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The Effects of NEXRAD Graphical Data Resolution and Direct Weather Viewing on Pilots' Judgments of Weather Severity and Their Willingness to Continue a Flight

Dennis B. Beringer
Jerry D. Ball
Civil Aerospace Medical Institute
Federal Aviation Administration
Oklahoma City, OK 73125

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16. Abstract

A study was conducted to determine how variations in displayed NEXRAD weather data resolution interact with the pilot's direct view of weather. Pilots (32) were assigned to one of four groups; 8km, 4km, or 2km resolution, and a baseline condition without NEXRAD imagery. Each flew the simulator from Santa Rosa, NM, with the intent to land at Albuquerque. Heavy precipitation moved into the area during the flight, and pilots were required to decide, using both the NEXRAD data and their out-the-window view, whether to continue or to divert to an alternate airport. Pilots spent more time looking at higher-resolution images than at the lower-resolution ones. Baseline- and 2km-condition pilots deferred their decisions longer than did the other two groups. Posttest NEXRAD image judgments reinforced the notion that higher-resolution images are likely to encourage pilots to continue flights with the expectation that they can fly around or between significant weather features. The presence of out-the-window viewable weather phenomena was seen to have a significant effect on how pilots regarded the NEXRAD data.

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The Effects of NEXRAD Graphical Data Resolution and Direct Weather Viewing on Pilots' Judgments of Weather Severity and Their Willingness to Continue a Flight

Electronic displays, including both integrated instrumentation suites and add-on displays, are becoming increasingly available for use in aircraft. The multi-function display (MFD) is found in both situations and can display navigation data (terrain, cultural features, routes), traffic data, and weather data. One popular form of weather data is the NEXRAD (NEXt-generation RADar) display, showing radar base reflectivity and thus precipitation (and implied convective activity) graphically referenced to geographic location. Its popularity is not surprising given that, of the top 10 weather data items that pilots indicate they need access to (Beringer & Schvaneveldt, 2002), 3 involve forms of precipitation and 5 involve indices of convection/turbulence. Additionally, the value of using an integrated navigation/weather graphical display over separated displays has been supported with performance data obtained by Ververs, Dorneich, Good, and Downs (2002).

Concerns have been raised that pilots may use these data tactically rather than strategically (see Latorella & Chamberlain, 2002, for a discussion), particularly when data are presented in comparatively high-resolution (2km blocks, the base resolution of the data), and there are some data to support this contention (Yuchnovicz et al., 2001). In a study reported by Latorella & Chamberlain (2002), participants who used a Graphical Weather Information System (GWIS) that included NEXRAD reported that a number of display features contributed to enhancing the display's attractiveness for tactical use (portrayed cell intensities, location of precipitation and/or convective activity relative to aircraft position, range rings, high resolution – higher than the 4 km used in that study – and airway graphics).

NEXRAD has a number of limitations (U. of Illinois, 1999; also see National Weather Service, 2003) that most pilots do not take into account in their usage of the data. First, the base inclination of the outgoing beam (0.5 deg) is such that, when combined with the curvature of the earth, its elevation is 14,700 ft at 124nm, reaching 50,500 ft at 248nm. Thus, precipitation (and convective activity) occurring at altitudes concerning GA aircraft may not be registered at the greater ranges. At the other extreme, if one chooses the "composite" radar image, this consists of 9 or 14 different scans from 0.5 to 19.5 degrees elevation, and the data thus cannot be elevation separated. Additionally, no data are available in the nearly 140 degrees directly overhead (the "cone of silence"). If precipitation was occurring at altitude directly overhead but was not reaching lower altitudes, it would not be detected by that particular radar and thus not shown in the resulting image.

The second area of concern is coverage. In most cases, the data are considered unreliable beyond 124nm from a radar facility, and in some cases the data become unreliable after 62nm. Most precipitation within 80nm is usually detected, with intense precipitation detected up to 140nm, but not so for light precipitation. Geographical coverage is of particular concern in areas of the western and northwestern U.S. where radar coverage is incomplete and there is the additional problem of obstruction by mountainous terrain.

Third, the angular nature of the sensing sweep means that resolution is not uniform across any image generated from a single radar, and the "blocks" of data appearing near the periphery (248nm) are wider than those near the station. Thus, although nominal base resolution is given as 2km (and the short-range, 124nm, products are of this form), areas on the fringe of a radar's coverage (and the 248nm "long-range" products @ 4km) will have coarser resolution.

Finally, the dynamic nature of weather phenomena may be difficult to capture in this form of data presentation. NEXRAD data received in the cockpit are always time-delayed from the actual observation at least 6 to 7 minutes following the actual radar scan. This means that an image on a cockpit display may be as old as 12 to 14 minutes before it is updated. This fact gives rise to the legitimate concern that pilots might be trying to make tactical decisions based upon "old" data. There is also the question of how much degradation is acceptable in the resolution of the data before pilots no longer feel that the displayed image is representative of the weather phenomena that they may be able to view directly through the windscreen. Previous studies were conducted in simulated zero-visibility IMC (Yuchnovicz et al., 2001; Novacek et al., 2001) and examined 8km and 4km resolutions, whereas data reported by Latorella and Chamberlain came from a system using only 4km resolution. Our study was designed to assess the effects of varying the resolution of displayed NEXRAD data further (down to 2km) on how pilots interpreted weather conditions along their route of flight and the resulting decisions made when the weather phenomena were directly visible.

METHOD

Equipment/Participants

The sessions were conducted in the Civil Aerospace Medical Institute's Advanced General Aviation Research Simulator (AGARS). The device was configured as a Piper Malibu, and the participants flew from the left seat. The navigation display was presented on a touch-sensitive 12" LCD suspended from the center window post (see Figure 1). While this is not the anticipated location for the display in most applications, it was the most expedient positioning that retained availability of all conventional instrumentation in the AGARS (no integrated Primary Flight Display was used). It also allowed the pilot to have direct access for touch activation of the panel. The display software was Echomap (from EchoFlight) and contained all of the features noted earlier that would encourage strategic use. The display, shown in Figure 2, presented a moving-map representation in track-up format with the aircraft position shown near the bottom of the display. Terrain was shown in a fashion similar to VFR sectional charts, with a compass-rose range ring overlaid. NEXRAD imagery was depicted with three levels of intensity of returns (green for low, yellow for medium, and red for high). Graphical and alphanumerical navigation data were shown on the left-hand side of the display and included destination identifier, altitude, cross-track error, ground speed, distance to destination, and estimated remaining time enroute. A cordless trackball was also available for the pilot's use in activating and manipulating the moving map/weather display.

The algorithm used to generate the displayed NEXRAD image was a conservative one, and the results of its operation on the original source data are depicted in Figure 3. Starting with the native resolution of 2km, one can see that there are red, yellow, green, and black areas represented in the original data. When the 8km by 8km area is divided into 4 blocks 4km on a side, each block is assigned the color of the heaviest precipitation occurring within that area. Thus, any 4km block that had a 2km red block within it becomes entirely red, and so on. Further, when the entire 8km by 8km area is reduced to a single block, it becomes completely red as that represents the heaviest precipitation within the depicted area. Use of this algorithm differs from either a "majority-rule" algorithm or an averaging algorithm where an area that was predominantly yellow, for example, would become all yellow when reduced in resolution, potentially masking an area of heavier precipitation with a resulting loss of data. The conservative algorithm, then, tends to make things look "worse" than they would be depicted if shown in native resolution, but does not "mask" or lose data depicting small areas of heavy precipitation.

Participants were 32 general aviation pilots from 19 to 70 years of age (mean = 34.6, median = 27), with total flight times ranging from 40 to 20,000 hours (median =

Figure 1. Weather display in the AGARS.

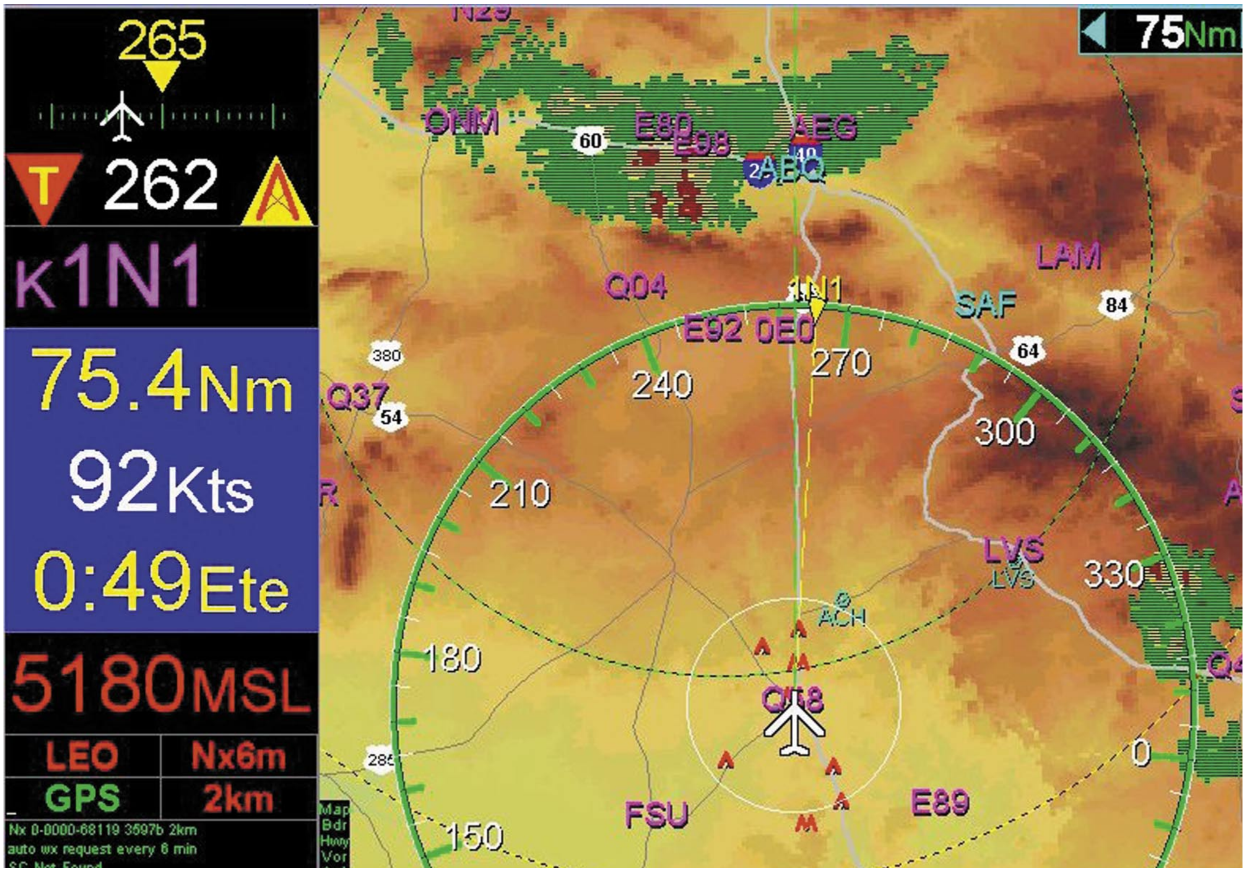

Figure 2. The EchoMap display showing sectional-style terrain representation, NEXRAD imagery, and graphical and alphanumeric navigation information.

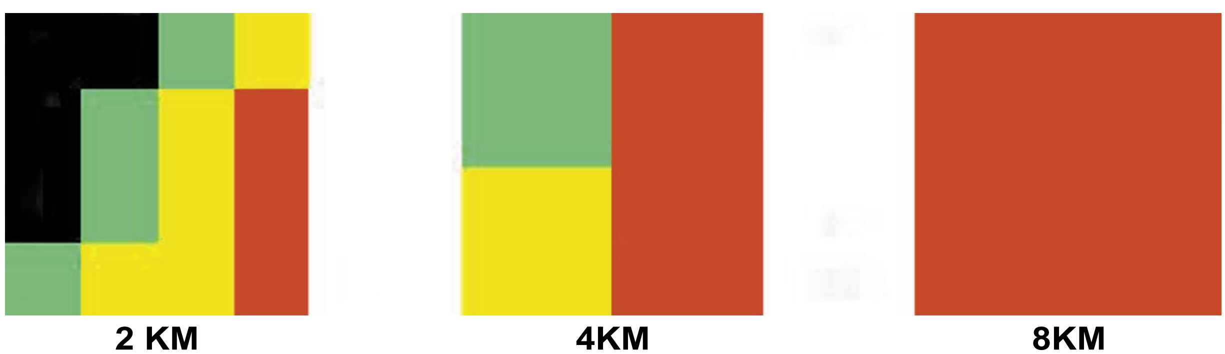

Figure 3. Effect of conservative algorithm as displayed resolution is reduced (block size increased).

460). Each was assigned to one of four groups: 2km data resolution, 4km data resolution, 8km data resolution, or baseline (moving map but no weather overlay). A pretest questionnaire was used to assess each pilot's overall flight experience (hours), by category (VFR, IFR, simulated IFR, total), in the last 12 months and in the last 90 days. They were also asked about their prior use of in-cockpit weather data/displays.

Procedure

Training. Pilots received demonstrations of the weather and navigation page and how to zoom in and out. Each pilot was shown how to select an alternate destination for the flight. Participants then took off, controlled the aircraft, and manipulated the display for the duration of a short practice flight. They also received an autopilot demonstration and viewed sample NEXRAD imagery on the cockpit display. At the conclusion of this practice, the participant returned to the departure airport and landed. Participants were then given the opportunity to take a break before continuing.

Test Flight. Participants took off from Santa Rosa airport in eastern New Mexico and flew a route at 9500 feet proximal to Interstate 40 and direct to Albuquerque (ABQ). This flight was conducted as VFR on top after climbing through an extremely thin cloud layer. Each pilot was encouraged to use the autopilot, and all eventually did so. NEXRAD data were automatically updated every 6 minutes and the data were 6 minutes old when first displayed. A sample comparison of identical source data displayed at the three resolutions appears in Figure 4. Recall from the previous discussion that the algorithm used to convert the 2km source data to 4km and 8km resolutions was a conservative one, causing any larger block containing a 2km red source square to become red in its entirety. All activities were recorded on videotape using two cameras: wide-cockpit-shot inset and a full-screen view of the navigation display. Flight-performance and eye-movement/gaze-point data were collected during the flight.

Data flights varied from 23 to 45 minutes in length. Pilots were instructed that they were the pilot in command, and were thus responsible for the safe conduct of the flight. Any decisions regarding the continuation of the flight were theirs to make. There were no circumstances

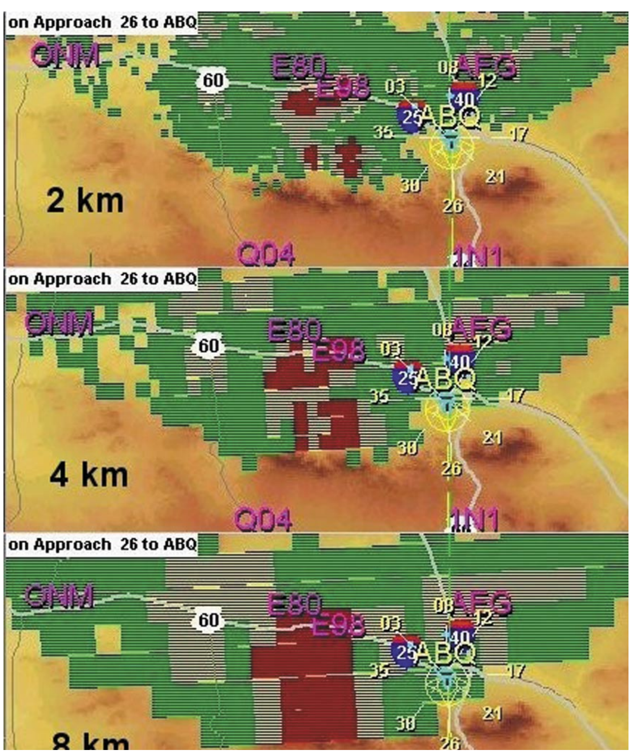

Figure 4. Images from same NEXRAD source data presented at 2km, 4km, and 8km resolutions.

requiring completion of the flight to ABQ. Afterwards, pilots participated in a rating session in which they viewed a series of slides of NEXRAD weather data comparable to what they had just experienced in the simulator, but at each of the three resolutions. Their task was to determine if, at any point in the series, they would opt to divert to a different destination. Pilots then completed a usability questionnaire and a posttest interview. The questionnaire focused on the pilots' decisions during their flights, their recollection of specific weather-related details, their evaluation of the usefulness of the weather display and confidence in using it, and their knowledge of the Aeronautical Information Manual recommendations for flying near thunderstorms. Follow-up questions were asked during the interview based upon responses to the questionnaire and experimenter observations.

RESULTS AND DISCUSSION

The primary focus of this study was the question of how pilots would respond to variations in the resolution of displayed NEXRAD data. Assessment of this response was based upon visual-performance data (how long they accessed the data), flight-performance data (how close they came to the significant weather, how long they deferred the decision about continuing the flight), and post-flight display-evaluation data (how they responded to equivalent weather data presented at differing resolutions in a non-flight environment).

Visual-performance

The flight was divided into three segments for analysis. Segment 1 began at take-off, Segment 2 started when the pilot reached cruise altitude, and Segment 3 began when the pilot made a decision about continuing the flight (deviate to alternate airport, circumnavigate the storm, penetrate the storm, etc.), and continued until termination of the flight. Gaze-point videotape data were reduced to the length of time the pilot spent looking at each of the three areas of interest (moving-map with NEXRAD overlay, out-the-window, and other). The "other" area of interest was defined as instrumentation, radios, charts, and any other visually head-down locations. Time spent looking at each area of interest was converted to a percentage of segment-time length. Means are presented in Figure 5.

A 4 X 3 repeated-measures multivariate analysis of variance (MANOVA) was performed using percentage of fixation time on each area of interest (3 dependent variables), where display condition was the between-groups factor and flight segment was the within-subject factor. Pair-wise comparisons were conducted to localize the effects. The MANOVA revealed a significant main

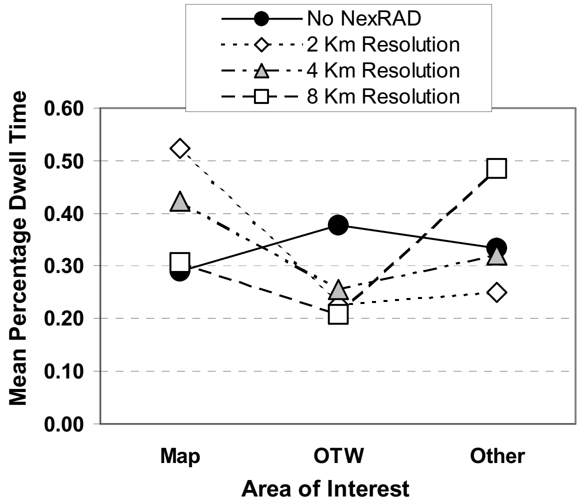

Figure 5. Mean percentage visual dwell time by display condition and area of interest for flight segment 2.

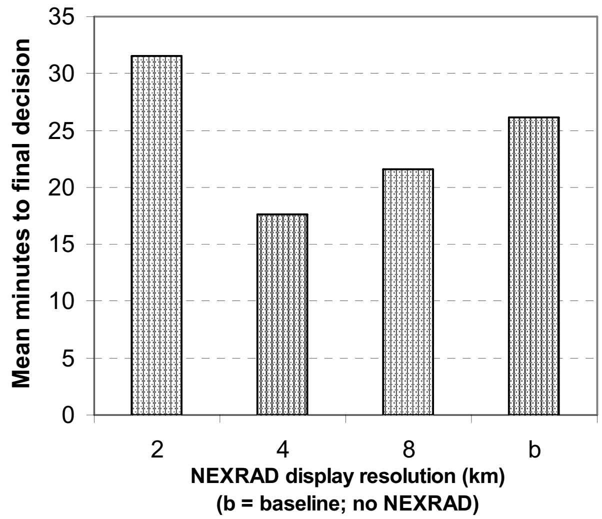

Figure 6. Mean time (mins) to decision by NEXRAD display resolution (km).

effect associated with group and segment [F(9,84)=2.336, p<.05, and, F(5,24)=18.463, p<.001, respectively]. However, the effect associated with the interaction of group by segment was not significant. Further univariate analyses showed significant effects for segment on MAP [F(2,56)=26.917, p<.001], OTW [F(2,56)=11.541, p<.001], and INST [F(2,56)=53.611, p<.001], and significant effects for group on MAP [F(3,28)=5.887, p<.001], OTW [F(3,28)=1.650, p<.001], and INST [F(3,28)=2.327, p<.001].

Pair-wise comparisons for segment 2 indicated the percentage of dwell time on the moving map was significantly different between NEXRAD resolutions of 2km and 8km, and between 2km and the baseline group. No other significant differences were observed. In Figure 5, the groups having NEXRAD data spent increasingly more time looking at the map display as resolution increased. The trade-off appears to be between time spent looking at the NEXRAD display and time looking at instrumentation and other in-cockpit features, as out-the-window percentages varied little between those three groups.

Flight Performance

Time to a decision, to the nearest second, was examined from notes made during each flight and from videotape records and was defined as the time from the beginning of the flight until a definitive decision was made regarding the continuation of the flight. These times were submitted to a one-way ANOVA, and the means are presented in Figure 6. A significant effect of display resolution was found [F(3,28)=4.34, *p*<.02]. This difference is clearly between the 4km and 2km conditions. The trend is largely linear from the baseline condition (b) and decreases with increasing NEXRAD-image resolution up to 4km. However, at 2km resolution, the delay in decisions makes a marked jump upwards. Attempts to "thread-the-needle" and land at ABQ were more prevalent in the 2km condition than in the other conditions, and decisions were delayed in the hope that the weather would change sufficiently to allow a landing at ABQ. It is unclear how to explain these results given the comparatively small sample size and the expectation that the trend might be a linearly increasing function from 8km to 2km. It would appear, however, that earlier decisions on the conduct of the flight occurred with the lower-resolution presentations.

Closest-approach distance (miles) to the convective cells (heavy precipitation) was measured by calculating the distance from the simulated aircraft's position to the thunderstorm's center of mass at each point along the flight path. These values were then used to determine the minimum separation maintained between the simulated aircraft and either the small or large convective cell. These minimum-separation distances were then submitted to a one-way ANOVA with display condition as the between-groups factor. Although no significant differences were observed between NEXRAD display resolution types [F(3, 28)=2.109, p=.122)], there was a trend for closer approaches with higher resolutions (Figure 7).

Physical separation maintained from convective cells suggests that the pilots with higher resolution NEXRAD imagery or no NEXRAD imagery tended to fly closer to the convective cells than is recommended by the AIM (7-1-27). It recommends "avoiding by at least 20 miles any thunderstorm identified as severe or giving an intense radar echo." Note that 17 (53.2%) of the pilots

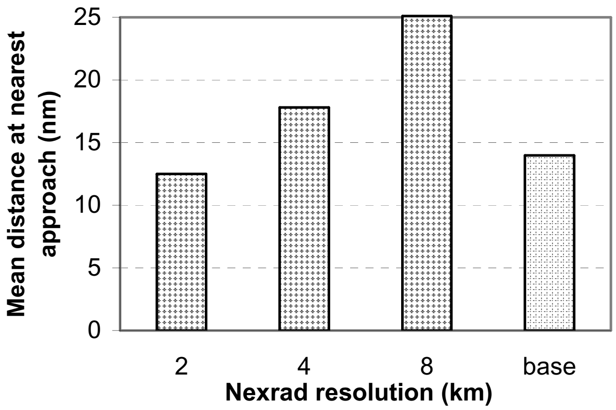

Figure 7. Mean closest approach (km) to the convective cells by NEXRAD display resolution (b=baseline, no NEXRAD).

Table 1. Frequency distribution of pilots by display resolution and proximity of approach (bold indicates < 20 nm).

	Closest approach (d) in nm			
NEXRAD resolution	d>25	25>d>20	20>d>15	d<10
2km	0	3	**1**	**4**
4km	3	1	**0**	**4**
8km	4	1	**3**	**0**
Baseline	1	2	**2**	**3**
Total	8	7	**6**	**11**
Total %	*25*	*21.9*	*18.8*	*34.3*

Table 2. Display usage categorization (tactical vs. strategic) by NEXRAD resolution.

	Display usage	
Group	*Strategic*	*Tactical*
Resolution 2	4	4
Resolution 4	4	4
Resolution 8	8	0
TOTAL	***16***	***8***

flew inside this recommended distance (see Table 1 for a further breakdown by display).

Additionally, the AIM (7-1-27) suggests not taking off or landing in the face of an approaching thunderstorm and to not attempt to fly under the thunderstorm even if you can see through to the other side. However, 7 (21.9%) pilots attempted to fly through or under the thunderstorm to land at ABQ. Note that *none* of the pilots using the 8km resolution display flew closer than 15 miles to the visible precipitation column (no pilots fell into the 10-15 mile category), whereas *half* of those in the 2km condition and almost half (3) of those in the baseline condition flew closer than 10 miles.

Actual diversions or nearest approach. Of those in the 8km-resolution flights, all (8) diverted to an alternate airport. In the other groups the results were: 4km, 7 (87.5%) diverted; 2km, 7 (87.5%) diverted; baseline, 5 (62.5%) diverted. It is also of interest to note that of the 5 who continued in the simulator, 4 also voted to continue, at some display resolution, in the posttest evaluations. For our purposes of posttest categorization, we operationally defined *strategic* usage as those decisions/actions involving significant planned changes to the overall route of flight or the selection of an alternate destination. In contrast, we considered highly localized maneuvers, heading and altitude manipulations, and any attempts to avoid hazards in the immediate proximity of the aircraft as tactical usage.

Categorization of pilots by inferred display usage is shown in Table 2. Referencing the eye-movement data, 8 (33%) of the pilots with displayed NEXRAD appeared to use the data display for tactical decision-making until they had penetrated the rain column or had flown into or under the cloud model. Of those 8, 7 transitioned to using the direct contact view once they were in or under the cloud. Only 1 of those avoided cloud entry, tracking along the edge of the front (approximately 7 to 8 miles from the edge of the storm) to the south until reaching an alternate airport (Belen). This pilot used the display tactically until discovering that he was going to penetrate the rain column, when he began using direct visual reference to the cell. Note that none of the pilots with the lowest resolution of NEXRAD exhibited tactical behaviors based upon display usage.

Post-flight interviews/questionnaires. It was evident from data obtained during the post-flight interviews that variables other than NEXRAD resolution were exerting a significant influence upon pilot behavior. Discussions with several pilots indicated that their willingness to continue was based on prior experience. One particular pilot with foreign military experience indicated that they (foreign air force) regularly flew through this type of weather to complete missions. Others indicated that they were going to fly as close as possible to their destination as long as they had some visual contact with the ground and did not experience turbulence. The simulator experience for these individuals (those choosing to fly close to the weather phenomena), then, did not present all of the cues that they expected as precursors of severe weather ahead. On the other hand, there were a large number of reports from the other pilots who indicated that the representation of the out-the-window weather was sufficient to signal that one should proceed only with extreme caution; commentary also rooted in experience.

Post-flight displayed-weather ratings. The slides shown in the post-flight session depicted regular intervals along a course inbound to ABQ and similar to the flight just taken by the participant (the slides for the 4km-resolution series are shown in the Appendix; Figures A1 through A6). Responses of pilots to the post-flight series of 6 slides for each data resolution (opting to continue after slide 6 was scored as 7) were submitted to a mixed-factor two-way ANOVA where the between-groups factor was display resolution flown and the within-subject factor was slide-series NEXRAD resolution. The main effects of both display resolution flown [$F(3,84)=5.45$; $p<.005$] and NEXRAD post-flight slide resolution [$F(2,84)=7.23$; $p<.005$] exhibited statistically reliable effects, but the interaction did not achieve significance. The means are presented in Figure 8. It can be seen that increasing resolution caused the pilots, with the exception of the baseline group, to delay their decisions to divert in a nearly linear fashion. The effect of resolution flown was also much as expected, with those who had flown the higher-resolution displays delaying more, overall. The baseline group showed the greatest willingness, in the post-flight assessment, to continue to the destination.

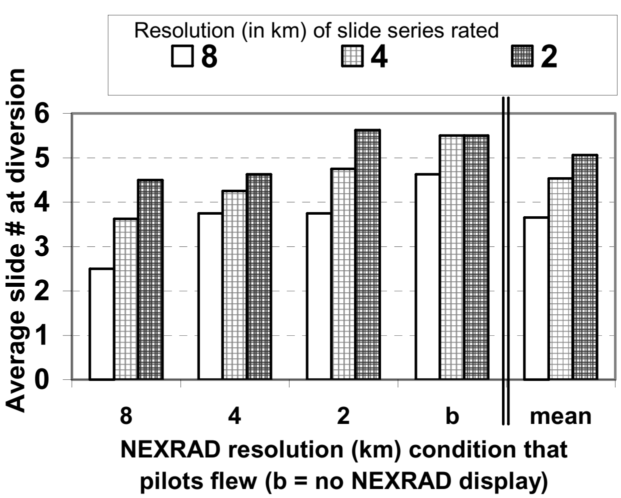

Figure 8. Mean post-flight slide-series diversion point by display resolution flown and depicted NEXRAD resolution on post-flight slides.

SUMMARY

The data from this study (also reported in Beringer and Ball, 2003) appear to support the contention that higher-resolution NEXRAD images encourage pilots to "shoot the gap" and attempt to navigate between areas of heavy precipitation. It was interesting that piloting behavior in the flight simulator was at some variance with posttest assessments, but this may be attributable to the availability of the out-the-window view in the simulator and the ability to compare the directly viewed weather with the NEXRAD image. The difference between making decisions in Visual Meteorological Conditions and in Instrument Meteorological Conditions is not trivial, and these data can be thought of as a first cut at this comparison. Many pilots commented during the posttest interview that their actions were in large part governed by the fact that they could see the weather outside. If one takes the posttest NEXRAD-image evaluations as more representative of decision making without direct visual reference to the weather, then there may be even more of a tendency to continue than was seen in the simulator. However, additional data in the context of a simulated IMC flight using high-resolution NEXRAD images need to be collected to determine to what extent this may be the case.

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APPENDIX A

Figures A1 through A6: NEXRAD images during approach to ABQ from the east, 4km resolution. The set of images shows the movement of the cells in a generally northeasterly direction as the aircraft approached ABQ. This was one of the three sets of images used in the post-flight static-images assessment.

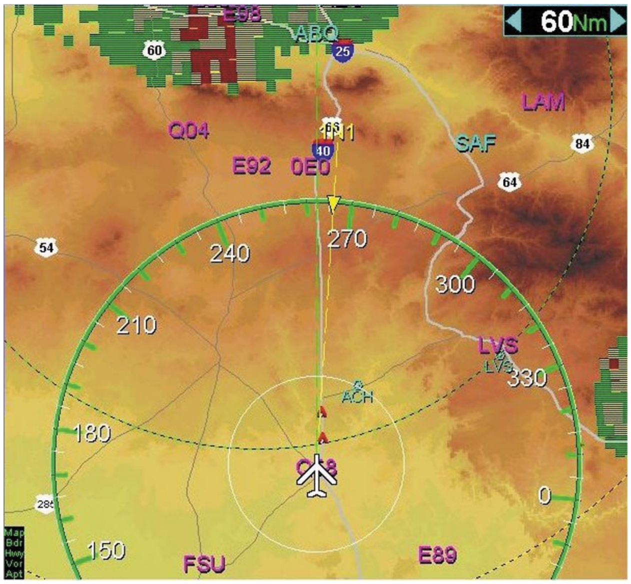

Figure A1. NEXRAD image at 100nm from ABQ.

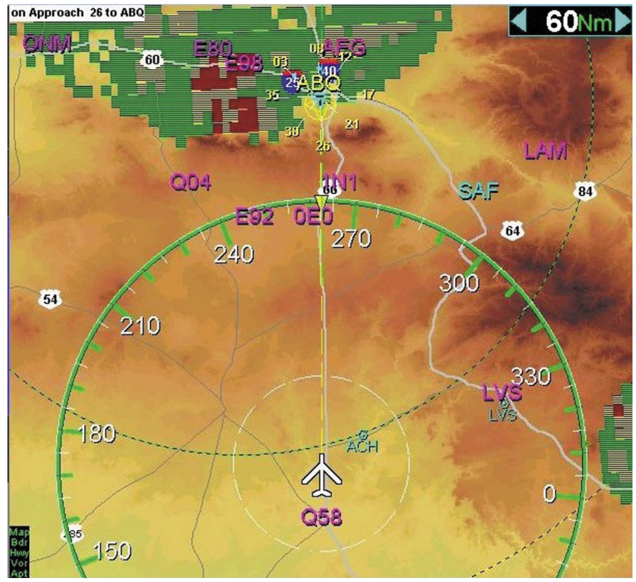

Figure A2. NEXRAD image at 82nm from ABQ.

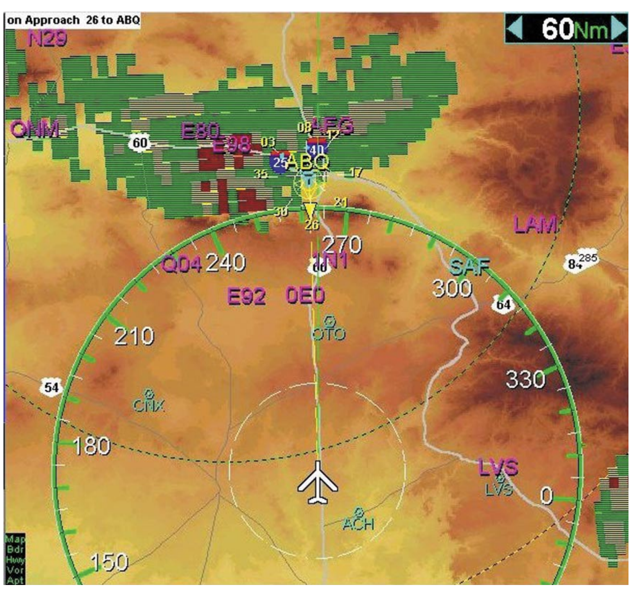

Figure A3. NEXRAD image at 65nm from ABQ

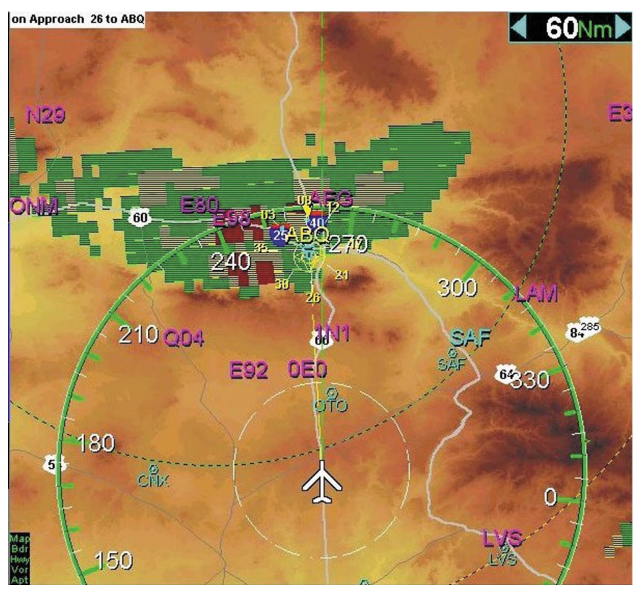

Figure A4. NEXRAD image at 49nm from ABQ.

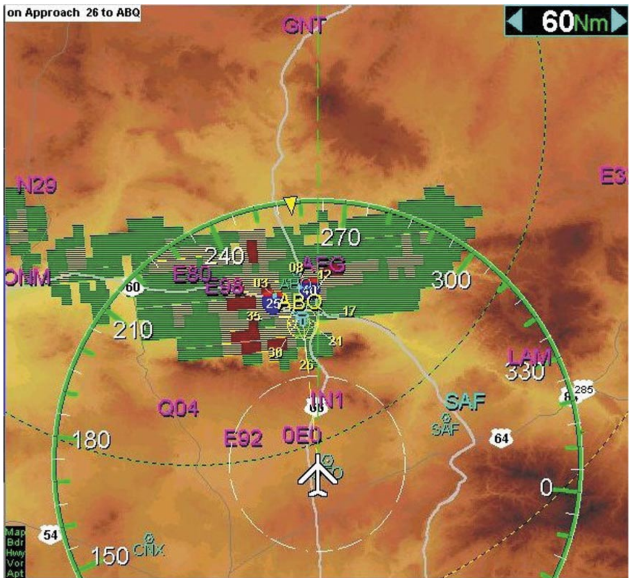

Figure A5. NEXRAD image at 32nm from ABQ.

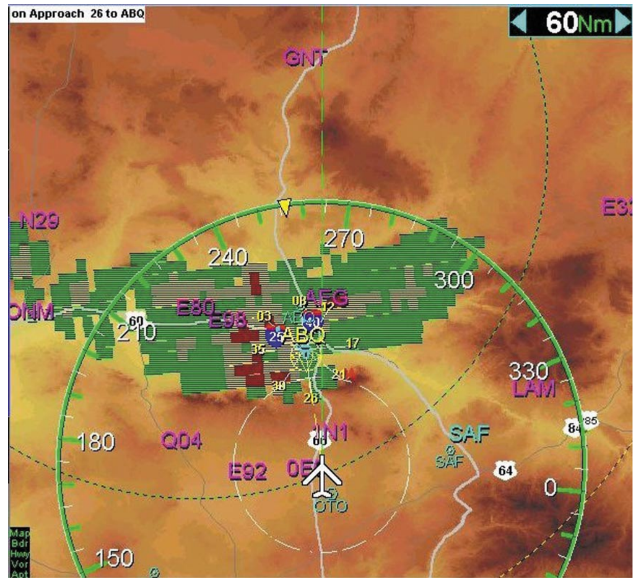

Figure A6. NEXRAD image at 25nm from ABQ.