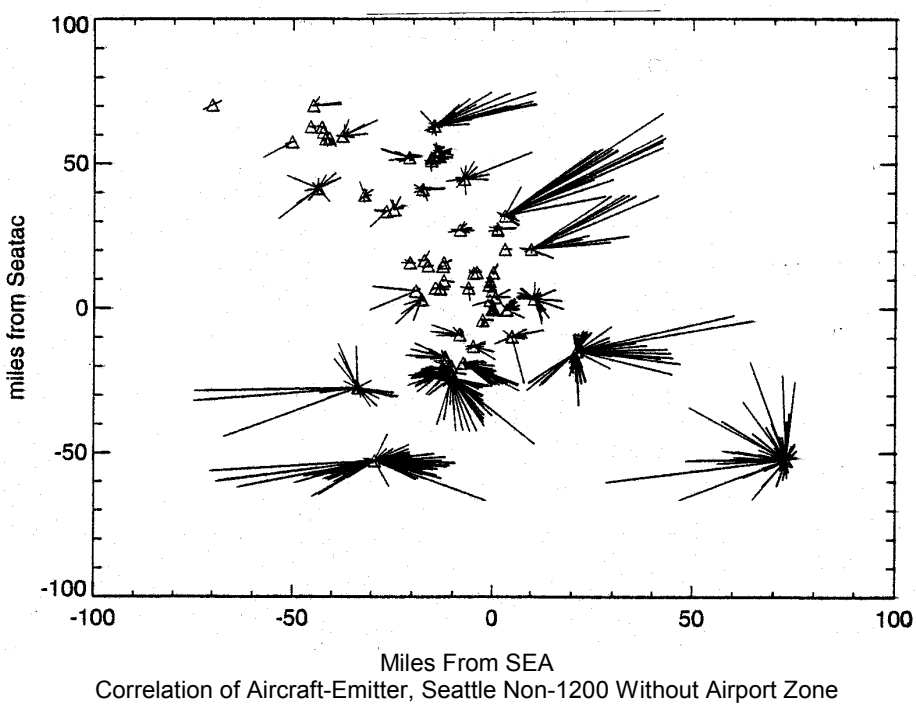


FIGURE 13. EMITTER LOCATIONS WITH VECTORS TO LOCATION OF CLOSEST APPROACH TO AIRCRAFT FLIGHT TRACKS, ALL NON-1200 CODE TRACKS

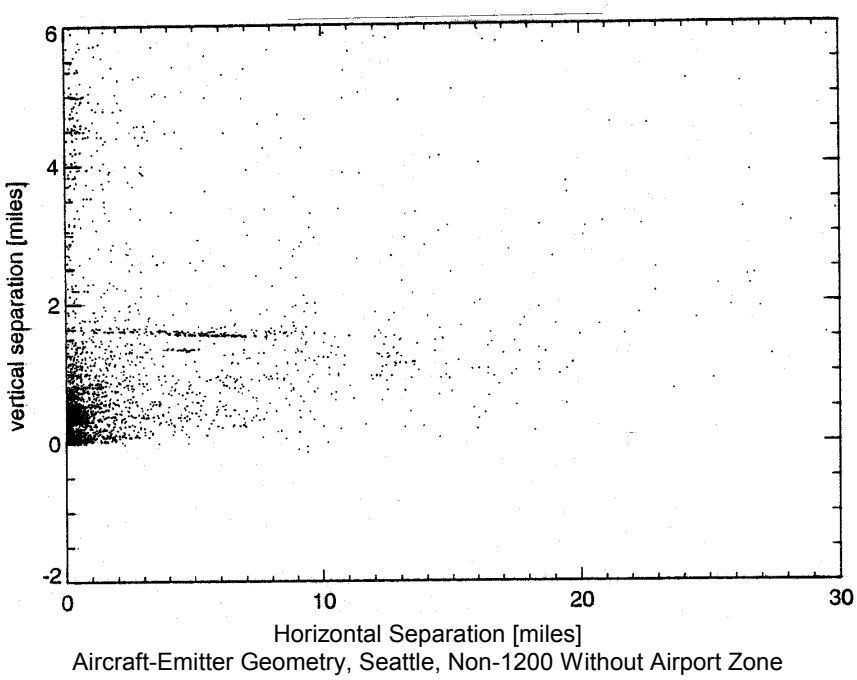


FIGURE 14. POSITION OF AIRCRAFT AT CLOSEST APPROACH WITH RESPECT TO EMITTER, ALL NON-1200 CODE TRACKS

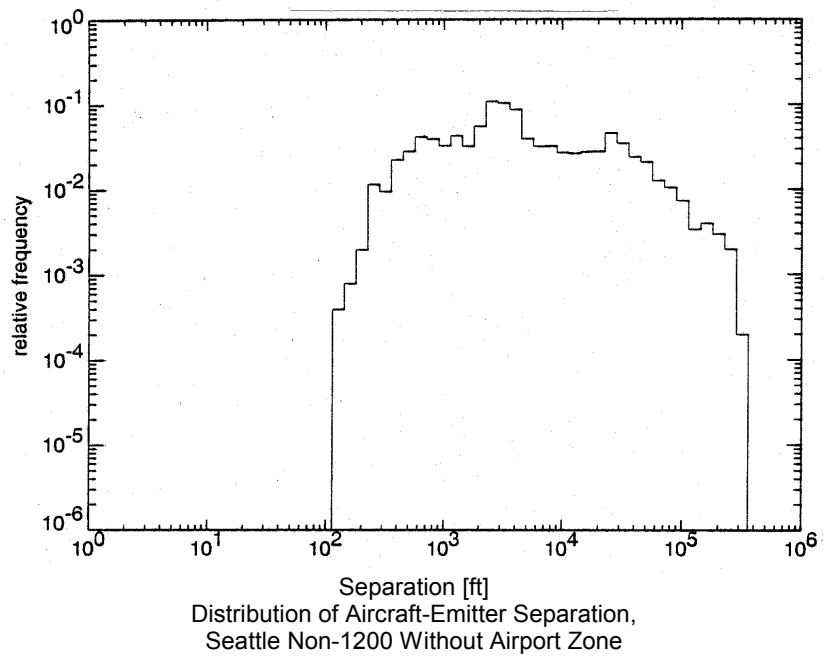


FIGURE 15. RELATIVE FREQUENCY OF CLOSEST APPROACH TO EMITTER, ALL NON-1200 CODE TRACKS

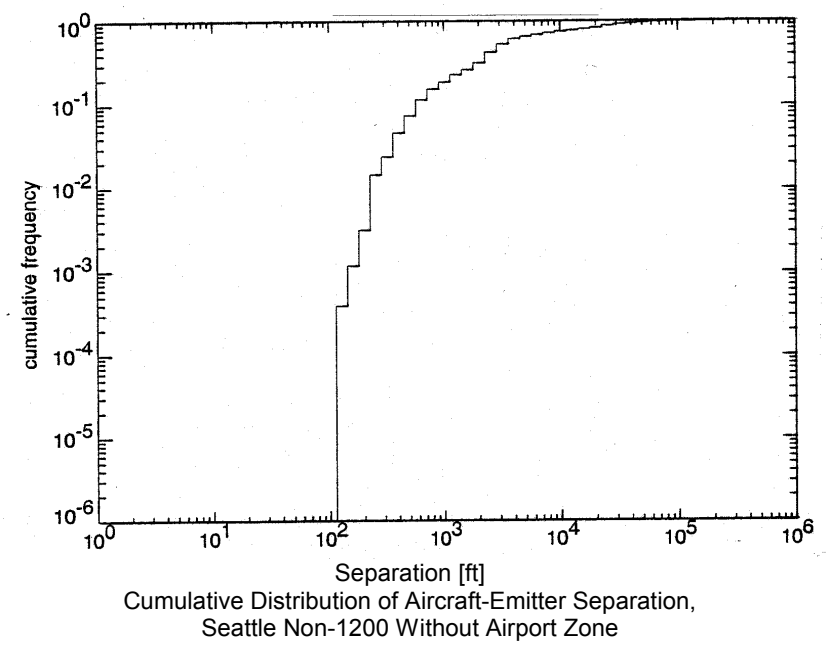


FIGURE 16. CUMULATIVE RELATIVE FREQUENCY OF CLOSEST APPROACH TO EMITTER, ALL NON-1200 CODE TRACKS

effect of excluding airport vicinities from consideration when determining the distance of closest approach to emitters. To this end, a list of airports in the Seattle area was obtained from the U.S. Government Public Airport/Facility Directory for the Northwest. From this listing (plus

McChord and Gray military airfields), the latitude and longitude of the extremes of each airport's runways was determined with the provision for an additional buffer zone defined by extending the latitude and longitude limits of the runways. The airport plus buffer zone extended from ground level to 1500-ft AGL. Figure 17 illustrates the extent of runways at SEA.

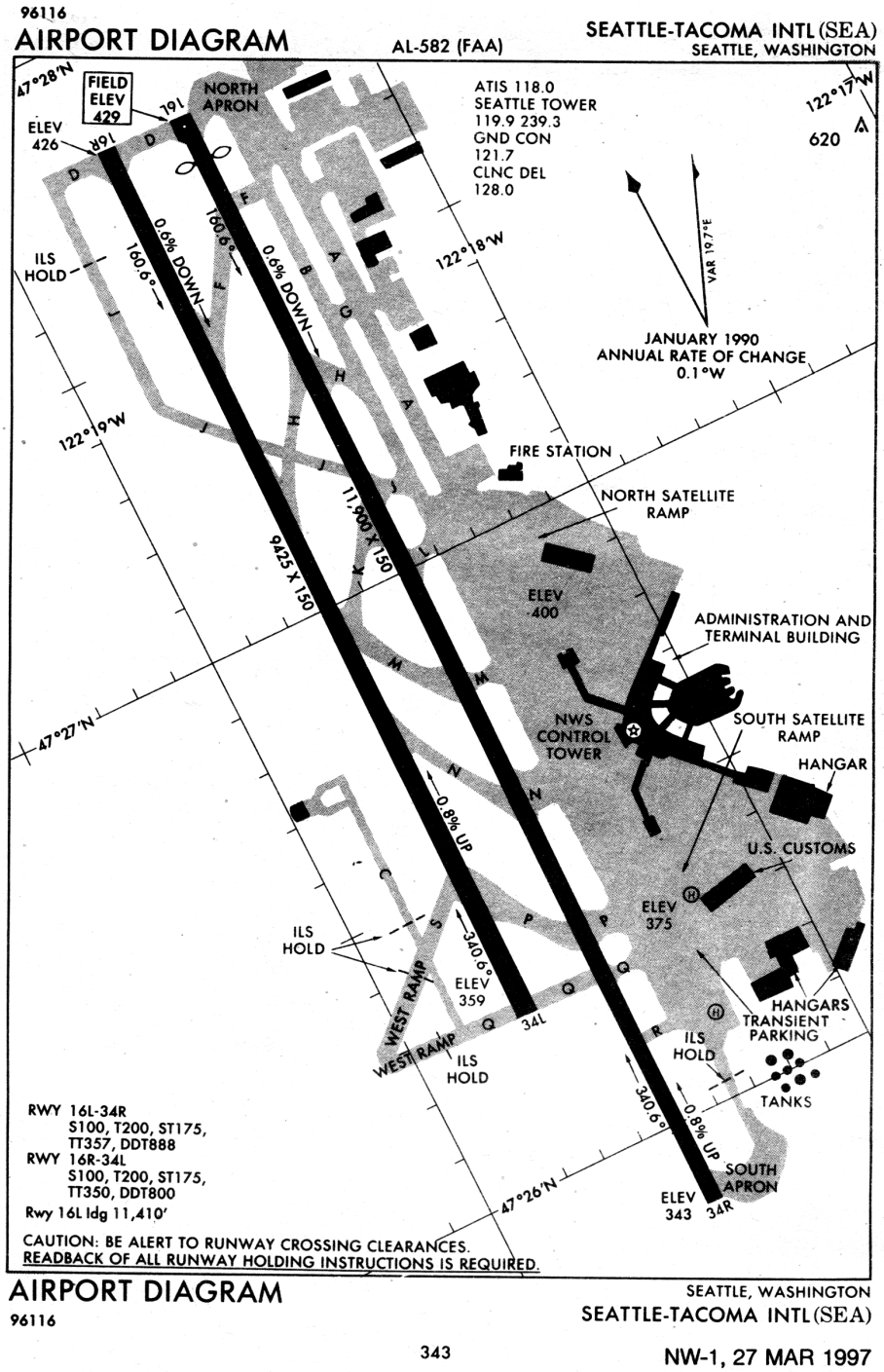


FIGURE 17. SEATTLE-TACOMA INTERNATIONAL AIRPORT DIAGRAM SHOWING LATITUDE AND LONGITUDE EXTENTS OF RUNWAYS

The size of the buffer zone beyond the runway limits in each direction was varied to assess its importance. For a two-mile buffer zone, figure 18 shows the airport locations and the exclusion zones used for closest approach determination. In figure 19 the locations of the candidate emitters are overlaid on top of airport locations. Clearly, there are a number of emitters located on or very close to airports. If the closest approach of an aircraft to an emitter is calculated only outside the airport zones just defined, figure 20 results (for a buffer of 2 nm). Using either the smallest value or the 1% value as a measure, the exclusion of the airport zones increases the distance of closest approach by approximately a factor of four. This is somewhat less than the effect observed in the Denver study.

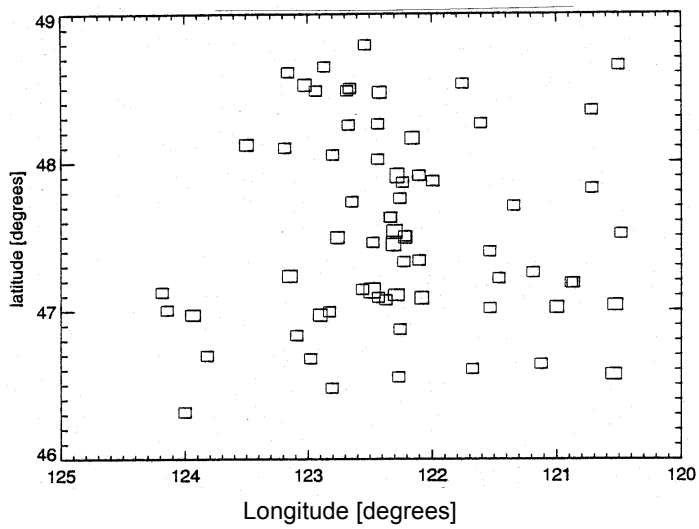


FIGURE 18. AIRPORT LOCATIONS IN THE SEATTLE AREA WITH AIRPORT ZONE USING TWO-MILE BUFFER

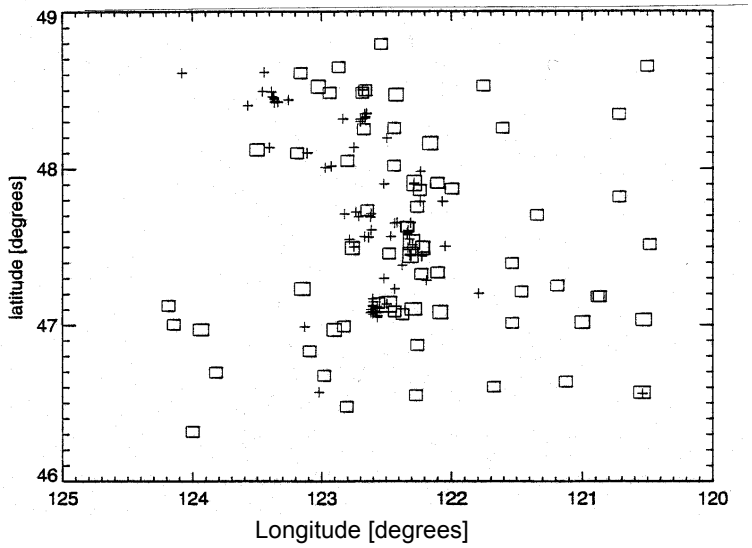


FIGURE 19. AIRPORT LOCATIONS IN THE SEATTLE AREA WITH TRANSMITTER POSITIONS (CROSSES) OVERLAID

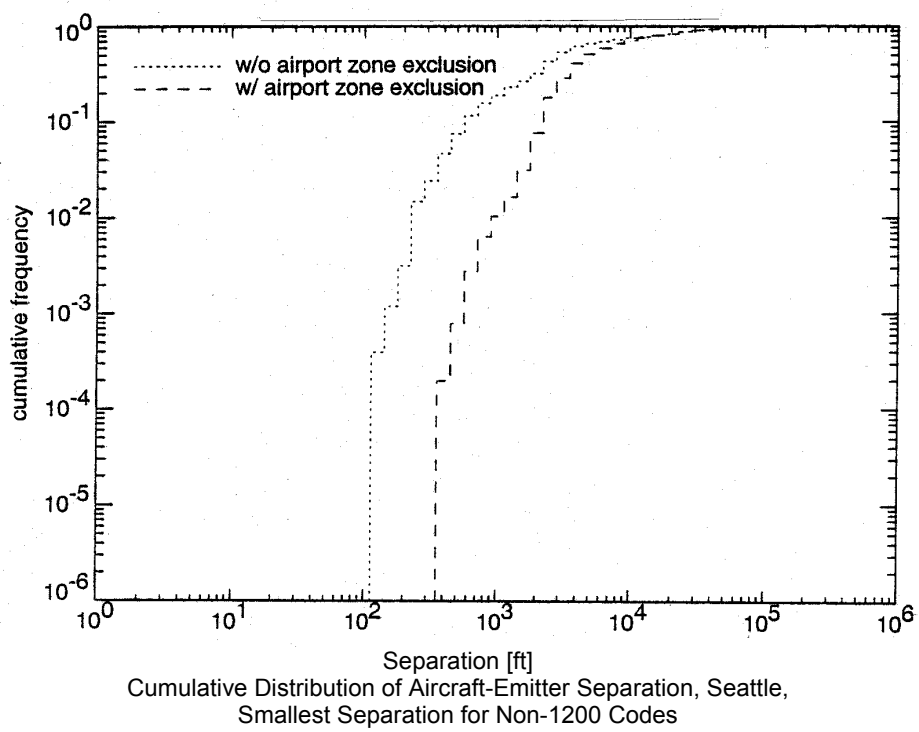


FIGURE 20. COMPARISON OF CUMULATIVE RELATIVE FREQUENCY OF CLOSEST APPROACH TO EMITTER, NON-1200 CODE TRACKS WITH AND WITHOUT EXCLUSION OF AIRPORT ZONE

SEATTLE-TACOMA INTERNATIONAL AIRPORT TAKEOFFS AND LANDINGS.

A very important subset of the aircraft flight data examined involved takeoffs and landings at Seattle-Tacoma International Airport. Approximately 1450 of the ~ 5100 non-1200 code flights originated and/or terminated at SEA. This classification was made by requiring either the first or last point of the track to occur within the airport boundaries with an altitude of less than 800 ft above ground level. Figure 21 shows the cumulative relative frequency for this class of aircraft operation. Also repeated on the same figure is the distribution for all non-1200 code flights. As far as the smallest value of distance of closest approach, it is clear that aircraft operations in and out of SEA generally have greater separation from emitters than do the remainder of the flights. Similar behavior was observed for flights into and out of DIA in the Denver study.

1200 CODE FLIGHTS.

Figure 22 compares distributions of 1200 code and non-1200 code flights using an airport zone with a two-mile buffer. While there appears to be systematic differences between the distributions for the non-1200 and the 1200 code tracks, the differences are not striking. This same relative behavior can also be found in the Denver data where the 1200 code data is much sparser and the number of 1200 codes tracks is an order of magnitude smaller. The effect of the exclusion of the airport zone in determining the distance of closest approach is seen in figure 23. This is to be contrasted with the same comparison for non-1200 code tracks made in figure 20.

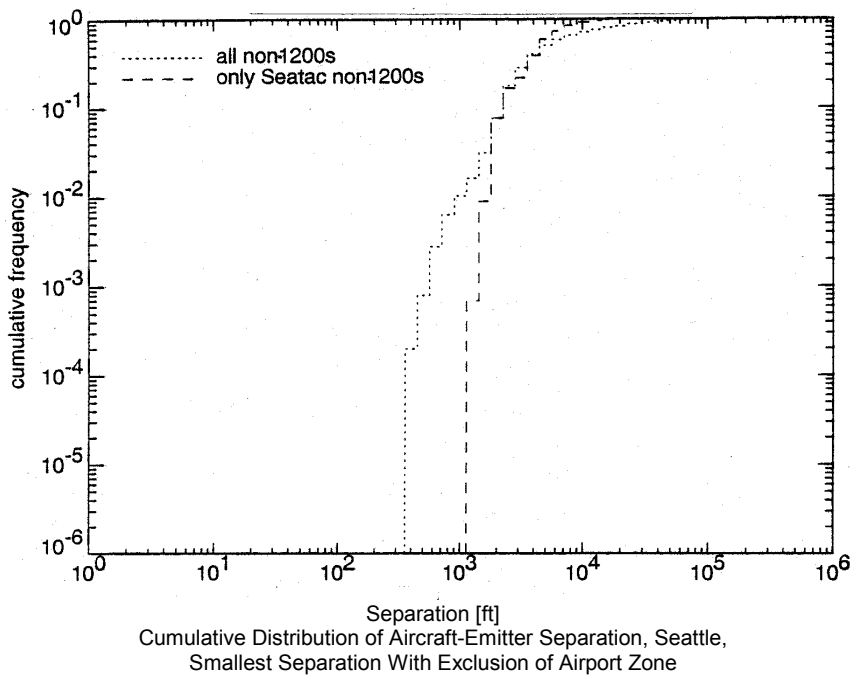


FIGURE 21. COMPARISON OF CUMULATIVE RELATIVE FREQUENCY OF DISTANCE OF CLOSEST APPROACH, ALL NON-1200 CODE TRACKS AND ONLY SEA NON-1200 CODE TRACKS FLIGHT OPERATIONS WITH EXCLUSION OF AIRPORT ZONE

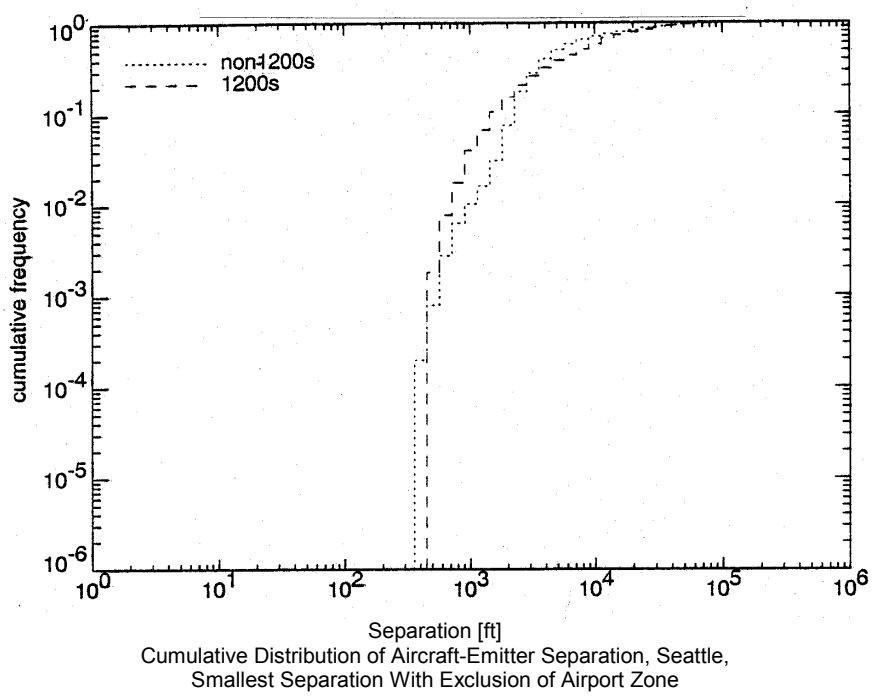


FIGURE 22. COMPARISON OF CUMULATIVE RELATIVE FREQUENCY OF CLOSEST APPROACH TO EMITTER, 1200 CODE AND NON-1200 CODE TRACKS WITH EXCLUSION OF AIRPORT ZONE

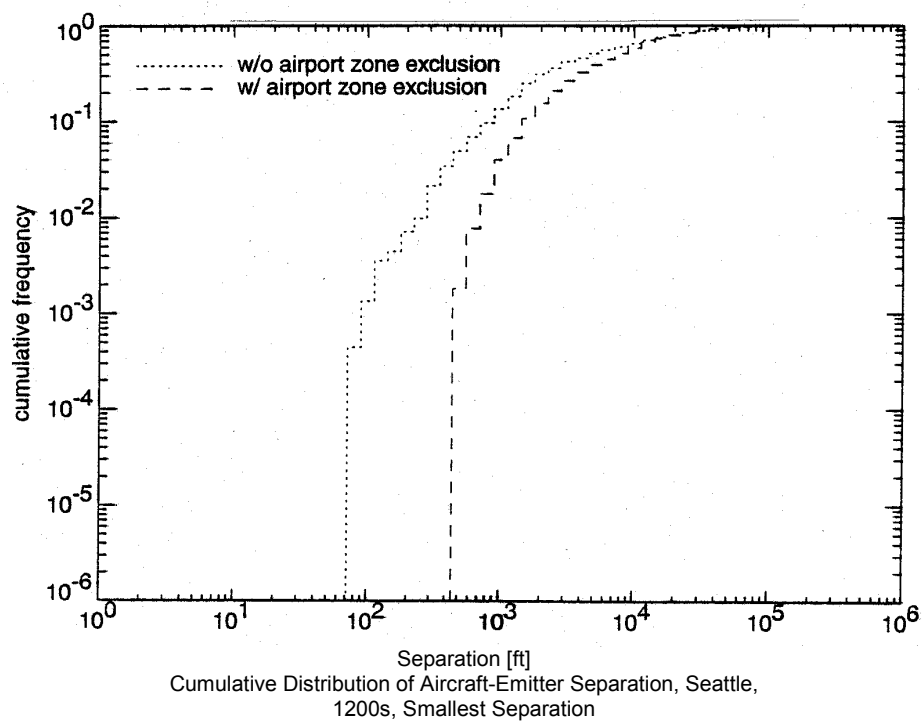


FIGURE 23. COMPARISON OF CUMULATIVE RELATIVE FREQUENCY OF CLOSEST APPROACH TO EMITTER, 1200 CODE TRACKS WITH AND WITHOUT EXCLUSION OF AIRPORT ZONE

OTHER EXCEPTIONAL FLIGHT CODES.

The 1200 beacon code data is presumed to represent a category of relatively local air traffic activity likely to be at lower altitude, flying slowly, and covering small distances. It has also been suggested that other flight activity of a local nature may be associated with certain beacon codes assigned by the SEA traffic control (TRACON). These beacon codes may have filed flight plans but may have fairly atypical flight patterns, e.g., traffic monitoring helicopters and some general aviation. Beacon codes with values of 02xx, 03xx, and 55xx are used for this type of activity in the Seattle area. Approximately 300 tracks have these beacon codes. The effect of excluding these beacon codes from the cumulative relative frequency distribution is exhibited in figure 24 which shows only as small shift to higher separation distances when an airport zone with a two-mile buffer is also required. By way of contrast, the same type of beacon code exclusion in the Denver data nearly doubled the smallest observed separation distance.

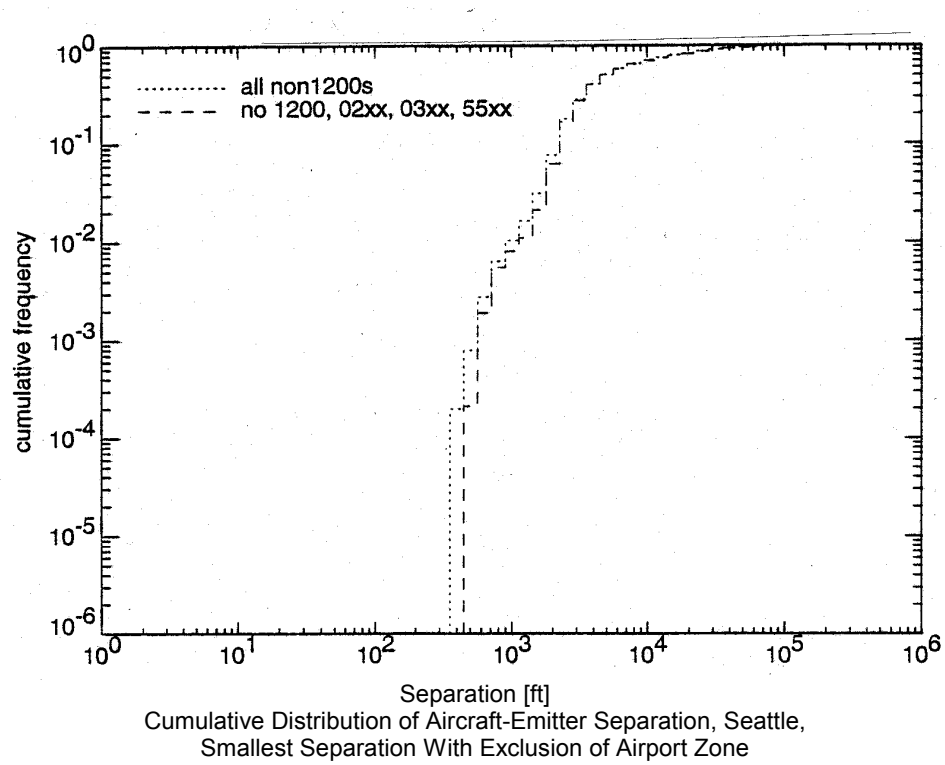
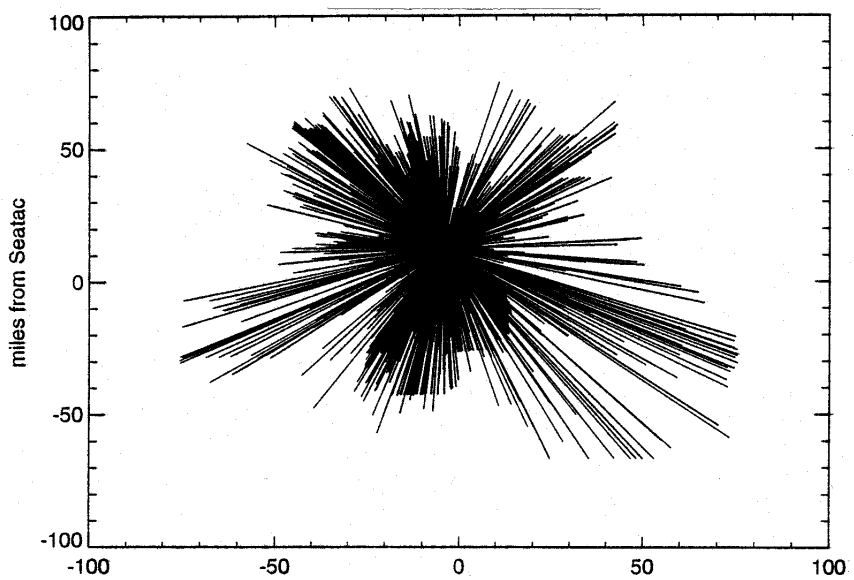


FIGURE 24. COMPARISON OF CUMULATIVE RELATIVE FREQUENCY OF CLOSEST APPROACH TO EMITTER, NON-1200 WITH AND WITHOUT VFR-TYPE BEACON CODES WITH EXCLUSION OF AIRPORT ZONE

OTHER DATA SELECTIONS.

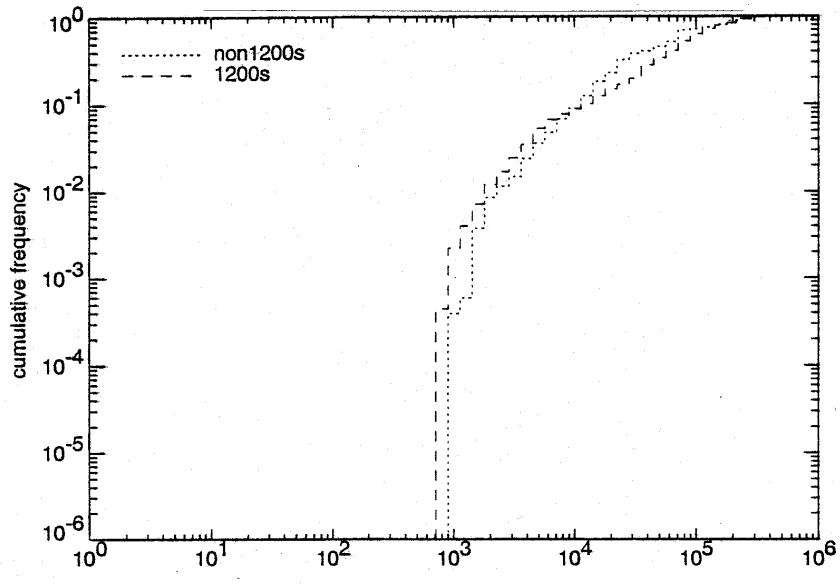
In order to investigate the effect upon the cumulative relative frequency distributions of closest approach, several other conditions were imposed upon the data. A few of them are presented, briefly, here.

SINGLE POWERFUL EMITTER. An instance of a driver transmitter occurs in the Seattle emitter set. This is a surveillance radar which is the most powerful emitter (EM) source in the US in its HIRF frequency band, 1-2 GHz. Figure 25 shows the separation distance pattern for this particular emitter for non-1200 code tracks, while figure 26 shows the cumulative relative frequency distributions for both the 1200 code and non-1200 code tracks. For this particular emitter in the Seattle area, the minimum separation distances are 700-900 ft. Of course, many distributions more or less like these are the basis for obtaining the overall closest approach distributions examined earlier.



Correlation of Aircraft-Emitter, Seattle, 1 Airport Runway Surface Radar Emitter (Ft. Lawton), Non-1200 Without Exclusion of Airport Zone

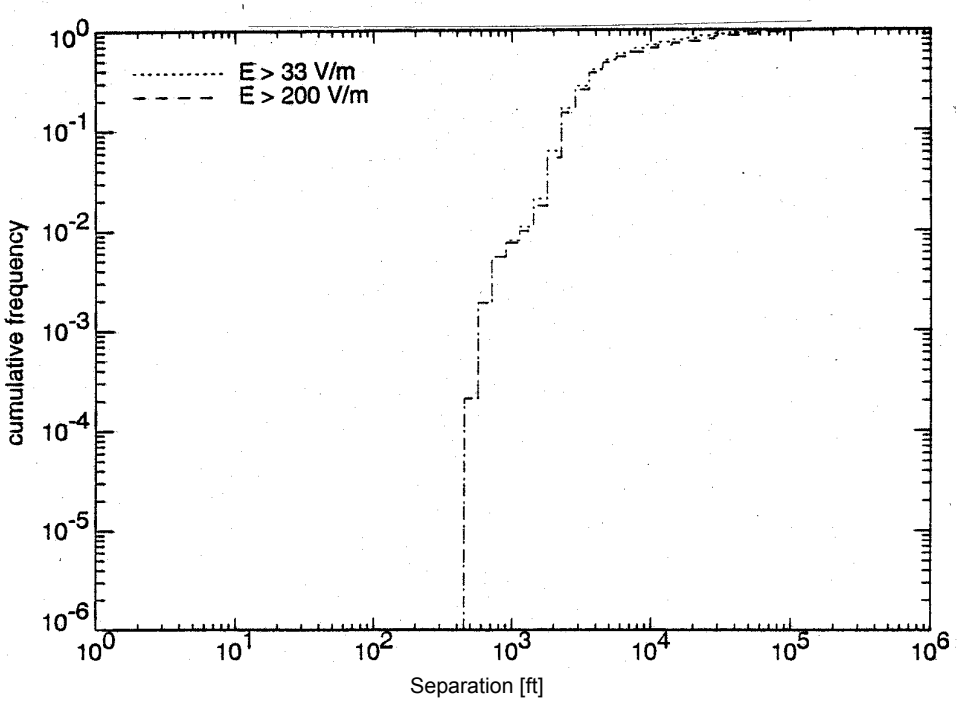
FIGURE 25. SINGLE AIRPORT RUNWAY SURFACE RADAR EMITTER LOCATION WITH VECTORS TO LOCATION OF CLOSEST APPROACH TO AIRCRAFT FLIGHT TRACKS, ALL NON-1200 CODE TRACKS



Cumulative Distribution of Aircraft-Emitter Separation, Seattle, Smallest Separation With Exclusion of Airport Zone, 1 Airport Runway Surface Radar Emitter

FIGURE 26. COMPARISON OF CUMULATIVE RELATIVE FREQUENCY OF CLOSEST APPROACH TO SINGLE AIRPORT RUNWAY SURFACE RADAR EMITTER, NON-1200 CODE TRACKS WITH EXCLUSION OF AIRPORT ZONE

HIGHER-POWER EMITTER GROUP. The initial group of 278 emitter entries considered for correlation with the aircraft positions was chosen by requiring an estimated electric field > 33 V/m at 100-ft separation. If the minimum electric field is required to be > 200 V/m, the number of candidate emitter entries drops to 119. Figure 27 shows the resulting cumulative relative frequency distribution for emitter-aircraft closest approach for this smaller set of emitter entries. As might be expected, a shift to larger separation distances is seen, but the effect is rather small.



Cumulative Distribution of Aircraft-Emitter Separation, Seattle, Smallest Separation
With Exclusion of Airport Zone, non-1200 code, 02xx, 03xx, 55xx

FIGURE 27. COMPARISON OF CUMULATIVE RELATIVE FREQUENCY OF CLOSEST APPROACH TO EMITTER FOR EMITTERS SELECTED BY DIFFERENT ELECTRIC FIELD LEVELS AT 100-FT, NON-VFR-TYPE CODE TRACKS WITH EXCLUSION OF AIRPORT ZONE

EMITTER-AIRCRAFT ELEVATION ANGLE AT CLOSEST APPROACH. Many powerful emitters, such as long range surveillance radars, are restricted in the elevation angle of their central beams. As a crude look at this effect, separation distances were considered to be valid candidates for closest approach only when the elevation angle was less than 45 degrees. Figure 28 exhibits the difference in the cumulative relative frequency distribution of closest approach when this elevation angle restriction is imposed. The effect is noticeable but on the order of 30% to 40% in magnitude.

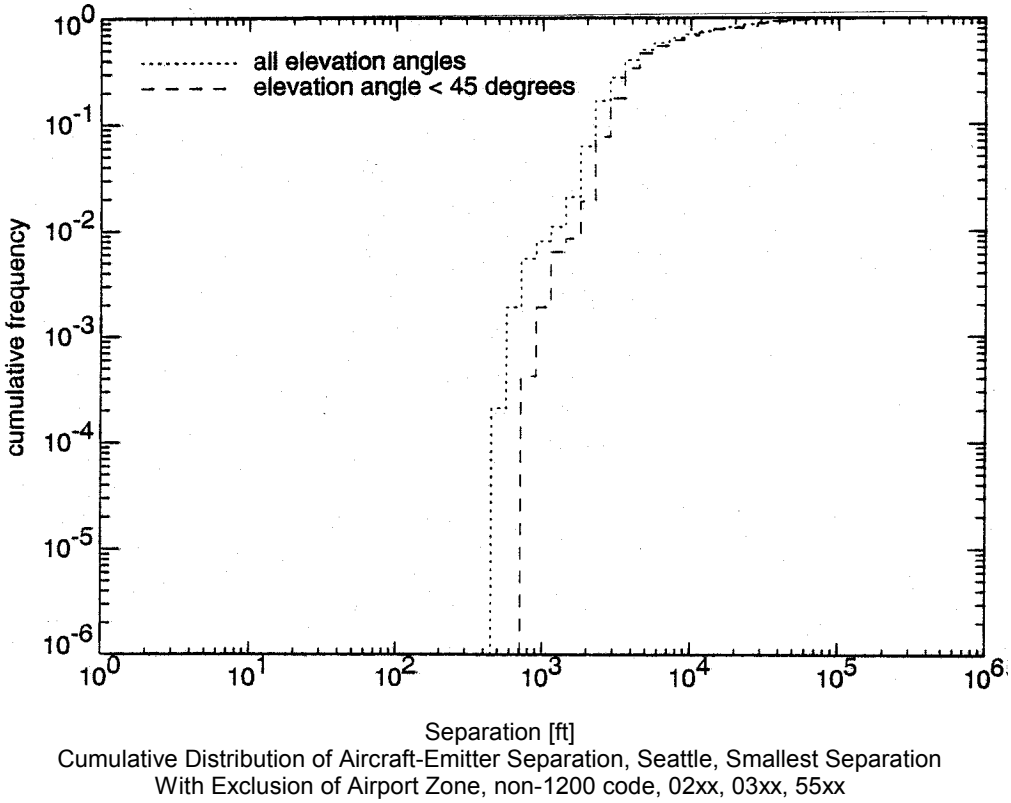


FIGURE 28. COMPARISON OF CUMULATIVE RELATIVE FREQUENCY OF CLOSEST APPROACH TO EMITTER FOR RESTRICTED EMITTER-AIRCRAFT ELEVATION ANGLES, NON-VFR-TYPE CODE TRACKS WITH EXCLUSION OF AIRPORT ZONE

APPROXIMATE ELECTRIC FIELD AT AIRCRAFT. In selecting the group of emitters which were used to find an aircraft's closest approach to any emitter source, the electric field for each emitter was estimated using a reference distance of 100 ft using equation 1. It is a straight-forward matter to calculate similarly the electric field at the aircraft location. This calculation assumed the following:

- Emitter power and antenna gain as entered in the Government Master File are reliable.
- The pertinent electric field to calculate for a simple-minded, worst-case estimate is the maximum value in the main beam of the antenna.
- Equation 1 serves as a reasonable starting formula for calculating the electric field.
- Non-far-field modifications to equation 1 are less than a factor of 2 in magnitude for frequencies > 0.4 GHz and distances > 100 ft from the antenna.

While there may be reservations about the completeness and accuracy of the information going into this calculation, its application to a full set of emitters and aircraft operations in a major metropolitan area provides a broad overview of electric fields encountered by aircraft. As such,

it complements the alternative approach which focuses narrowly on a very few of the largest emitters and which employs only informed hypothesizing about aircraft-emitter separation geometry.

When the largest electric field experienced by an aircraft replaces the minimum distance of closest approach as the figure of merit, the dotted distribution in figure 29 results. In this plot, the cumulative frequency represents the fraction of flights which encounter an electric fields less than the value indicated on the x-axis. 1200 code, 02xx, 03xx, and 55xx aircraft operations are not considered in this case and the electric fields considered are only those exterior to airports and their two-mile buffer extensions. The dashed distribution shows the effect upon the electric field cumulative frequency distribution when a previously considered restriction, elevation angle less than 45 degrees, is also imposed.

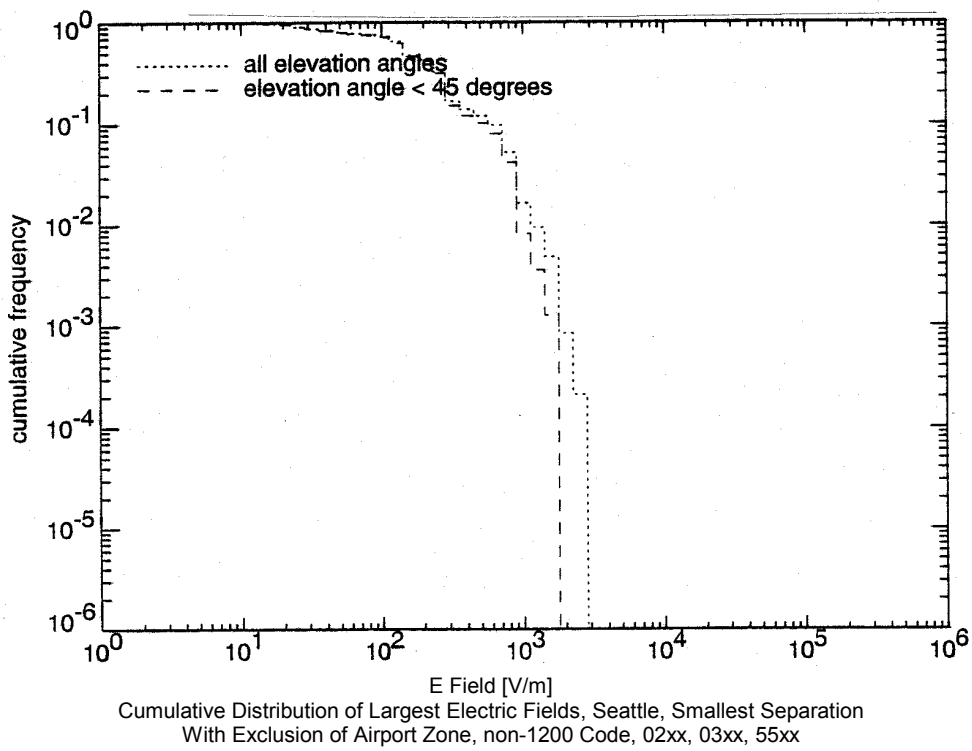


FIGURE 29. COMPARISON OF CUMULATIVE RELATIVE FREQUENCY OF LARGEST AIRCRAFT ELECTRIC FIELD FOR RESTRICTED EMITTER-AIRCRAFT ELEVATION ANGLES AND NON-VFR-TYPE CODE TRACKS WITH EXCLUSION OF AIRPORT ZONE COMPARISON OF DENVER AND SEATTLE RESULTS

COMPARISON OF DENVER AND SEATTLE RESULTS

The main motivation for examining the correlations between aircraft flight positions and emitter locations in the Seattle area was to expand the data sample of such correlations and, through comparison with the previous Denver study, to understand the airport to airport variations of the correlations. Some of these comparisons are presented now.

DISTANCE OF CLOSEST APPROACH.

Using the distance of closest approach of non-1200 code aircraft flights to any of the candidate emitters yields the cumulative frequency distributions in figure 30 for Denver and Seattle. The two airport regions have noticeably different forms and a crossover occurs at the 1% level for ~ 200-ft separation. The information below a few tenths of a percent in each distribution may retain data processing artifacts and is probably not reliable for detailed analysis. Still, it appears that while Denver has the smallest absolute separation values, relatively more of the Seattle flights have smaller separations than Denver flights.

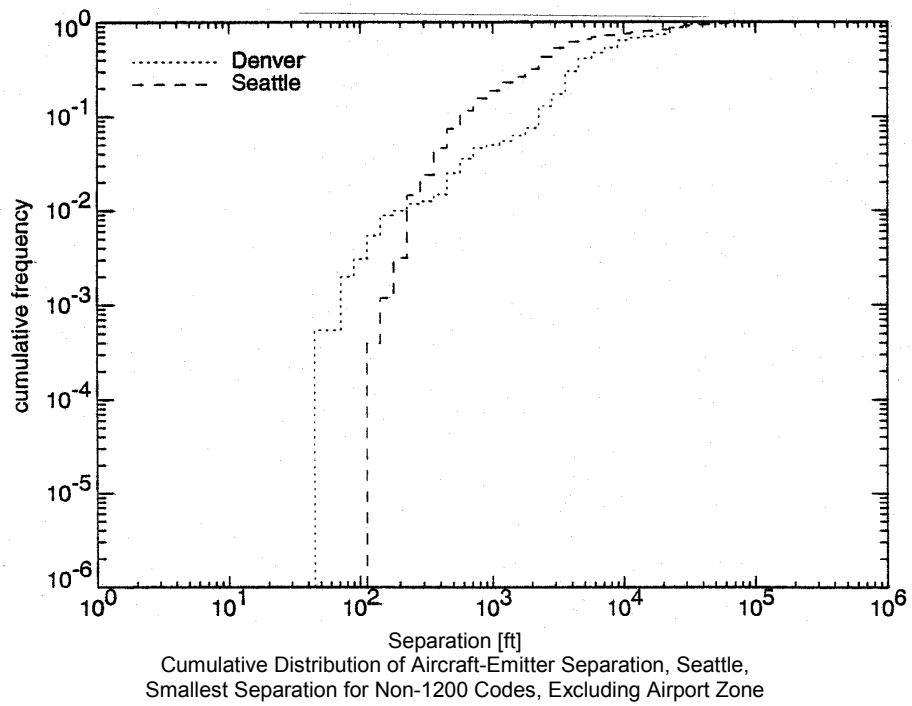
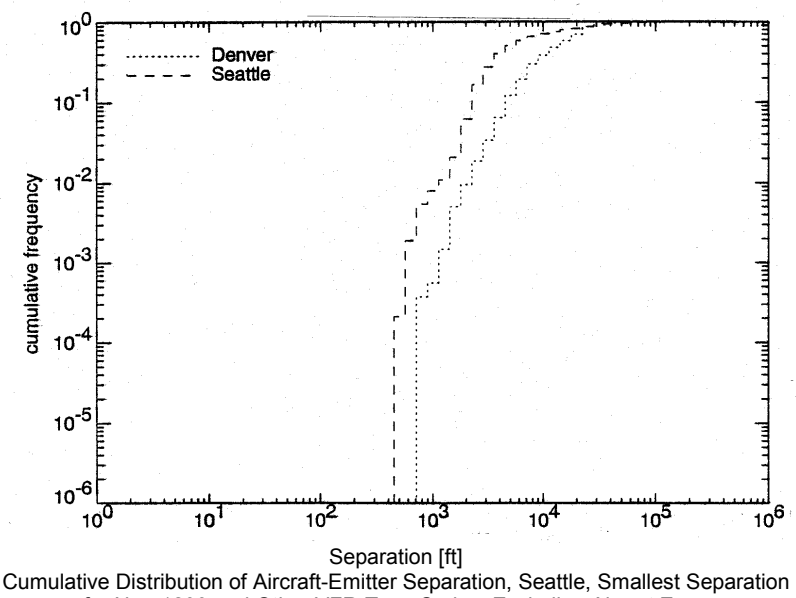


FIGURE 30. SEATTLE-DENVER COMPARISON OF CUMULATIVE RELATIVE FREQUENCY OF CLOSEST APPROACH TO EMITTER, NON-1200 CODE TRACKS EXCLUDING AIRPORT ZONE

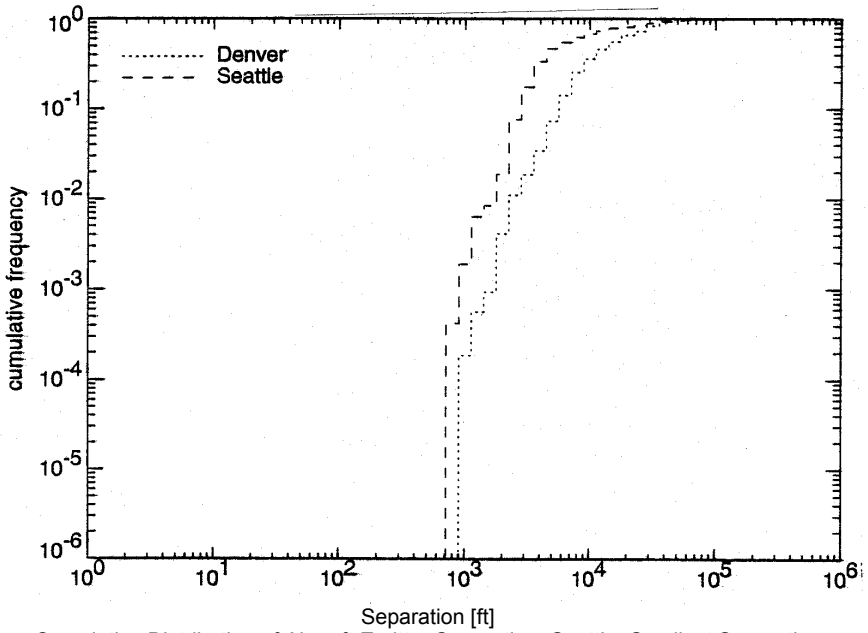
When other visual flight rule-type flight operations are excluded and only separations outside airport zones are considered, figure 31 results. No crossover of distributions occurs in this plot and, while still different, the Denver and Seattle results appear much more alike. This is due mainly to a greater removal of the smallest distances of closest approach from the Denver data. Now Seattle has both the smallest absolute values and relatively greater proportion at smaller values.

Imposing an additional requirement considered earlier, elevation angle from emitter to aircraft less than 45 degrees at closest approach, leads to the curves in figure 32. With respect to the previous figure, the minimum closest approach for both cities is pushed to a larger value. The relative effect is similar for both curves.



Cumulative Distribution of Aircraft-Emitter Separation, Seattle, Smallest Separation for Non-1200 and Other VFR-Type Codes, Excluding Airport Zone

FIGURE 31. SEATTLE-DENVER COMPARISON OF CUMULATIVE RELATIVE FREQUENCY OF CLOSEST APPROACH TO EMITTER, NON-VFR TYPE CODE TRACKS EXCLUDING AIRPORT ZONE



Cumulative Distribution of Aircraft-Emitter Separation, Seattle, Smallest Separation for Non-VFR-Type Codes, Excluding Airport Zone and Angles > 45 degrees

FIGURE 32. SEATTLE-DENVER COMPARISON OF CUMULATIVE RELATIVE FREQUENCY OF CLOSEST APPROACH TO EMITTER FOR RESTRICTED EMITTER-AIRCRAFT ELEVATION ANGLES, NON-VFR-TYPE CODE TRACKS EXCLUDING AIRPORT ZONE

MAXIMUM ELECTRIC FIELD.

A preliminary look at distributions using the estimated maximum electric field encountered by an aircraft in flight is given in figure 33. This plot is only for non-1200 code aircraft operations but does not have any restrictions with regard to airport proximity. The crossover effect noted in the distance of closest approach distributions is barely observed, occurring at the not too reliable level of 0.1%.

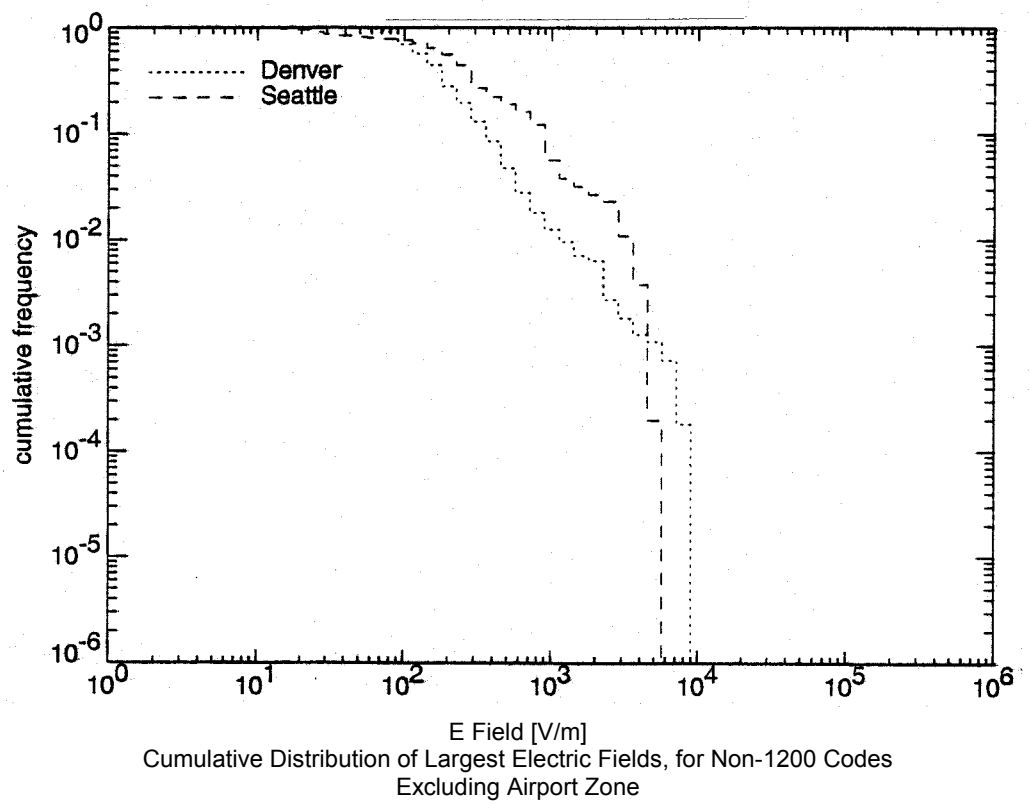


FIGURE 33. SEATTLE-DENVER COMPARISON OF CUMULATIVE RELATIVE FREQUENCY OF LARGEST AIRCRAFT ELECTRIC FIELD, NON-1200 CODE TRACKS EXCLUDING AIRPORT ZONE

When other VFR-type flight operations are eliminated and airport zones are excluded, the distributions for Denver and Seattle are much more similar out to the 0.2% levels seen in figure 34. In both of the figures, the largest electric fields encountered by aircraft occur in the Denver area. For the data considered, this is probably an appropriate conclusion.

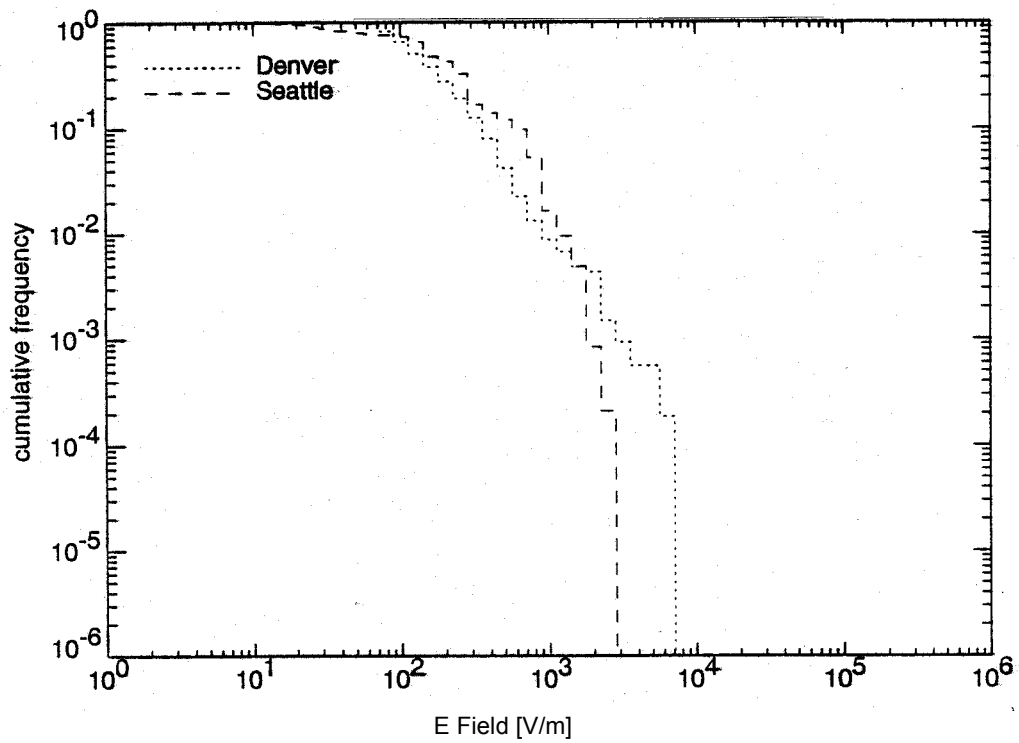


FIGURE 34. SEATTLE-DENVER COMPARISON OF CUMULATIVE RELATIVE FREQUENCY OF LARGEST AIRCRAFT ELECTRIC FIELD, ALL NON-VFR-TYPE CODE TRACKS EXCLUDING AIRPORT ZONE

INFERENCES FROM COMPARISONS.

It is clear that that conclusions drawn from comparisons of the Seattle and Denver studies can depend on several factors:

- figure of merit chosen to form the frequency distributions; e.g., separation or electric field
- restrictions on data sampling; e.g., non-VFR codes, exclusions of airport zones, elevation angle etc.
- type of comparison; e.g., absolute extreme values, 10%, 1%, 0.1%, or 0.01% levels

Factors of two variations are seen in the absolute extreme values between Seattle and Denver, but these values are probably associated with more suspect data. For absolute extremes and at the 0.1% relative level, Denver usually is worse with regard to possible HIRF considerations, but not always (see figure 32). In other relative comparisons, the range of variation can be even larger for given separation or electric field values, but for 0.1% to 1% levels the variations are more often a factor of 1.3 or so.

DATA RESOLUTION AND UNCERTAINTY

There are several limitations and sources of uncertainty within the data used in this study. Many of these are technical in nature, arising from the inherent resolution of instrumentation such as radars or altimeters. Others are more procedural in nature such as computer code processing of radar data, number of digits recorded, or accuracy/completeness in entering emitter data into the Government Master File. As needed, all of these factors have been dealt with in this study in the ways previously described.

DATA DEFECTS.

For review, identified factors are separately listed below for emitter information and for flight position information.

- Emitters Factors:

  - discretization of emitter locations
  - lack of arc-second values in latitude/longitude values
  - mobility of some transmitters within their assigned area
  - missing or inaccurate site elevation or antenna height values
  - ambiguity between transmitter power and effective radiated power

- Flight Position Data Factors:

  - radar resolution
  - minimum altitude of radar tracking
  - instrumentation and processing confusion for radar data
  - limitations of SAR tapes for recording desired data
  - discretization of aircraft positions
  - altimeter resolution to nearest 100 ft
  - inherent altimeter accuracy and barometric variations
  - degeneracy of all 1200 code radar information

RESOLUTION EFFECTS.

To grasp the impact of some of these effects, the resolution degradation due to discretization was examined. Aircraft flight position data is recorded on a SAR tape as an (x,y) coordinate pair in the en route air traffic control center's own coordinate system. The units of recording are 1/16 nm (~ 380 ft). Emitter longitude and latitude are recorded in the Government Master File to the nearest arc-second (~ 100 ft for latitude). Clearly, separation distances calculated using aircraft and emitter positions recorded in this way have definite limits in precision. It should also be clear that the relative error will increase as the true separation distance decreases. A small Monte Carlo calculation was undertaken to quantify the resolution smearing associated with discretization. A true separation distance was recalculated in the following manner:

1. Select the true distance x and generate the emitter $(0,0,0)_{em}$ and aircraft $(x,0,0)_{ac}$ positions.

2. Rotate the aircraft position to a new position $(x',y',0)_{ac}$, this is done repeatedly in 1° step from 0-360°.

3. Translate both the emitter and aircraft positions to $(x'',y'',0)_{em}$ and $(x'',y'',0)_{ac}$. The translation is independently and randomly generated for both the x and the y direction and 500 translations are generated for each rotation angle.

4. Discretize the emitter and aircraft positions to $(x''',y''',0)_{em}$ and $(x''',y''',0)_{ac}$, for the emitter, round to the nearest 1/60 nm, for the aircraft, round to the nearest 1/16 nm.

5. Calculate the resolution smeared separation distance as s=$\sqrt{(x'''_{ac}-x'''_{em})^2+(y'''_{ac}-y'''_{em})^2}$.

Figure 35 shows the ensemble of recalculated distances for a true distance of 1000 ft. Approximately 1% of the time one can expect a true separation of 1000 ft to have a calculated value of < 500 ft. If a distribution of true separations is used (solid line), the smeared relative frequency distribution traced by the dotted line in figure 36 results. The cumulative form for this same starting distribution is shown in figure 37. In both of these latter two plots, the solid line represents the true distribution and the dotted line represents the result which would be calculated using the SAR tape processing procedures described earlier in this report. In the cumulative frequency distributions, changes on the order of a factor of two are seen between true and calculated values when the levels are 1% or less. Thus, low-level tails observed in the plots of distance of closest approach and aircraft electric field are likely to be enhanced by the processing procedures for the available recorded data.

In this quick look at the effect of discretization upon resolution, the effect of altitude has been neglected (z = 0). It can also be included in a straightforward manner if required. With respect to the calculation just performed, altitude introduces two competing effects. Its 100-ft resolution would add slightly more smearing at 0 or very small elevation differences between the emitter and aircraft. The main effect, however, is to add a term in quadrature in the discretized calculation of the separation distance. This would tend to decrease the discrepancy between true and calculated values, especially if more of the separation is attributable to the z coordinate, altitude.

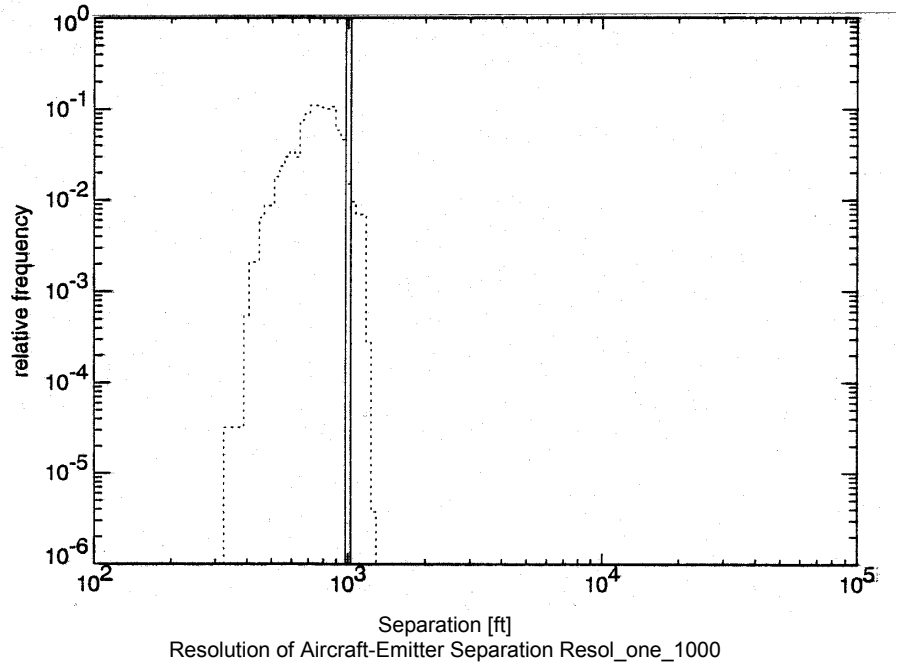


FIGURE 35. RESOLUTION SMEARING INTRODUCED IN RELATIVE FREQUENCY BY DATA DISCRETIZATION FOR 1000-FT TRUE SEPARATION DISTANCE
(Solid Line = True, Dotted Line = Smeared)

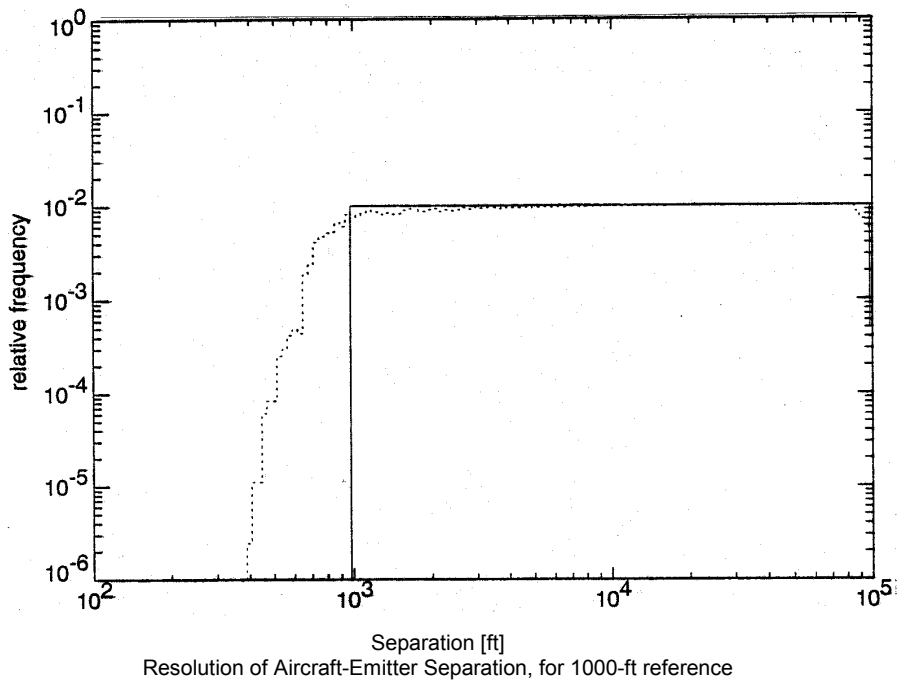


FIGURE 36. RESOLUTION SMEARING INTRODUCED IN RELATIVE FREQUENCY BY DATA DISCRETIZATION FOR A SIMPLE DISTANCE DISTRIBUTION
(Solid Line = True, Dotted Line = Smeared)

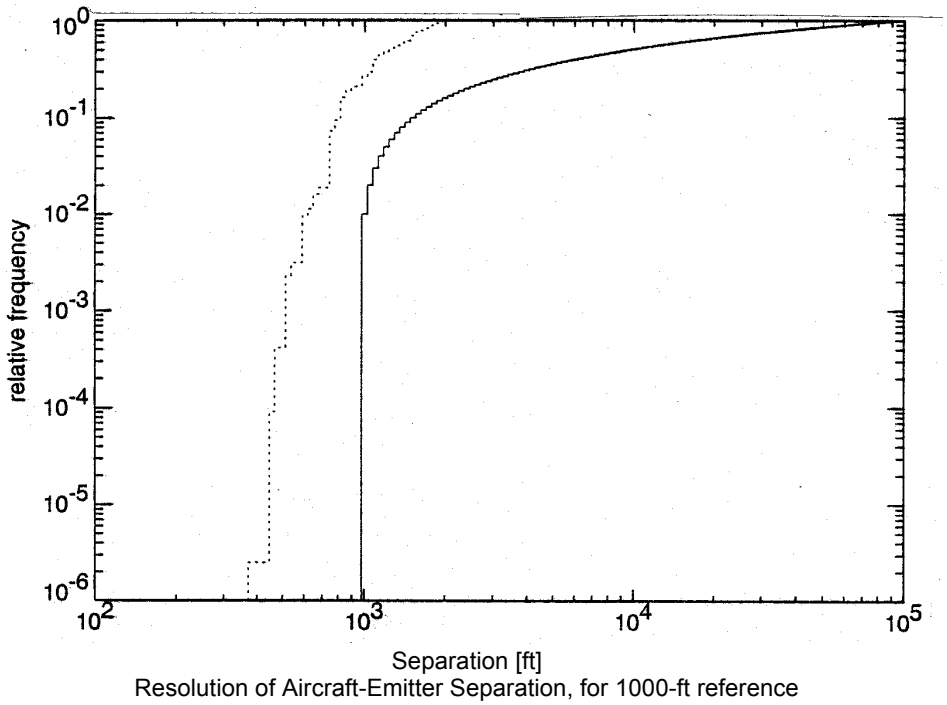


FIGURE 37. RESOLUTION SMEARING INTRODUCED IN CUMULATIVE FREQUENCY BY DATA DISCRETIZATION FOR A SIMPLE DISTANCE DISTRIBUTION
(Solid Line = True, Dotted Line = Smeared)

AIRPORT SAMPLE LIMITATIONS.

In addition to emitter and flight position information and data processing, there are issues associated with this investigation which affect its validity for use in a larger context. These issues mainly result from the limited sampling nature of the study.

Study Sampling Factors:

- two areas, two airport, two sets of emitters, two geographies
- three-day sample period for each area
- one weather pattern for each area
  ~ 5000 flights/area - accuracy-confidence limit ~ 1/(number of samples)

SUMMARY AND CONCLUSIONS

The correlation of emitter positions and in-flight aircraft positions in the Seattle area has been examined in detail for a three-day period. An initial set of > 6000 emitters was reduced to ~ 270 when frequency was restricted to > 400 MHz, and a minimum potential electric field level was required. The resulting candidates were used in determining the closest approach of aircraft to emitters. In-flight aircraft positions as a function of time were obtained from FAA air traffic

control SAR tapes with much processing and checking of the data to obtain the flight tracks for use in the correlation studies. Special considerations were given to the effects of:

- bounding the immediate vicinity of area airports;
- the special category of beacon code 1200 corresponding to aircraft operations without filed flight plans;
- the category of beacon codes 02xx, 03xx, and 55xx associated with special use aircraft operations more typical of VFR behavior;
- elevation angle; and
- proximity of only the strongest emitters.

Relative frequency distributions were plotted either as a function of the distance of closest approach of an aircraft to any emitter or as a function of the maximum electric field estimated to be experienced by the aircraft. Cumulative forms of these distributions were also examined for extreme values and observed values at specified levels of likelihood. The usefulness of the study was augmented by direct comparisons of distributions obtained by similar processing of aircraft flight position and emitter information in the Denver area.

The primary conclusions are:

- The Seattle data used appears trustworthy and represents > 6000 emitters and > 5000 flights observed over an area approximately 120 x 120 square miles.
- The closest approach of aircraft to emitters in the Seattle area involves > 40 different emitters spread throughout the region.
- With no exclusions, some aircraft are observed to pass within 150 ft of an emitter.
- If the areas around airports are excluded from consideration, the closest proximity of aircraft to emitters increases by a factor of three when an additional two-mile buffer is added to the airport boundaries.
- For non-1200 code flights a slightly smaller distance of closest approach is observed for 02xx/03xx/55xx beacon codes.
- While 1200 code flight tracks have a noticeably different characteristics, the cumulative relative frequency of closest approach is not dramatically different from that of non-1200 code tracks, when airport zones are excluded.
- When beacon codes 1200, 02xx, 03xx, and 55xx are excluded and airport zones with a two-mile buffer are excluded, the minimum distance of closest approach observed is ~ 550 ft and the 1 % level occurs at ~ 1100 ft for the Seattle data.

- Seattle and Denver have many common characteristics with regard to the correlation of emitter locations and aircraft flight positions but distinct differences are also clear. In particular, relative differences up to a factor of two are seen in extreme values and low frequency levels.

- For Seattle and Denver, at least, simple minded consideration of maximum electric field levels encountered by aircraft leads to different conclusions than would be drawn by consideration of only distance of closest approach.

Other items worthy of consideration and further investigation include:

- Determination of the generality of these results by similar studies at airports beyond Seattle and Denver, perhaps in Europe.

- Evaluation of the usefulness of exclusion zones around airports upon distance of closest approach to emitters in assigning HIRF certification levels, perhaps using more deterministic methods of evaluation within these zones.

- Employment of information regarding the different categories of aircraft operation, as evidenced by beacon codes such as 1200, and other codes encompassing flights operating under visual flight rules in assigning HIRF certification test levels.

- Extension of the present methodology to calculate the angle and incidence and polarization of the illuminating EM field at the point of closest approach for each aircraft flight.

- Consideration of the effect of proposed free flight air traffic patterns upon the distribution of the closest approach of aircraft to emitters.

REFERENCE.

1. Elliott, James R. and Perala, R. A., "Statistical Study of the Distance of Closest Approach of Aircraft to Ground-Based Emitters," DOT/FAA/AR-98/75, Federal Aviation Administration, William J. Hughes Technical Center, Atlantic City International Airport, NJ, 1999.