5.13 AIRCRAFT ENCOUNTERS WITH THUNDERSTORMS IN ENROUTE VS. TERMINAL AIRSPACE ABOVE MEMPHIS, TENNESSEE

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1. INTRODUCTION*

To date, very little attention has been given to quantifying the effects of thunderstorms on air traffic in enroute airspace. What types of storms cause pilots to deviate from their nominal flight routes? What types of storms do pilots fly through? Around? Over? When thunderstorms are forecast to affect a particular region, how many planes will need to be rerouted? Which ones? Which aspects of the storm need to be accurately forecast in order to answer those questions? How does the forecast accuracy affect the quality of airspace capacity predictions? Quantitative answers to these questions would contribute to the design of useful decision support tools.

Federal Aviation Administration decision support tools are being equipped with the ability for air traffic managers to define dynamic 'flow constrained areas' (FCAs). Each FCA will be a polygon in latitude/ longitude space with ceiling and floor altitudes and a motion vector. One primary use for FCAs will be to define regions that do, or probably will, contain convective thunderstorm activity. These tools will help air traffic managers decide which planes to re-route around the weather and which planes have a reasonable chance of flying through, between, or over the storms. Although it will be helpful to have the ability to manually define FCAs in the traffic managers' tools, the efficiency of the solutions that will be worked out with those tools would be greatly enhanced by answers to the questions posed above.

In our prior work (Rhoda et al., 1999a, 1999b, 2000) we have attempted to quantify the behavior of pilots who encounter thunderstorms in terminal airspace during the final 60 nautical miles of flight. In this study we compare the storm avoidance behavior of pilots in enroute airspace with that of pilots who encountered the very same storms at lower altitudes, in terminal airspace. The study is preliminary, but it complements the terminal work, affords some insight into pilot behavior, and raises questions that should be addressed in a larger study.

2. METHODOLOGY OVERVIEW

Weather and flight track data were collected in the vicinity of Memphis, Tennessee, which serves as an intersection of several busy enroute jetways. Data were collected for 43.5 hours over six thunderstorm days in the late spring and early summer of 1999. Aircraft were identified that flew over the Memphis area in 'enroute' airspace that is controlled by air traffic controllers at the Memphis Air Route Traffic Control Center. The overflights were examined for instances where they penetrated or deviated around storms. The storm encounters were characterized using two-dimensional (2-D) and three-dimensional (3-D) weather radar data.

The six days in this study were previously used in a larger study to examine the behavior of pilots in the final 60 nautical miles of flight before landing at Memphis International Airport (MEM). (Rhoda et al., 2000) The aircraft in that study were in 'terminal' airspace that is controlled by air traffic controllers at the Memphis Terminal Radar Approach Control at the airport.

3. ANALYSIS IN ENROUTE AIRSPACE

Aircraft surveillance data were collected from the Memphis Airport Surveillance Radar (ASR-9) to record aircraft positions every five seconds in the airspace within 60 nautical miles of the MEM airport. To identify aircraft that were in enroute airspace, the surveillance data were filtered to eliminate planes that spent any time at all below 12,000 feet. The remaining 1,187 flights were considered to be overflights.

Weather radar data were collected using the MEM ASR-9, the MEM Terminal Doppler Weather Radar (TDWR), and the Memphis WSR-88D (NEXRAD). The ASR-9 is a fan beam radar that generates a 2-D, plan-view, storm reflectivity map every 30 seconds. The TDWR and NEXRAD are pencil-beam Doppler radars that take up to 6 minutes to scan at multiple elevation angles in order to sample the storm reflectivities in 3-D. For the purpose of this study, the data from each set of TDWR and NEXRAD scans were interpolated to construct 3-D Cartesian representations of the storms.

In air traffic control terminology, radar reflectivity values are often expressed using the National Weather Service's 6-level VIP scale. One may convert between range corrected reflectivity (dBZ) and the VIP scale as follows: Level 1 = 18-29 dBZ; Level 2 = 30-40 dBZ; Level 3 = 41-45 dBZ; Level 4 = 46-49 dBZ; Level 5 = 50-56 dBZ; Level 6 = 57+ dBZ. Most airborne weather radars show level 1 precipitation in green, level 2 in yellow, and level 3+ in red/magenta. (AjT, Inc., 1999)

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3.1 Identifying Penetrations

Encounters were identified where the planes appeared to fly through level 2+ precipitation for 25 or more seconds according to the 2-D ASR-9 weather product. There were 369 such apparent penetrations. See Figure 1. Penetrations of level 1 precipitation were ignored because they are so common and the weather is generally considered to be harmless.

Because the storms are three-dimensional, there is some ambiguity in a 2-D analysis. If an aircraft appears to penetrate a storm, it is not clear whether it actually flew through the storm, over the storm, or under the storm. If it did fly through the storm, then it is not clear what reflectivity levels it actually encountered. Examination of 3-D data from the pencil-beam radars can give a better indication of the reflectivities actually penetrated. The 3-D analysis is not perfect either, however, because the TDWR and NEXRAD take up to six minutes to complete their elevation scans so the reflectivity value at the location of the aircraft may be up to six minutes old. The average age of the data is between 1.5 and 3 minutes. This study employs the simplifying assumption that the most recent 3-D value that corresponds to the aircraft's position does indeed represent the reflectivity encountered by that aircraft.

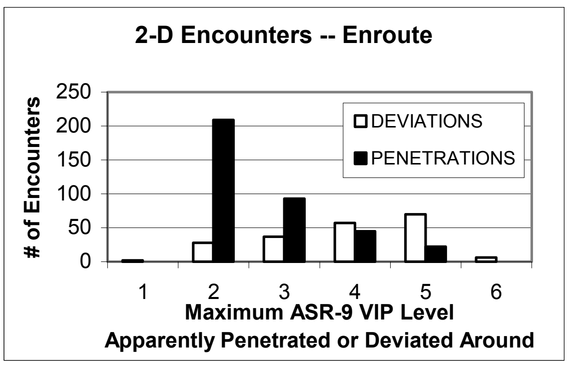

Figure 1. Distribution of maximum ASR-9 VIP levels apparently penetrated and deviated around by enroute aircraft. Note that penetrations of VIP level 1 were ignored in this study.

Examination of the 3-D data from the pencil-beam radars yields the following breakdown for the 369 apparent penetrations:

157 cases flew over the top of all measurable precipitation; the aircraft were above the storms.

143 cases flew through weak radar reflectivities in the 0.5 to 17.5 dBZ range. Air traffic managers often refer to the storms' 'echo tops' which are defined to be the highest altitude with 18+ dBZ reflectivities. These aircraft were flying at altitudes technically considered to be higher than the measurable precipitation.

64 cases flew through radar returns in the 18-30 dBZ range, which corresponds to level 1 precipitation. These planes were flying at or below the radar echo top altitudes but they were not flying in level 2+ reflectivities as was indicated in the 2-D analysis.

Five cases flew through 31-41 dBZ radar returns. These planes flew through level 2 precipitation.

A thorough examination of the TDWR and NEXRAD data revealed one additional 3-D storm penetration that did not show up in the 2-D analysis. The plane appeared to fly through level 1 precipitation in 2-D but was actually in level 2 in 3-D. So there were a total of six instances where pilots in enroute airspace penetrated level 2 data in this dataset. There were no instances where they penetrated higher reflectivities.

3.2 Identifying Deviations

Analysts examined animated loops of weather and flight tracks and identified aircraft that obviously changed course when they had storms in front of them. The analysts used a computer to draw a box around the storm in each plane's path and then analysis software extracted the weather variables from each of the Cartesian bins inside the box.

This methodology is more difficult to apply to overflights than terminal traffic for at least two reasons. First, the turns in enroute airspace are not as dramatic or obvious as those made in the terminal airspace. Enroute planes can often avoid storms by adjusting their course by only ten or twenty degrees. Second, enroute planes are moving at much higher speeds than those in the terminal and therefore tend to deviate when farther from the storms. Some pilots may have changed their courses to avoid storms that were in the study area while the planes themselves were still outside the study area. Those deviations could not have been identified with this dataset.

Hence, it is quite likely that there were more deviations on these six days than were identified by the human analysts. Also, just because a plane changed course at a time when a storm was in its apparent path does not mean that the pilot turned because of the weather. A future, more comprehensive study should compare each plane's flight path with the path listed in its flight plan. This might make it possible to flag deviations automatically. It is likely that a human analyst would still be required to identify and delineate the storms that seemed to cause each deviation.

The human analysts identified 200 deviations in enroute airspace. Figure 1 shows the distribution of maximum 2-D VIP levels in the storms that appeared to cause the deviations. Figure 2 shows the distribution of echo top values compared to the aircrafts' altitudes at the time that they changed their courses. Most of the storms that caused deviations extended up higher into the atmosphere than the altitude of the plane. There were almost 40 encounters where the echo tops were below the aircraft but were within 5,000 feet of the aircrafts' heights. There were a few storms with echo tops that were more than 10,000 feet below the altitude of the aircraft. Those probably represent encounters where the change in course was either not caused by weather or where the analyst did not correctly identify the storm that caused the deviation.

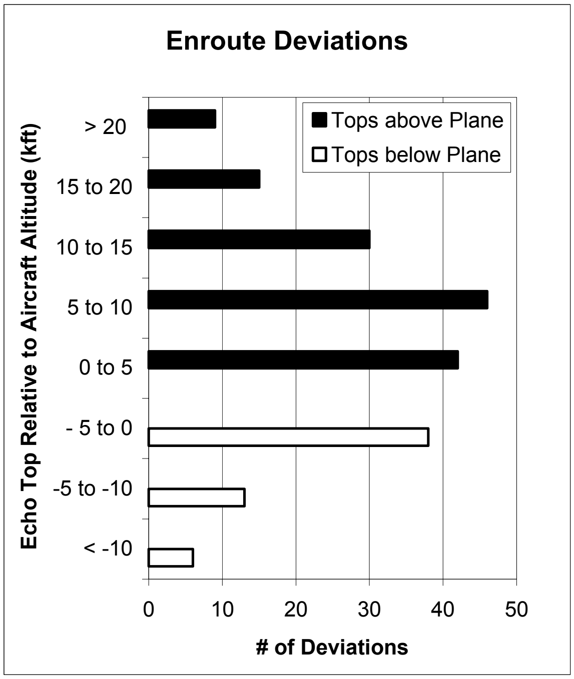

Figure 2. Distribution of the heights of the radar echo top altitudes with respect to the aircrafts' altitudes at the times when they deviated from their flight paths.

4. PILOT BEHAVIOR IN THE TERMINAL AREA

Again, these six days were part of a larger study of aircraft flying in terminal airspace that were arriving at MEM. The weather data employed in that study were the same as the data employed here and the methodology for identifying terminal area penetrations and deviations was similar to that described above. The aircraft that flew in the terminal area encountered the same storms as those in the enroute airspace but at lower altitudes and during a different phase of flight.

The 728 aircraft in the terminal behavior study on these six days appeared to penetrate level 2+ storms 414 times and they deviated around storms 444 times. Figure 3 shows the histogram of maximum ASR-9 2-D weather values apparently penetrated and deviated around in the terminal study as well as the distribution of maximum VIP levels actually penetrated in 3-D.

5. TERMINAL VS. ENROUTE ENCOUNTERS

The difference in the number of storm penetrations in enroute and terminal airspace is striking. Pilots almost never penetrated level 2+ precipitation in the enroute regime whereas they penetrated it hundreds of times in the terminal.

These data do not lead to firm conclusions but it seems likely that pilots in terminal airspace have several disadvantages when compared to their enroute counterparts: Pilots in the terminal area are flying at low altitudes and may be unable to tilt their airborne radars up high enough to assess the intensity of the storm cores. Airborne radars in the terminal airspace are more likely to be subject to ground clutter. Terminal area pilots are busier than pilots at cruise altitudes. Terminal area pilots often turn in order to join the pattern of aircraft lining up to land on the runway. It is difficult to assess the intensity of precipitation when the plane is not pointed in the direction of the storm. Enroute pilots are able to manipulate the tilt of their airborne radars to assess precipitation intensity as a function of height. They often have some lateral room in which to deviate. Enroute pilots on jetways in many parts of the country are less likely than terminal pilots to have other streams of traffic nearby at the same altitude. Enroute pilots may also have more room to maneuver vertically than terminal area pilots.

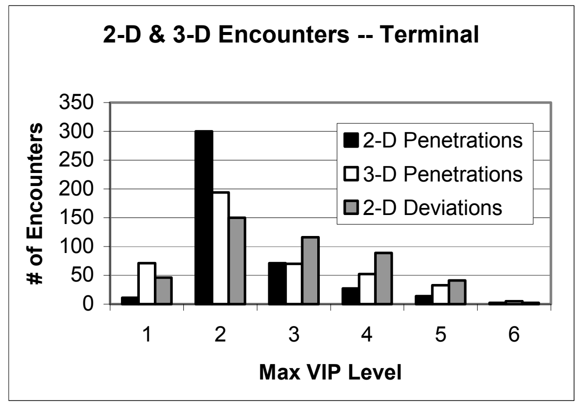

Figure 3. Distribution of maximum VIP levels a) apparently encountered in 2-D analysis, b) apparently deviated around in 2-D analysis, c) actually penetrated in 3-D analysis. The 2-D VIP levels are from the ASR-9; the 3-D VIP levels are from TDWR & NEXRAD.

Furthermore, the 'cost' of deviating around a storm in enroute airspace may often be lower than that of deviating when a plane is near the airport. Planes that deviate in the final minutes of flight usually forfeit their position in the landing queue and have to 'go to the end of the line' which may very well mean encountering more storms on the next approach. The deviation may cost them a significant amount of time and put them back in the middle of storms that they recently threaded their way through. In extreme cases, pilots may feel that they only have enough fuel to make one approach at the nominal landing airport before diverting to their alternate destination. In those cases, a deviation might mean a diversion, which carries a high cost indeed. Deviating in enroute airspace may also mean a long delay if the flight path is completely blocked but it can often be accomplished by a slight turn followed by another slight turn to get back on course after passing the storm. These deviations may be so slight that they do not add appreciable time or distance to the trip.

6. PREDICTING ENROUTE PILOT BEHAVIOR

The data in this study give reason for guarded optimism about the goal of predicting enroute pilot behavior. The behavior in the enroute regime is much more consistent than that in the terminal airspace. The enroute pilots deviated in most cases where the echo tops were above their altitude and they deviated in all but six cases when there was 30+ dBZ precipitation in front of them. This corresponds very well to the conventional wisdom that commercial airline pilots avoid flying through thunderstorms. Enroute pilots do not avoid flying over thunderstorms, however, so it will be very challenging to predict where pilots will and will not fly based on two-dimensional representations of storm intensity that are typically viewed by air traffic managers (e.g., ASR-9 precipitation, vertically integrated liquid water, maximum reflectivity in the column, or reflectivity in the lowest NEXRAD elevation scan) There were more than 100 cases where planes appeared to fly through level 3+ weather based on 2-D data when in fact they were in clear air or level 1 precipitation. Weather products that do not take altitude into account are of limited usefulness in predicting enroute pilot behavior

7. CONCLUSIONS

Our previous work in the terminal area indicates that it is impossible to use weather data to predict pilot behavior in the final 10-15 miles of flight. Until at least one pilot deviates, nearly all pilots stay on course even when strong storms move into the approach path. That work also indicates that it is possible to predict the behavior of pilots that are transitioning from the enroute airspace to terminal airspace with the intention of landing. Because the storm tops extend much higher in the atmosphere than the air traffic that is transitioning into terminal airspace, there is no option of flying over the storms so the pilots tend to deviate around strong precipitation until they get quite close to the arrival airport. Therefore 2-D representations (and forecasts) of storm intensity may be used to predict pilot behavior in that regime. The study described here indicates that at higher altitudes it becomes difficult again to predict avoidance behavior with today's 2-D storm intensity products. The option of flying over the storms means that the notion of storm height must be incorporated into air traffic management decision support tools in order to make efficient use of airspace.

Nearly all of the work being done in convective weather forecasting today is two-dimensional. The forecast products are interpreted (and scored) as the probability that there will be precipitation of a certain reflectivity at each 2-D location at the forecast time. Some of the cutting edge forecast products are based on vertically integrated liquid water (VIL) which is a 2-D representation of the water from ground level to the top of the storm. (Mueller et al., 1999; Robinson et al., 2002; Wolfson et al., 1999) The products do not, however, forecast the probability of radar reflectivity at a particular altitude. This study indicates that a good prediction of echo top altitudes would be a useful addition to the current forecast products.

That is not to say that pilots will or should fly at the echo top altitudes. They are trained to avoid the tops of rapidly-growing storms and they are aware that severe turbulence can occur even in the clear-air above, and downwind from, strongly convective storms. Future examinations of enroute behavior should include variables that account for the rate of storm growth and decay in the time periods leading up to the encounters.

It is also true that pilots do not always have a lot of room to deviate. Even in enroute airspace, pilots may be crowded by other streams of traffic or by nearby thunderstorms. In those situations the cost of a deviation may increase which may in turn increase some pilots' willingness to penetrate precipitation.

The study described here is limited in its geographic extent and the number of days examined but the results are somewhat encouraging. A much larger dataset of 3-D enroute storm encounters should be compiled and analyzed to determine whether or not these results are typical. The larger dataset should be analyzed in light of storm growth and decay conditions, turbulence reports, and any lateral or vertical constraints.

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