SIMULATING GROWING THUNDERSTORM ECHOES FOR WEATHER RADAR TRAINING

By John T. Klehr
Link Flight Simulation Division of The Singer Co.
Binghamton, New York

Summary

When rapidly growing thunderstorms appear enroute, a pilot makes many flight path decisions on the basis of his training and experience in the interpretation of radar echoes displayed in the cockpit. Echoes from more severe thunderstorms first appear at high-to-middle altitudes, and they possess other growth and decay characteristics that make their echoes distinguishable from the echoes of less severe thunderstorm types at various stages in their development. A color weather radar simulator can now be used to provide such training by modeling in four dimensions the dynamic growth characteristics of various thunderstorm types.

Introduction

Each year, about a dozen radar-equipped aircraft are involved in thunderstorm-related accidents[1]. Along certain flight routes, airborne weather radar typically provides the only source of continuous current weather information at flight altitudes. Ground-based radar information is used to isolate general areas and coverage of echoes for flight planning, but, to avoid individual storms, greater reliance is placed upon a pilot's decision-making ability. Pilots base their decisions upon in-flight observations, i.e., upon visual sightings or airborne radar inputs. Flight crews often misinterpret radar echoes because they do not understand the attenuation and distortion caused by radar physics, and they often lack knowledge of the echo growth and shape characteristics of different types of thunderstorms. Weather radar techniques taught in classroom training sessions may not transfer well to actual cockpit experiences with thunderstorms.

Real-World Pilot Training

Pilots are told that, to avoid thunderstorms, they should circumvent any echo from a severe thunderstorm by 20 mi or fly 10,000 ft above the radar top of a thunderstorm, but thunderstorm radar tops have been measured that ascend at 1,000 to 3,000 ft/min and dissipate just as fast. Pilots are instructed to regard as severe any thunderstorm with a radar top that exceeds 35,000 ft, but storms that are building rapidly may contain ice at their upper levels and appear less than severe because ice particles have comparatively low radar reflectivity. For the best indication of storm intensity, a pilot is told to tilt the antenna down to the lower portion of the rainfall shaft. A well-trained pilot will use the tilt and range controls extensively to interrogate storm volume and obtain more informative weather radar displays.

Radar Return Strength

The strength of a radar return depends upon many factors, including the drop size, the composition, and the amount of hydrometeors contained within the radar beam volume. Because turbulence is often associated with strong rainfall gradients, and since drop size is almost directly proportional to the rate of the rainfall, pilots are instructed to observe the packing of the echo contours. Wet hail is the best natural reflector of radar energy, but small hail shafts may be poor radar targets; they may not fill the radar beam and may be averaged away. Pilots are told that the best way to detect hail-containing storms is to recognize their characteristic echo shapes, i.e., scalloped edges, thin protruding fingers, hooks, and U-shaped echoes, but hail may fall several miles away from the cloud. Pilots are told not to deviate downwind around a storm; a less turbulent area is usually found upwind[2].

The strength of a radar echo also depends upon the range to the storm and the attenuation that results when a beam passes through precipitation to and from the storm. The maximum range of a typical 3-cm-wavelength airborne weather radar is given as about 300 nmi, but pilots are instructed to classify any echo which appears beyond 100 miles as "severe." The physics of radar propagation causes all radars to "lie," especially at the shorter wavelengths used in airborne applications. It has been shown that a 3-cm-wavelength radar produces a maximum reflectivity about 15 dBZ lower than that produced by a 10-cm-wavelength radar observing the same storm[3]. Such strong attenuation distorts echo shapes and conceals echoes located behind strong foreground echoes. Beam spreading also distorts the displayed echoes, and a wet or icy aircraft radome causes extreme attenuation and echo distortions. In the past, a pilot's ability to recognize how and when a radar is distorting the real world has been acquired only by hazardous in-flight experiences.

Safe, Realistic Training

Pilot classroom training in using and interpreting weather radar displays must be reinforced in a safe cockpit situation. Unfortunately, most weather radar simulations used for training pilots were designed from a point of view that facilitated the electronics design rather than from one that was meteorologically sound. Typically, thunderstorms are shown as static, with no growth or decay and with little or no movement. The simulations contain an inadequate number of the altitude slices that would permit training in tilt control management, and they may not be able to represent the rapidly changing echo sizes and shapes associated with dynamic thunderstorms. Pilots have been unable to observe features as they are described in their classroom training and have been unable to obtain adequate hands-on experience in the use of weather radar in a simulator.

To meet the needs for improved pilot training, a superior color weather radar simulator has recently been developed and programmed to portray realistically the four-dimensional growth characteristics of various thunderstorm types.

Background -- Echo Growth Characteristics of Thunderstorm Types

All thunderstorms develop and decay with time. They depend upon the existing atmospheric temperature and wind structure, which, in turn, vary with geographic location and season. The simplest type of thunderstorm, the air-mass thunderstorm, has been studied extensively; three distinct stages of development during its 20-to-30-min. lifespan have been identified (Figure 1). Every thunderstorm begins as a cumulus cloud, which swells and grows vertically at a rapid rate. During this initial,

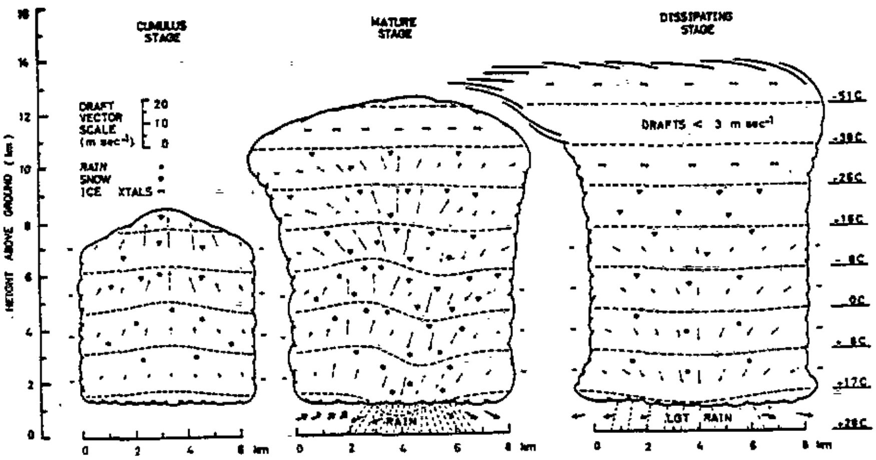

Figure 1 The Byers-Braham model of a thunderstorm cell. (From Chisholm, 1973.)

or cumulus, stage, the storm consists primarily of a warm, moist updraft (up to 50 ft/s), in which cloud droplets grow into supercooled raindrops as they are swept up beyond the freezing level. At first, since the particles are too small to reflect the radar beam, the cumulus stage produces no radar echo. The first radar echo is observed after the cloud top extends above the freezing level, and it indicates the presence of numerous, sizable water drops. The rate at which the first echo grows in size and intensity depends upon the updraft strength and the cloud density. It has been observed that the higher the altitude at which the first echo appears, the more likely it is that the thunderstorm will develop severe weather, perhaps including hail, tornadoes, and strong outflows. Ice, snow, and rain droplets may coexist in the cloud during this cumulus stage, but all the precipitation is supported by the updraft, and no precipitation reaches the ground.

As the raindrops grow too large to be supported by the updraft, they fall, and they drag the air along; this produces a strong downdraft, which is characteristic of the mature stage. Drier outside air is entrained, and this is cooled as the raindrops evaporate; this strengthens the downdraft and produces strong winds and heavy surface precipitation. During the mature stage, the radar echo peaks in intensity and in vertical extent; the maximum intensity tracks the descent of the precipitation to the surface (Figure 2).

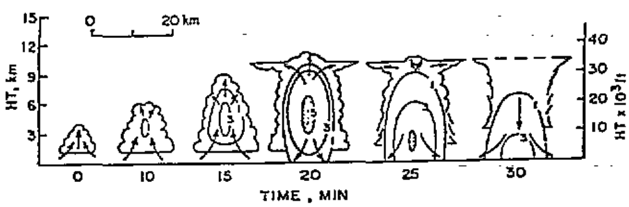

Figure 2 The ordinary thunderstorm developing in an unstable airmass, with daytime heating of the Earth's surface. Contours are in 10's of dBZ. (After Wilk, et al., 1978 adapted from Chisholm and Renick, 1972)

During the dissipation stage of the air-mass thunderstorm, the downdraft becomes more extensive; the updraft is cut off from its supply of moist, warm inflow air, and the storm begins to self-destruct. Precipitation soon ceases, and after that the cloud itself begins to dissipate. During the dissipation stage, the radar echo weakens rapidly, lowers in altitude, and soon disappears entirely.

Under the atmospheric influences of specific wind and temperature structures, thunderstorms may become better organized than the self-destructing air-mass thunderstorm. A low-to-middle-altitude wind shear environment will permit the updraft to be separated from the destructive effects of the downdraft; this results in a thunderstorm that may last for a number of hours. Such more severe thunderstorms usually consist of more than one updraft and downdraft pair, and they often occur in a line or group of similar thunderstorms. Figure 3 shows the Time-Height Profile of the maximum reflectivities from a thunderstorm cell observed on 13 July 1978 in southeastern Wyoming[4]. The dotted lines indicate cloud top and cloud base locations, measured from time-lapse photography, and the solid lines indicate the contours of the maximum reflectivities, in 5-dB increments. Although this storm was multicellular and lasted for several hours, it had many of the growth characteristics of a simple air mass thunderstorm. The visual cloud was observed about 15 min. before the 20-dBZ echo first appeared at about 28,000 ft (8.5 km), and its vertical size subsequently grew rapidly. The 30-dBZ contour first appeared at about 30,000 ft (9.2 km), and it subsequently fell rapidly, indicating the formation of a heavy rain shaft. When the 30-dBZ contour reappeared later, a second cell rejuvenated the growth of precipitation.

Thunderstorm Models

Wilk and Dooley[5] developed simple models of time-dependent reflectivity profiles for six types of thunderstorms, which ranged from a non-severe, convective air-mass thunderstorm to a very severe, tornadic supercell thunderstorm (Figure 4). Wilk and Dooley also provided data on each model's reflectivity vs. height profile at various time steps. Figure 5 shows three of these six types of thunderstorms; data from these are used in the weather radar simulation discussion that follows.

Profile 1 -- The first type of thunderstorm simulated is the non-severe convective air-mass thunderstorm (Profile 1 in Figure 5 and a Time-Height Profile of maximum reflectivities in Figure 6). This first type represents the random showers and thunderstorms that occur most often in a conditionally unstable air mass but never produce

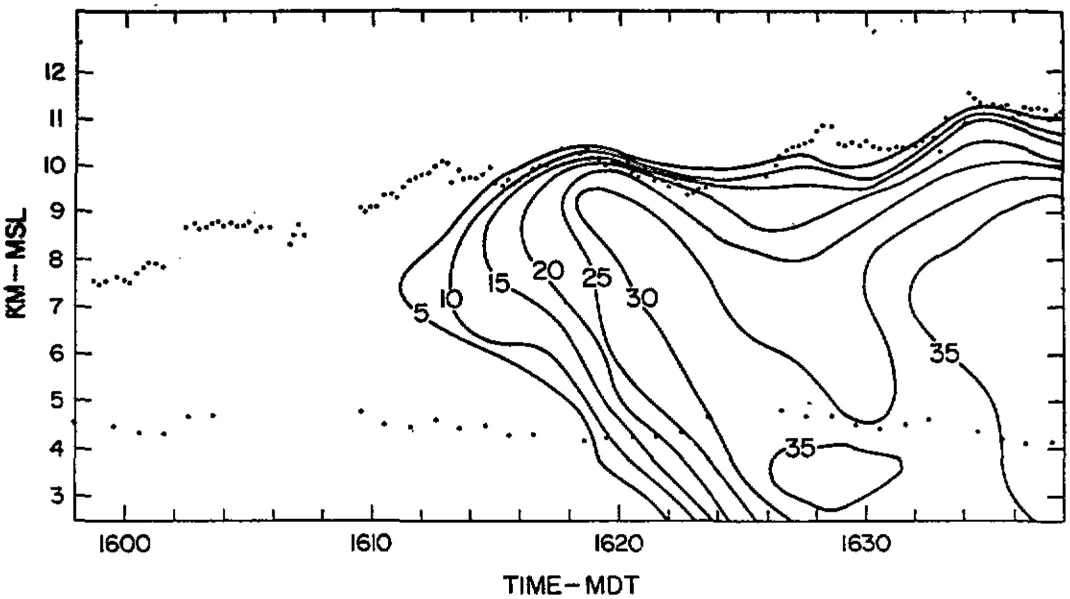

Figure 3 Time-height profile of maximum reflectivities from a Wyoming thunderstorm in 1978. Contours are at 5 dB intervals from 5 dBZ. Dotted lines indicate cloud top and cloud base measured from time-lapse photography. (After Breed, 1983.)

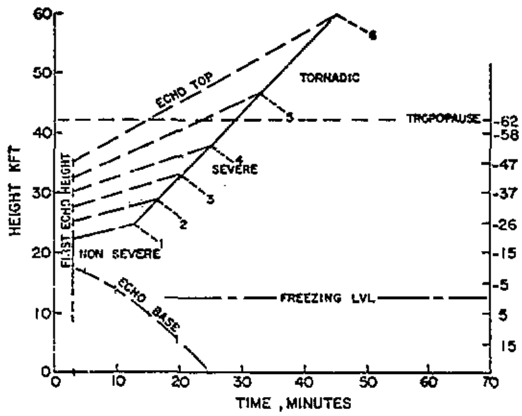

Figure 4 Precipitation growth and descent patterns used to simulate reflectivity profiles. (Wilk and Dooley, 1980)

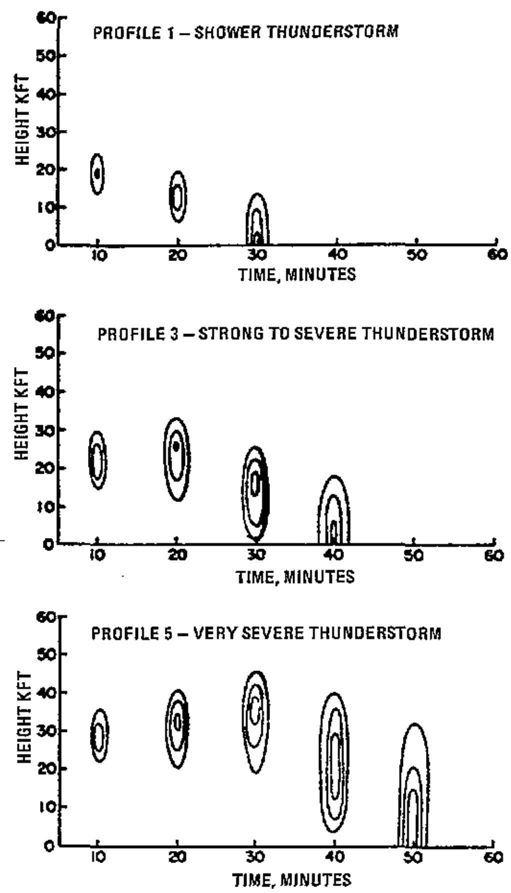

Figure 5 Vertical reflectivity cross sections used to represent initial echo growth in storms of increasing severity. Reflectivities are given at 10 dB intervals beginning with 20 dBZ. (After Wilk and Dooley, 1980.)

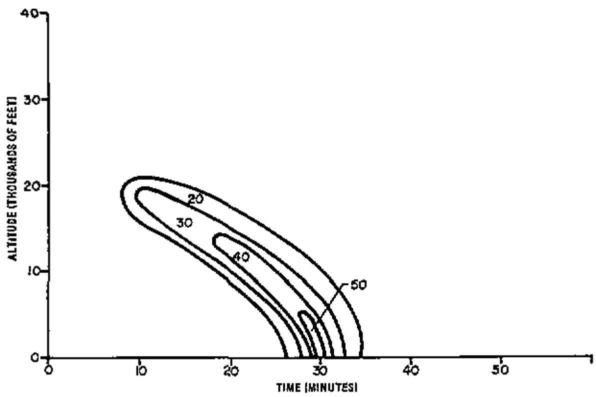

Figure 6 TYPE 1 -- SHOWERS AND WEAK THUNDERSTORMS

severe weather. The first 20-dBZ echo appears at about 20,000 ft, but heavy rain (40 dBZ) occurs only from below 13,000 ft to 16,000 ft and without severe weather. This type of thunderstorm is usually not detected beyond a 100- to 130-nmi range.

Profile 3 -- The second type of thunderstorm, which represents the most common type of severe thunderstorm, is shown in Profile 3 in Figure 5 and as a Time-Height Profile in Figure 7. It is usually easy for an aircraft to circumnavigate this type of storm while enroute, but it may be dangerous for the aircraft to penetrate its cloud boundary. These severe thunderstorms are dangerous to aircraft that attempt landings or takeoffs within a few kilometers of the storm. The first 20-dBZ echo appears between 20,000 ft and 25,000 ft, and the maximum reflectivity exceeds 50 dBZ and remains at a height of 20,000 ft to 25,000 ft until the storm begins to dissipate. Precipitation reaches the ground surface about 30 min. after the first echo is detected[5].

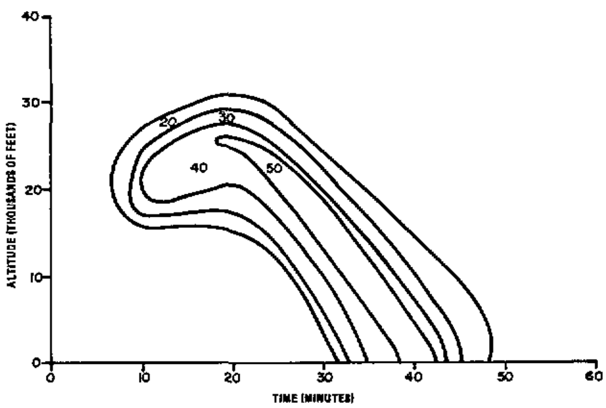

Figure 7 TYPE 2 -- STRONG THUNDERSTORMS

Profile 5 -- The third class of thunderstorm simulated represents very severe thunderstorms, which may produce large hail or tornadoes. These thunderstorms may exist in heavy squall lines with damaging gust front winds and heavy rain. Echo development for such very severe thunderstorms is shown as Profile 5 in Figure 5 and as a Time-Height History in Figure 8. These thunderstorms require aviation warnings, because of the large amount of hail, which may be carried some distance from the storm center, and because of the strong winds and turbulence associated with the gust front, which moves ahead of the spreading downdraft. The first echo of these severe thunderstorms begins very high (at 25,000 to 30,000 ft), and the reflectivity increases very rapidly because of the strong and persistent updrafts. These storms are well-organized; a strong wind shear separates the updraft from the downdraft and produces a clear vault area, which may show in the radar signature as a hook echo. These storms are detected as strong thunderstorms even at a 100-nmi range[5].

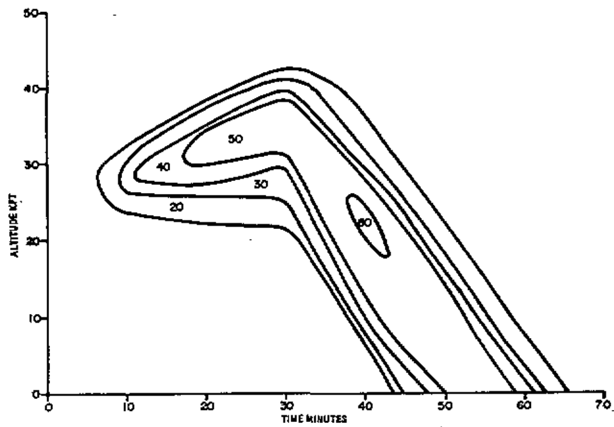

Figure 8 TYPE 5 -- VERY SEVERE THUNDERSTORMS

A Meteorological Approach to Radar Simulation

When a pilot observes a weather system, it is composed of many storms, each of which contains numerous thunderstorms cells, all at different stages of development or decay. The entire storm mass appears to be moving in the direction of the prevailing mid-level winds, but individual storms may appear to be moving in slightly different directions. When the aircraft is flying at cruise altitude, with zero antenna tilt, the weather radar displays the horizontal slices of the storms that are intercepted by the radar beam. If the antenna is tilted downward, the radar displays flight-altitude slices of only the nearby storms and displays lower-altitude slices of more distant storms. Only three or four colored contour shapes are displayed for each thunderstorm cell slice, but these shapes change because of attenuation and thunderstorm growth and decay with time.

The purpose of weather radar training and weather radar simulation is to enable pilots to interpret these attenuated colored shapes. If it is to be used in the same manner that a pilot uses his airborne weather radar system, a weather radar simulator must recreate the results of the physical laws that govern radar propagation and attenuation within the atmosphere and must also recreate the four-dimensional growth and decay characteristics of various types of thunderstorms.

A weather radar simulator has been developed that encompasses the meteorological aspects of thunderstorm dynamics and atmospheric attenuation. Pilots can now be trained in the use of weather radar in the manner described by the weather radar pilot's manual, and they can observe dynamic thunderstorm echoes while in the complete safety of a flight simulator.

The simulator for this weather radar system uses a 16-bit microprocessor-based computer with about 1 Mbyte of core and 10.8 Mbytes of disk storage capacity. The system provides for attenuation due to range, precipitation, and radome icing, as well as for beam smearing. Ground clutter is simulated, with the altitude band displayed according to tilt control position. A color monitor and a digitizing pad are required to generate a weather scenario.

Weather Radar Simulation

The weather radar simulation begins by generating a precipitation contour, the shape of *which is digitized from that of a real-world* contour. Four levels of precipitation reflectivities can be used; green represents the 20-30 dBZ band; yellow, 30-40 dBZ; and magenta, above 50 dBZ. The four contours are digitized with respect to a common cell centroid and combined to form one altitude slice. A cell is composed of up to sixteen altitude slices built around a common centroid, and it can be moved or rotated as a unit with respect to a storm reference point. A storm is composed of as many as twenty individual cells, and it can be moved or rotated as a unit with respect to a scenario reference point. The scenario reference point can be located anywhere on earth by latitude and longitude. A scenario may contain *as many as ten individual storms, but only* one of the ten stored scenarios can be displayed at one time. The instructor can set the initial scenario location and rotation and also the initial time elapsed into the scenario's development. Before the real-time simulation, the instructor can preview the scenario at an accelerated buildup rate.

As each colored contour is generated off-line, it is assigned a display priority from 1 to 16; higher priorities usually are assigned to higher reflectivities. Within this priority system, different priorities can be assigned to contours of the same color in different cells; this permits merging cells and also permits the growth of new *cells or shapes from within existing contours.* Three turbulence contours, which represent light, moderate, and severe levels, can be digitized at this time with respect to the common cell centroid and assigned priority levels within an independent set of sixteen priorities. Before the entire cell is stored on the computer disk, contours are digitized to scale and combined to form slices. Each contour can have a shape different from that of any other contour in any slice of the cell. If blank slices are used, each cell can be given a vertical size different from that of other cells in the storm.

Datafiles

The user creates datafiles to model the movement, rotation, and growth and decay characteristics of the contours, slices, cells, and storms that comprise the complete scenario:

- The growth and decay table contains, for all cells, the percentage size of the displayed contour for each slice at each of the 32 stages in the growth and decay cycle(s). The growth and decay table relates stage to size.

- The storm datafile contains, for each cell in the storm, the range and bearing from the storm reference point and the rotation angle at each of the 32 stages of development. The amount of time each cell will hold in each stage and the amount of time to interpolate to the next stage are also given at each one of the 32 stages. The storm data table can be used in wraparound mode for cyclical development of any cell, cell development can be frozen at any chosen stage, or the cell may skip stages in the development cycle. The storm data table relates time to stage.

- The scenario datafile contains the initial location, rotation angle, and movement for each storm in the scenario. It also identifies for all cells which growth and decay table is to be used for all cells in the scenario. When a scenario is *generated off-line*, all data-files are compiled into a real-time load, which is ready for execution when requested by the instructor.

Applications to Special Thunderstorm Environments

The growth and decay table can be thought of as *representing the atmospheric conditions* that cause particular types of thunderstorm development characteristics. A dry environment can be modeled, in which thunderstorms grow rapidly but produce little or no rain at the ground, and this dry environment can be combined with a high cloud base environment to model the radar characteristics of the Denver, Colorado, microburst environment by changing only the growth and decay table values. If a moist, tropical environment is modeled in the growth and decay table, the same set of contours, slices, cells, and storms can be used to simulate thunderstorms in Miami, Florida.

The first echo appearance at mid-altitude and the subsequent growth and decay characteristics of particular thunderstorm types can be simulated by using the growth and decay table. The data from Wilk and Dooley[5] for the three thunderstorm types described above were modeled into one growth and decay table for simulation. At three locations within the table, two stages of zero size were placed, so that the cell could disappear for move*ment to a new location through the use of the storm* data table. After it completes the first set of growth and decay characteristics, the cell can continue through stages to a new set of thunderstorm characteristics, or the cell can skip all the stages for the other two types of storms and cycle repeatedly through the original set of characteristics at the original location. This allows the set of contour slices for one cell to take on the growth and decay patterns of up to three different thunderstorm types. With storms that contain many cells, the number of apparent appearances of different thunderstorm types can increase dramatically.

Our weather radar simulation system permits recreating very complex and dynamic storms, such as a right-moving multicellular thunderstorm (Figure 9). New cells develop on the right flank of the storm mass. As a cell develops and decays, it follows the direction of the prevailing mid-level winds (Figure 10). The entire storm appears to move to the right of the prevailing winds, and the storm may continue for many hours. Such multicellular thunderstorms, which commonly exist in squall lines, create many difficult flight path decisions for a pilot.

Motion, Visual and Aural Interfaces with the Simulator

As the simulated aircraft penetrates a precipitation contour, the precipitation level is transferred to the host computer to be used in simulating the sounds of rain and hail. The precipitation level can also be used to calculate a reduction in visibility or RVR (runway visual range) for the visual simulation.

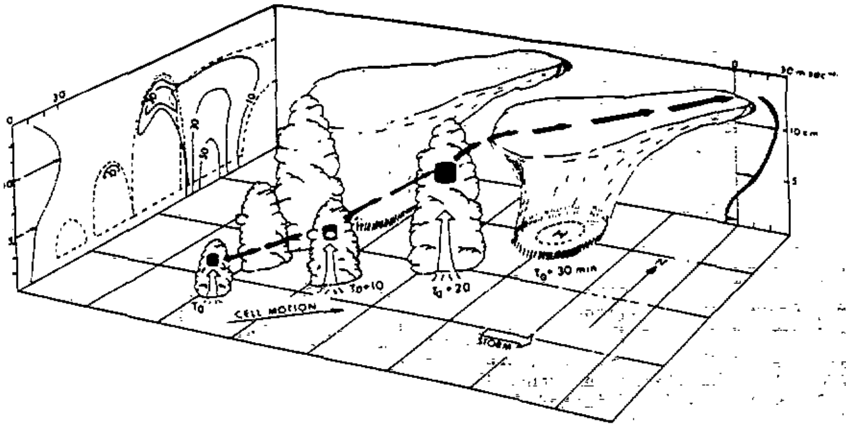

Figure 9 Schematic view of a multicell storm. At the initial time, the storm consists of four cells at different stages of development. The development of the youngest (southernmost) cell at successive times is indicated. The *heavy dashed arrow is the trajectory of a parcel in the growing cell. A vertical section of the radar echo at the* initial time is shown, as well as an indication of the wind profile. (From Chisholm and Renick, 1972.)

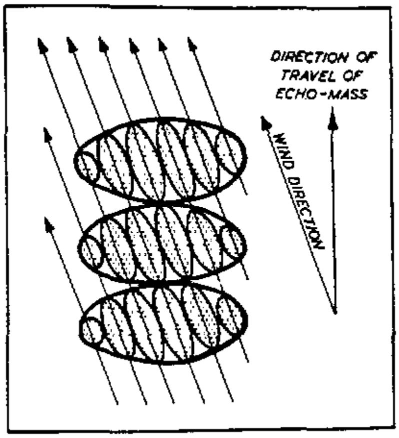

Figure 10 Formation of new cells on the right flank of a multicell thunderstorm and their eventual decay on the left flank, causing the whole storm to travel to the right of the winds (Browning and Ludlam, 1960).

For each cell slice, three turbulence contours are created in exactly the same manner as the four levels of precipitation but are not displayed during the simulation. The turbulence contours, which are given their own set of priority levels and stages in the growth and decay table, are created around a cell centroid, and they move with the precipitation contours, according to the information contained in the storm data table. As the aircraft penetrates a turbulence boundary, the turbulence level is sent to the host computer to be used in turbulence models that provide motion cues during the simulation. Wind and turbulence models can be moved from the host computer to the weather radar system and can be coordinated easily with the aircraft's location in the storm. We may use this process in future weather simulation.

Conclusions

The methods of weather radar display interpretation described in pilot manuals may not be observable in most weather radar simulations. The transfer of training for flight path decision-making from the simulator to the real world requires excellent modeling of the dynamic growth and decay characteristics of thunderstorm echoes. To recreate these dynamics, a weather radar simulator must be designed from a meteorological frame of reference. A color weather radar simulation system now available provides the required flexibility to model complex thunderstorm echoes in four dimensions. Data for three thunderstorm types have been programmed into this system to permit simulating very complex and highly dynamic multicellular thunderstorms. When this type of thunderstorm appears enroute, a pilot must make many flight path decisions by interpreting the weather radar displays in the cockpit. This type of training can now be performed realistically in the safety of a flight simulator.

References

1) Trammell, Archie, "How to Avoid Thunderstorms Although Radar Equipped," AOPA Pilot, July 1981.

2) Pilot's Manual with Radar Operating Guidelines - RDR-4A Airborne Weather Radar System, Bendix Corporation, ACS-1024A - 284.

3) Metcalf, James I., "Airborne Weather Radar and Severe Weather Penetration," Flight Crew, Summer 1983.

4) Breed, Daniel W., Case Studies on Convective Storms, Case Study 1, 13 July 1978: First Echo Case, NCAR Technical Note PB84-147479, November 1983.

5) Wilk, Kenneth E., and Dooley, J. T., FAA Radars and Their Display of Severe Weather (Thunderstorms), FAA-RD-80-65, July 1980.

About the Author

John Klehr is a systems engineer for Link Flight Simulation Division of The Singer Company in Binghamton, New York. He has worked extensively in the areas of meteorological modeling for commercial flight simulators. He is a member of the American Meteorological Society and the American Institute of Aeronautics and Astronautics. He has an MS in Atmospheric Science from Colorado State University, Fort Collins, Colorado. He has published in the Journal of Atmospheric Sciences and Monthly Weather Review. In 1983, he presented a paper entitled "A Four-Dimensional Thunderstorm Model For Flight Simulators."