Antenna Tilt: The Key Radar Control

Tilt management skills are critical to using airborne radar properly, but first you must understand the academics.

by Archie Trammell

We in aviation have known since first flight that a poor attitude-an incorrect mind set can kill. Not quite so obvious, however, is that someone else's faulty attitude may cause your accident. We now have a crystal clear example that the latter can be true.

In its investigation of the Delta Lockheed L-1011 crash in a thunder-storm at Dallas/Fort Worth Airport in August 1985, the NTSB interviewed Delta's systems manager for training, who said *“. . . . with any airborne radar device, written instructions and classroom academics are highly in-adequate . . . “* It's largely something that has to be learned by experience."

The NTSB let the statement go un-challenged in its report on the accident, but we must not.

To let it be said that classroom instruction in the fundamentals of radar need not precede knob twiddling is to leave a dangerous attitude uncorrected. Such a belief is no different than thinking that the only way to teach a captain how to use a flight director is to load the airplane with 200 unsuspecting souls and dispatch him into an area of 200-and-a-quarter weather. Moreover, the statement is totally contrary to historical experience. It says that each succeeding generation of pilots must start from zero and learn from his or her own mistakes, never benefiting from radar operating techniques and methods worked out by others in thousands of hours. The truth is that without a background in the basics, no amount of trial and error will teach you how to use an airborne radar.

It's also revealing of the abilities of the Delta systems manager himself, who has not learned the first fundamental about airborne radar operation. He doesn't understand tilt management, the prerequisite to all other radar skills. If he did, he would have never said in a follow-on statement to the NTSB interviewer, *"The primary use of this type of radar, or any airborne radar with which I have any experience, is en-route weather avoidance. When you get into the approach environment . . . to get any useful work out of the radar, you have to do an awful lot of playing with the antenna tilt, and [since] you are also very close to the ground . . . you get a lot of ground return. So, it's least useful in the approach phase of the flight."*

About 20 minutes of radar ground school - of ‘classroom academics’ - will prove him totally wrong. Setting up a radar so that ground returns are eliminated from the display is nothing more than applied sixth-grade geometry and fourth-grade mathematics.

Let's examine just two of the "academic" facts and see how they might have prevented the Delta 191 accident if they had been passed on to the crew in a ground school. Incidentally, these facts are not new. They were discovered by Captain Robert N. Buck of TWA during World War II and proven by the original Project Rough Rider pilot, Jim Cook of Dallas, in hundreds of thunder-storm penetrations between 1953 and the present.

Fact one is that a radar, which is an acronym for radio detection and ranging, detects and displays to the pilot on his indicator those objects-and those objects only-that are swept by the radar beam. That beam is a narrow cone ranging from three to 10 degrees in diameter. It sweeps in a plane relative to the earth, selected by the pilot with an antenna tilt control.

The pilot, therefore, has total control of whether ground returns are detected and displayed. All a pilot has to do is select a tilt setting that results in the swept area being above all ground objects. Ideally, the tilt should be set so that the bottom edge of the conical beam sweeps on a plane parallel to the surface of the earth, as in Figure 1.

With the bottom of the beam sweeping on a plane parallel to the surface of the earth, only those objects that extend upward through the altitude of the aircraft are detected and displayed. Thus, at terminal-area altitudes (any altitude below 15,000 feet), only tall threatening weather is displayed; ground returns are eliminated from the display.

Fortunately, setting the tilt to the proper position is very simple to do. First, adjust the tilt control until the bottom edge of the beam is sweeping along the ground on the 20 NM arc. You can easily identify where the bottom of the beam intersects the earth. From the bottom of the beam outward the radar indicator will be filled solid with a band of returns all across the swept sector; from the bottom of the beam inward the radar indicator will be blank (see Figure 2).

Next, divide your altitude in thousands of feet AGL by two. Finally, note the tilt setting with the bottom of the beam sweeping on the 20 NM arc, then increase tilt by a number of degrees equal to the calculation (example: you are at 12,000 feet AGL; 12 divided by two equals six. With the bottom of your beam sweeping on the 20 NM arc, the tilt index is at minus four degrees, let's say. If so, raise tilt to a setting of plus two degrees-minus four plus six equals a positive tilt and the bottom of your beam is now sweeping an area from 12,000 feet AGL upward. Anything depicted on your radar indicator is an object with a height greater than 12,000 feet AGL.).

Had the Delta 191 crew been aware of this procedure (we call it TIP, for threat identification procedure), they would have known that significant weather was on or near the approach to DFW Runway 17L at least 14 minutes before impact. At 1751:19 hours (impact was at 1805:55), the second officer saw rain ahead. At 1752, just 41 seconds later, the aircraft was descending through about 12,000 feet AGL, headed almost directly toward the airport, which was about 40 NM away. At 1752:00 TIP would have revealed a contouring cell at the 35 NM range directly between them and the airport. At 1756:00, when the aircraft was at 7,000 feet, 25 NM from the airport and headed directly toward it, TIP would have revealed a contouring cell at the 23 NM range. The crew would have known a storm was in progress on or very near the final approach course at least six minutes before flying into it.

The Magic Radar Formula

Had the Delta crew run a height evaluation procedure (HEP) on the storm at 1756:00, they would have known it was exceedingly hazardous for a terminal operation.

To understand how HEP works, one must first become familiar with what we refer to as "the magic radar formula," which is the basis for all radar tilt-management procedures, tricks and shortcuts. Since the radar beam is angular (a cone with a width measured in degrees) and tilt management is strictly an angular manipulation of that beam, one must have a method for converting degrees into feet; namely, distance times 100 equals feet per degree at that distance.

The dimension across a degree changes constantly as the distance from the origin increases - your radar antenna being the origin in this case. To determine how much the beam is shifted up or down per degree at a certain distance, put two zeros behind the distance in nautical miles and you have the answer in feet. At 10 NM, for example, one degree is 1,000 feet (10 followed by two zeros). At 20 NM, one degree is 2,000 feet across, at 37 NM one degree is 3,700 feet across and so forth.

The formula isn't as accurate as trigonometry, but a pilot doesn't have time for trig during an approach. The formula is more accurate than your tilt control, however, which has a degree or more of variance in it under the best of conditions.

Incidentally, you can use that formula to prove why TIP works. You can also use it to modify TIP to better suit the situation. At high altitudes (above 15,000 feet AGL) put the bottom of your beam on the 40 NM arc and divide your altitude AGL by four rather than two.

At 32,000 feet AGL, for instance, 32 divided by four equals eight. Put the bottom of your beam on the ground at 40 NM, raise tilt eight degrees and the bot-tom of your beam is level to the earth at an altitude of 32,000 feet AGL. (We can ignore the fact that the earth is round as long as the distance of interest is 60 NM or less.)

Why does raising the bottom of your beam eight degrees place it parallel to the surface of the earth? Because at 40 NM, each degree raises the bottom of the beam 4,000 feet and 4,000 feet times eight equals 32,000 feet. If the bottom of your beam is on the ground 40 NM ahead and you raise it eight degrees, the bottom of your beam at a point 40 NM ahead will now be at the same altitude as your antenna; there-fore, the bottom of your beam will be parallel to the earth's surface at an altitude of 32,000 feet AGL.

If you prefer to divide by three, five or eight, place the bottom of your beam on the ground at 30, 50 or 80 NM, respectively. TIP still works. We'll let you calculate why.

Antenna Stabilization

Before proceeding, we must clear up a prevalent misconception. Many pilots think that tilt directs the radar beam up or down relative to the pitch attitude of the aircraft. In fact, the pilot's manual for the radar that was installed in Delta 191 states that*, "Selected (tilt) angle is in relation to the longitudinal axis of the aircraft."*

Totally wrong. Selected tilt angles are relative to old Mother Earth. In aircraft that do not have antenna stabilization, or when stab is turned off, tilt angles are relative to the longitudinal axis of the aircraft. However, all airliners, and virtually all corporate turbine aircraft, have stabilized antennas.

With stabilization, a reference from the aircraft vertical gyro is biased into the tilt knob logic. Therefore, tilt settings command the angle at which the centre of your beam sweeps relative to the plane of the earth directly below the aircraft. Change pitch or roll attitude and the angle of your beam and beam sweep remain unchanged with respect to the horizon.

It's very important to understand that result. It's also very important that pilots of aircraft that do not have stabilized antennas, or when stab is off, always correct tilt selections for deck angle excursions from level flight. Otherwise confusion will reign.

Notice what antenna stabilization does for you. Once a TIP is conducted, or once the beam is set to any desired angle relative to the earth, you do not have to mess with the tilt control again. With stabilization, the beam inclination stays where you left it relative to Earth, as your attitude and altitude change, which means you can perform a TIP once and the bottom of your beam will remain level with the earth as you climb or descend. TIP once and what you see on your radar intrudes through your current altitude even as that altitude is changing in a climb or descent. (This discussion assumes that the aircraft is in reasonably stable flight. Manoeuvres and speed changes introduce a number of errors into the antenna stabilization system due to gyro excursions. But those errors also affect the flight control system and other flight management procedures and so must be the subject of a broader, dedicated discussion at a later time. Suffice it to state here that when gyro errors may be a factor, TIP and other tilt-management procedures must be conducted more frequently - at no more than two-minute intervals - in order to zero out the system.)

The HEP

Now, with "the magic radar formula" and stabilization well under-stood, how do you conduct a height evaluation procedure?

First perform TIP, which places the bottom of the beam level at your current altitude. Next, note the distance to any echo of interest and your tilt setting. Finally, raise tilt until the echo becomes so weak that you can just barely see it on the indicator (the echo becomes weaker because the beam begins to over-scan it). Now, the distance to the echo multiplied by 100 multiplied by the tilt difference equals the height of the storm above your aircraft's current altitude.

Let's use Delta 191 at 1756:00 as the example. The flight was about 7,000 feet AGL, 23 NM from that cell over the approach course. At least seven degrees of up-tilt from TIP would have been required to reduce the echo to just detectable (calculating 23 times 100 times seven: 16,100 feet). Adding the current altitude, 7,000 feet, yields a radar top of about 23,000 feet. A 23,000-foot-high contouring storm located directly on the localizer is bad news to anybody.

A Shortcut HEP

But a reasonable question is, does a crew have time for that much knob tweaking and mental arithmetic during a busy approach?

Normally, yes. With practice, the entire TIP and HEP tilt manipulations re-quire only 15 or 20 seconds. But even 15 seconds can be too long at times. In that event, use the tilt-up technique, TUT for short. That is, adjust tilt so that the centre of your beam is angled up 10 degrees.

To accomplish that you must know where true zero degrees tilt is - true zero degrees tilt being the setting that results in the centre of your beam being parallel to the earth. It's probably not at the zero-degree mark on the tilt control because of antenna installation errors and/or stabilization gyro excursions. To find it, execute a TIP, then lower tilt one-half your beam width (see Figure 3 to find your beam width). With a 12-inch antenna (assuming X-band radar) true zero degrees tilt is at TIP -4.0 degrees; with an 18-inch antenna, it's at TIP -2.5 degrees; with a 30-inch antenna it's at TIP -1.5 degrees.

When using the + 10-degree procedure, ignore the fact that your beam is a cone, that it has a width. Assume that radar tops are at the centre of your beam, which will build in a safety cushion.

Now, with + 10 degrees on the tilt, echoes displayed at a distance of 30 NM or more have radar tops at least 30,000 feet above your current altitude. Those displayed at distances of 20 NM or more have radar tops of more than 20,000 above you. (note: HEP and TUT give you an estimate of radar tops - not the top of the storm. For overflight planning, hazards may exist several thousand feet above the radar top of a weather system.)

Research has proven that the hazards associated with a weather system are directly proportional to its radar height. In the terminal area, any storm with a radar top in excess of 20,000 feet AGL is a potential killer. In addition, any echo that contours at any distance with + 10 degrees of tilt is a no-go when operating below 15,000 feet.

From that comes three absolute, life-and-death, terminal area rules.

1. With + 10 degrees of tilt, any echo that first appears on the display at 20 NM or greater - whether contouring or not - must be avoided.
2. Any echo that contours at any distance with + 10 degrees of tilt must be avoided

regardless of how tall it is.

3. With +10 degrees on the tilt and after the gear is out, if a contouring echo is detected inside the five nautical mile arc and cannot be avoided, initiate a missed approach immediately. On departure, don't go.

Looking back over the string of 23 thunderstorm-related air carrier accidents that have occurred in the last quarter century, the TUT rules alone would have prevented 16. And the false alarm rate of the rules is very low. The best data available indicate that abiding by those rules will result in an average of only 16 delays per year per major airport - a small price to pay, when you consider the cost of one fatal accident.

Surface Analysis

As important and useful as the + 10 degrees tilt procedure is, it must be frequently alternated with the Surface Analysis Procedure (SAP), especially in the terminal area.

The SAP requires that the tilt be adjusted so that the bottom of your beam slopes downward four degrees (TIP minus four degrees).

That tilt setting and the 50 NM range setting (or as close to 50 NM as possible with your particular range selector) should be considered your normal terminal area radar configuration. Adjust tilt to TIP and TUT for several sweeps at frequent intervals, but always return it to the SAP position. Shorter or longer range selections should be used only intermittently, the exception being when within 10 NM of the runway on approach. As the airport draws near, a 25 NM or even 10 NM range selection is appropriate, but do not fail to go back out to 50 NM on occasion with tilt set at TUT to survey your missed approach path - just in case.

Whenever the bottom of your radar beam is slanted down four degrees your radar display will provide you with three vital types of information:

(1) A terminal area radar map

With the bottom of your beam down four degrees, the radar will paint a band of ground from 25 NM outward when the aircraft is at 10,000 feet AGL. On arrivals, the 25 NM works inward 2.5 NM per 1,000 feet of descent so that when crossing the marker inbound, your radar will be displaying ground from about four nautical miles outward to the edge of your indicator.

Ground painting terminal areas frequently on VMC days is critical. A pilot who flies into a given terminal six or more times per year should know the radar signature of the area so well that he can fly to the centre of the airport with no guidance other than radar. He should be able to point out, on the indicator, every lake, ridge, mountain peak, shopping centre, tank farm and rail-road yard in a 25 NM radius of the middle marker. Such ability is called radar professionalism. It is often useful and sometimes lifesaving.

By knowing where the major radar landmarks are, a pilot can quickly identify storms in the airport vicinity just by glancing at the radar indicator and without touching any radar control. They are the strong echoes that weren't in a particular location last trip. Mountain peaks, suburban developments and tank farms don't grow overnight. After identifying a weather echo either with TIP or by ground mapping, the wise pilot watches what happens with his tilt set at the SAP position. If the echo gets stronger or larger over a period of four or five minutes, it's a rapidly growing storm. If it gets smaller and weaker minute to minute, it's likely to be a dissipating storm.

Interestingly, during the eight min-utes from 1751:19 to 1759:37 that Delta 191 was vectored straight toward DFW, a cell that was six nautical miles north-east of the airport over mostly farmland dissipated from Level 3 to nothing. At the same time, a second cell at four nautical miles southwest of the first, grew from nothing to Level 3. It was the second cell that spewed out the downburst as Flight 191 flew into it.

(2) Terrain threat warning

With a four-degree down slant to the bottom of the beam, over flat terrain, ground should be painted from the 25 NM arc outward as the aircraft passes through 10,000 feet AGL. At 5,000 feet it should be on the 12 NM arc. Crossing the marker it should be on about the four nautical mile arc.

If your radar indicator doesn't agree during a climb or descent, something is not right, including the possibility that you may not have as much terrain clearance as you think.

Over mountainous terrain, a ground echo that intrudes inside the 10 NM arc with tilt adjusted for SAP should command your undivided attention. You are less than 4,000 feet above a peak. Perhaps you are below it. One that intrudes itself inside the five-nautical-mile arc is cause for alarm, unless you have it visually, because you cannot be more than 2,000 feet above its peak. Within about two minutes you'll discover if you are below the peak.

(3) Radar shadow enhancement

This skill is the most important of all. Failure to identify a radar shadow is the greatest cause of convective weather accidents. The tragedy is that they just about jump off the scope at you when you're aloft if you would just select the 50 NM range and adjust your tilt so the bottom of your beam is angled down four degrees.

The radar shadow in the accompanying photo (Figure 4) is that black wedge trailing off into the distance at the 11 o'clock position. The black area on the right is a large lake. Shadows always point directly away from the antenna. They have a feathered edge, as in the photo, and they continue outward as far as ground returns can be painted. (If the sides of a shadow come together in the distance, you are above the object casting it.)

Radar shadows are caused by a weather system so dense that radar energy cannot penetrate it just as a shadow from a flashlight is caused by an object so dense that light is not able to penetrate it).

Notice in the photo that energy is penetrating the left side of the storm; it cannot penetrate the right side.

The rule is, never, never, ever continue toward a radar shadow. Failure to recognize a shadow and abide by the rule is the cause of 90 percent of convective weather accidents. Eastern Air-lines Flight 66 crashed in a shadow at JFK in 1975; Southern's Flight 242 crashed in a shadow at New Hope, Georgia in 1977; Air Wisconsin crashed in a shadow northeast of Omaha in 1980; Pan American crashed in a shadow on take-off at New Orleans in 1982; USAir crashed in a shadow at Detroit in 1984; Delta Airlines Flight 191 crashed in a shadow at DEW in 1985; a corporate Westwind crashed near several shadows in 1986.

Evidence is abundant that airplanes cannot fly through weather that casts a shadow. Rainfall rates in a shadow-producing storm frequently exceed the certification limits of the aircraft and engines. In addition, shadowing storms will contain microbursts, downbursts, large hail, extreme turbulence and very possibly, tornadoes. A storm casting a shadow can be identified with tilt up, but the clues are subtle and easily misread. With the SAP technique they cannot be missed. Those who know how to identify and read such indications are safe pilots; those who don't may as well turn off their radar. It's useless to them. (By the way, don't rely on the gimmicks of some newer radars that purport to identify shadows but often do not indicate a shadow where there is one. Put your tilt down and watch for the real shadows.)

In these few pages we have barely exposed the tip of an iceberg. We've touched on only two of hundreds of techniques, shortcuts and radar facts that can never be discovered in years of self-education. We hope that the NTSB will have second thoughts on their tacit agreement with the statement: *“. . .with any airborne radar device, written instructions and classroom academics are highly inadequate."*

Meanwhile, don't let that attitude be the cause of your accident. Practice the TIP, REP, TUT and SAP techniques until they become second nature with you. Then steer far, far away from all radar shadows.

Those Confusing Side Lobes

The fundamental truth in understanding tilt management is that radar detects and displays only those objects that fall within the limited area of the three degree to 1 degree conical beam. Objects not "illuminated" by the finite dimensions of the beam are not detected.

But for every rule there is an exception. If the antenna installation is poorly engineered or if the radome is imperfect, ghost images appear on the indicator. Several weather echoes can be seen in the accompanying photograph. The one at 12 o'clock and two nautical miles, however, is not weather. It's a false echo.

False echoes are commonly referred to as "side lobe returns," or simply as side lobes, although in reality they are caused by refracted energy from the main beam. Metal objects in the radome cavity, water trapped In the honeycomb of the radome, a metallic paint strip around the nose or one of those horrible plastic nose caps can generate side lobe returns. The cause should be corrected by taking the aircraft to a first-class radome repair shop, but almost no one bothers, so pilots must learn to live with false echoes.

In some instances a spear of refracted energy points downward, bounces off the ground and shows up as an echo at 12 o'clock. No matter where you place the tilt, there is the echo at 12 o'clock. In other instances the spear points to the side so that you see a side-lobe return, also at 12 o'clock, only when flying abeam a storm.

In still other instances, you see no side lobe return when your radome is dry; you see one only when your radome is wet or has ice on it. Whenever you're in weather, you always have a false, contouring storm at 12 o'clock, never more than five or six miles distant.

A necessary radar skill is learning to recognize and ignore side lobe returns. There are several ways to identify them. First, just observe your radar on clear days. Execute TIP and if you see an echo, it's a side lobe. Mark it in your mind as something to ignore.

If you see side lobe returns only when in weather, however, identifying them gets a little trickier. One clue is movement. An echo that you cannot catch up to is a side lobe return because storms never move as fast as an airplane flies. An exception (there's that exception again) is when you descend. A side lobe caused by energy spilling off the antenna and pointed straight down will appear at a range roughly equal to aircraft altitude AGL. Therefore, when you're descending or flying toward rising terrain, it will appear that you're overtaking a side lobe - which is something else you must observe on several flights and learn to ignore.

If all else fails, select the 50 NM range (or as close to 50 NM as possible), run your tilt down until you have a solid ground paint from 10 or 15 NM outward, then back way off counter-clockwise on your gain control. If a shadow appears behind the suspect echo, it's real; if not, it's a side lobe because side lobes do not cast shadows.

Business &Commercial Aviation / June 1987