13 Takeoff

Takeoff is optional.
Landing (sooner or later) is mandatory.

The most important part of taking off is making the decision to do so. Discussion of decisionmaking (section 13.7) will be postponed until after we have discussed normal takeoffs --- not because it gets lower priority, but just because it's hard to appreciate an abnormal situation unless you understand the normal situation.

Also: Before taking off, remind yourself of your duty to see and avoid other traffic, as discussed in section 16.2. You remain responsible until the aircraft is parked at the end of the flight.

13.1 Simplest Takeoff

This section presents a "case study" of a takeoff in which the pilot has to do remarkably little work. (In subsequent sections we will describe ways in which you can get better results by doing a little more work.)

This procedure applies when you have a well-paved runway with plenty of length and no obstructions to worry about. As shown in figure 13.1 and table 13.1, part way down the runway you rotate so that the pitch attitude is about 7.5 degrees. You then just hold that pitch attitude. Period.

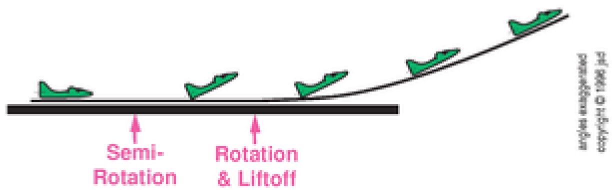

Figure 13.1: Simplified Takeoff

	Angle of Attack	Angle of Climb	Pitch Attitude	Incidence	Airspeed
Initial roll	4.5°	0°	0.0°	4.5°	small, incr.
After rotation	12.0°	0°	7.5°	4.5°	increasing
At liftoff	12.0°	0°	7.5°	4.5°	6% below V_Y
Initial climb	decr.	incr.	7.5°	4.5°	increasing
Steady climb	7.0°	5°	7.5°	4.5°	10% above V_Y

Table 13.1: Simplified Takeoff

Remarkably, at the moment of liftoff, the pilot doesn't have to do anything. The plane lifts off when it is ready, that is, when it has enough airspeed to support its weight at a 12 degree angle of attack. This will occur a few knots below V_Y, assuming V_Y corresponds to a 8.5 degree angle of attack (which is pretty typical; see also section 2.4). To construct the last phase of the scenario (asymptotic climb), I made some additional assumptions, namely that your engine is just powerful enough to provide a climb gradient of 5° at a speed 10% above V_Y. In particular, I imagine climbing out with airspeed = 83 knots and vertical speed = 735 feet per minute, in an airplane where V_Y is 75 knots. These are certainly believable numbers.

Note that before liftoff, most of the engine power is going into increasing your kinetic energy; a little is needed to overcome drag, and none is going into potential energy. Then, in the initial climb, we have a funny situation where we are climbing and accelerating at the same time. Finally, in the asymptotic climb phase, most of the power is going into potential energy; some is needed to overcome drag and none is going to increase airspeed.

The technique just described is smooth, simple, and elegant, but it has drawbacks. It does not give optimal climb performance (see section 13.3), it can cause problems if there is a gusty wind (section 13.2) or a crosswind (section 13.5), and it can cause problems if climb performance is impaired for any reason (section 13.7.1 and section 2.9).

13.2 Normal Takeoff

Imagine that you are using the simplified technique of the previous section, that is, rotating early and letting the airplane “fly itself off” whenever it is ready. Then imagine that just after liftoff, a gust of wind comes along and robs you of a few knots of airspeed. This will cause the airplane to settle back onto the runway. This is not elegant. To get around this, use a refined procedure: do not rotate until the airplane has a few knots more than the liftoff airspeed. This means that liftoff will occur right then, while you are rotating. It also means that by the time you are airborne, you can stay airborne even if you lose a few knots.

Here is another issue to consider: Most runways are not perfectly smooth. If the nosewheel hits a bump at 50 knots, it is likely to knock the nose of the airplane into the air, which has several disadvantages: (1) It will cause your passengers to be bounced around more than is necessary. (2) It could cause a premature liftoff. (3) It causes unnecessary wear and tear (and possibly outright damage) to the airframe.

To deal with this, you can use a second refinement, called *semi-rotatation*. That is, fairly early in the takeoff roll, rotate to a pitch attitude of 3 degrees or so. This is enough to get the nosewheel slightly off the ground, but not so much that the airplane will lift off (at any reasonable speed), and not so much that the nose will obstruct your vision (in most airplanes). This semi-rotation involves a pretty tiny pitch attitude compared to, say, proper landing attitude. When the airspeed reaches V_X or thereabouts, you raise the nose another few degrees, whereupon you will get a nice positive lift-off.

Finally, here is a third refinement: You know that the airplane will climb more rapidly at V_Y than at any other airspeed. Therefore, during the earliest part of the climb-out, where the plane is both climing and accelerating, you should watch for the point where the airplane reaches V_Y. At that point, you should make one more pitch adjustment: increase the pitch attitude a small amount (another 2.5 degrees, according to the numbers in our scenario) and trim to maintain V_Y. figure 13.2 and table 13.2

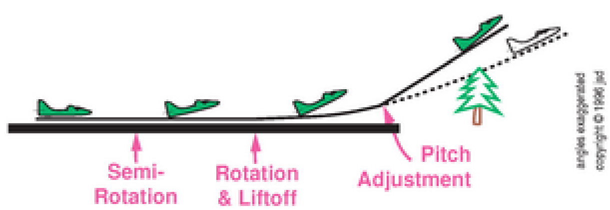

Figure 13.2: Normal Takeoff

	Angle of Attack	Angle of Climb	Pitch Attitude	Incidence	Airspeed
Initial roll	4.5°	0°	0.0°	4.5°	small, incr.
After semi-rotation	7.5°	0°	3.0°	4.5°	increasing
Just after rotation & liftoff	12°	0°	7.5°	4.5°	just above V_X
Initial climb	decr.	incr.	7.5°	4.5°	increasing
Steady climb	8.5°	6°	10.0°	4.5°	V_Y

Table 13.2: Normal Takeoff

The last phase of this scenario assumes your engine can sustain a 6 degree climb gradient at V_Y. In particular, I imagine 800 feet per minute at 75 knots.

In the figure, the dotted-line flight path and the uncolored airplane show the results you would have obtained using the simplified procedure described in the previous section. Remember that by climbing out at V_Y you gain more altitude (per unit time) than you would at any other airspeed.

* Flaps for Normal Takeoff

Extending the flaps for takeoff will improve your ability to see over the nose. This is because it increases the incidence; therefore the airplane will fly at a lower pitch attitude (for any given angle of attack). If the Pilot's Operating Handbook recommends flaps for a short-field or soft-field takeoff, there's no law against using them even when the field is long and smooth.

* Perceiving the Airspeed

Choosing an attitude and letting the airplane "fly itself off" as described in the previous section has the advantage that you don't need to look at the airspeed indicator, meaning you can devote all your attention to outside references. However, this can get you into trouble if you choose the wrong attitude (see section 2.9). Airspeed, not attitude, is your best information about angle of attack (section 2.12).

At the opposite extreme, certainly it is not a good idea to devote *all* of your attention to the airspeed indicator. Fortunately, you can use your eyes (to perceive your speed relative to ground references), your ears (to perceive the sound of the engine and the sound of the wind on the airframe), and your fingertips (to perceive the forces on the yoke). This means you can get qualitative information about airspeed while keeping most of your attention focused outside. Every so often, though, you should glance at the airspeed indicator to supplement the qualitative information with quantitative information.

13.3 Obstructed-Field Takeoff

This section describes the procedure to use when you have a well-paved runway with an obstruction relatively nearby in the departure area.[1]

Plan the takeoff carefully. Take into account density altitude, runway slope, headwind or lack thereof, et cetera. Make sure you know the value of V_X under these conditions, and choose a suitable rotation speed V_R as discussed below.

Use the proper flap settings, as specified in the Pilot's Operating Handbook. Here's a useful cross-check: on most light aircraft, when you extend the flaps for an obstructed-field takeoff, you will observe that the angle of the flap matches the angle of a fully-deflected aileron.

Start at the beginning of the runway. If the taxiway leads you onto the runway some distance from the beginning, you will have to back-taxi on the runway, back to the very beginning.

Open the throttle smoothly, but not so slowly that you use up significant amounts of runway before the engine reaches full power. Some people advocate using the brakes to hold the aircraft stationary until the engine comes up to full power, but this is rarely necessary; if you open the throttle properly the airplane will move only a few feet while you're doing so.[2]

As shown in figure 13.3 and table 13.3, you should choose a rotation speed V_R at or near V_X --- that is, quite a bit higher than what you would use for a soft-field takeoff (section 13.4) or even a normal takeoff. The idea is to use the wheels to support the weight of the airplane until you have built up a lot of energy. It's OK to semi-rotate a little bit, to take some load off the nosewheel, but you don't want the wings to be producing significant lift until you're ready to climb away. Then rotate smoothly to the "climb-out" pitch attitude, whereupon the airplane will lift off immediately. Climb away at V_X. Trim for V_X. After you have cleared the obstruction, you can accelerate to V_Y. Finally, after you have reached a comfortable altitude, you can accelerate to "cruise climb" speed and trim again.

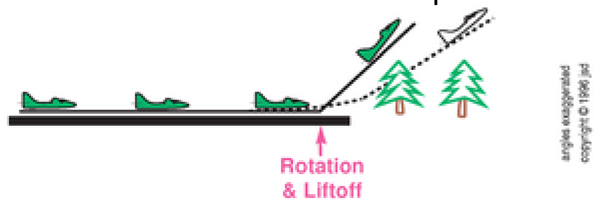

Figure 13.3: Obstructed-Field Takeoff

	Angle of Attack	Angle of Climb	Pitch Attitude	Incidence	Airspeed
Initial roll	4.5°	0°	0.0°	4.5°	small, incr.
climb	13.0°	7°	15.5°	4.5°	V_X

Table 13.3: Obstructed Field Takeoff

In the last phase of the example scenario, I imagine a climb rate of 780 fpm at 63 knots, which gives a climb gradient of 7 degrees.

In the figure, the dotted-line flight path and the uncolored airplane show the results you would have obtained following the normal-takeoff procedure, that is, accelerating while climbing and then climbing at V_Y. Note that using by using obstructed-field procedure, you have not climbed as high, but you have better obstacle clearance because you have not flown nearly so far horizontally.

It may seem paradoxical that you get better obstacle clearance by staying on the runway *longer*, but it's true (if the obstacle is not too near the runway). The rationale is as follows: You want to pass over the obstacle at a reasonable altitude with a reasonable airspeed. This requires a certain amount of energy. To maximize energy you want to minimize drag throughout the maneuver. Keeping the airplane on the runway until reaching a high speed is rough on the airplane, but supporting its weight with the wheels usually involves less drag than supporting its weight with the wings. To say it another way: rolling resistance is less than induced drag, unless the field is quite soft or bumpy.

Once airborne, you want to climb at V_X until you have cleared the obstacles, for reasons discussed in section 7.5.4.

The idea of choosing V_R to be equal to V_X is only an approximation. There are exceptions:

- For example, if you are facing a 20-foot-high billboard that is the only obstacle in the area, it is theoretically logical to zoom over at a speed several knots below V_X, then dive back down on the other side.[3] Short-term altitude gain (as given by the law of the roller coaster) is more important than long-term rate of climb (as given by the power curve).
- On the other side of the coin, if the elevation of your departure airport is near the absolute ceiling of your airplane (so that you will have very little rate of climb once airborne) and if the

runway is long and well-paved but obstructed, then it makes sense to stay on the runway (or at least in ground effect) until the speed is well above V_X.

Still, for typical circumstances, choosing V_R at or near V_X is a reasonable guideline.

* Skimming versus Wheelbarrowing or Flap-Popping

The procedure outlined above (staying on the runway at high speed, with the flaps extended) may not be possible in your airplane. Depending on the incidence of the wings, the airplane may fly itself off well before you reach the desired rotation speed.

Usually the best way to deal with this situation is to let the airplane come off the ground, and then skim along in ground effect, rather like a soft-field takeoff.

Another possible procedure (which is usually *not* recommended) is to keep the flaps retracted until you are ready to leave the runway. Less flaps means less incidence. A big disadvantage is that “popping” the flaps like this increases your workload at a time when there are lots of other things you should be attending to. Another disadvantage is that you run the risk of extending the flaps past the takeoff position to the landing position, creating lots of drag, which is really not what you want in this situation. If your POH calls for this procedure, go ahead, but be careful. Make sure you have some sort of detent to block inadvertent over-extension.

An even worse situation arises if you try to keep the plane on the ground by pushing forward on the yoke. This is called *wheelbarrowing*. What happens is that while you are holding the nose wheel down, the main wheels come off the ground. You are counteracting the incidence with a negative pitch attitude. The steering becomes dangerously unstable. There is also a risk of the propeller striking the ground.

13.4 Soft-Field Takeoff

Sometimes you want to get the airplane airborne at the lowest possible airspeed, using the shortest possible takeoff roll. For example, gooey mud on the runway will cause tremendous amounts of friction on the wheels. The sooner you become airborne, the sooner you are free of that friction and the better you will be able to accelerate. Additional reasons for using soft-field procedure will be given below.

The procedure is as follows: Extend the flaps as recommended by the manufacturer; in the absence of a specific recommendation, extend the flaps so that they just match a fully down-deflected aileron. The idea is to get the most coefficient of lift without undue drag.

At the beginning of the takeoff roll, pull the yoke *fully* backward. Early in the takeoff roll, the nose will rise, as indicated in figure 13.4. Allow it to rise to the pitch attitude that corresponds to the stalling angle of attack, or slightly less. This is typically about 15 degrees nose up.

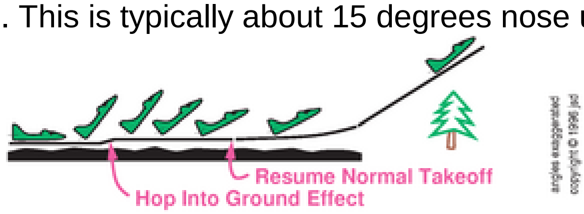

Figure 13.4: Soft-Field Takeoff

To maintain this pitch attitude as the aircraft accelerates, you will have to gradually let the yoke move forward. You will become airborne at a very low airspeed --- roughly the stalling speed.[4] If you were to maintain the liftoff attitude, a typical airplane will accelerate poorly while climbing poorly, but that's not what we want. (A lower-powered airplane might get into a situation where it can neither accelerate nor climb.) Instead, gradually lower the nose, so that you fly parallel to the ground, remaining one foot above the ground. As the aircraft accelerates in ground effect, the required angle of attack will decrease, so you will see the pitch attitude get lower and lower.

There are two ways of completing the maneuver.

- If the field is unobstructed, remain in ground effect until the pitch attitude (and angle of attack) have decreased to their normal takeoff values, as discussed in section 13.2. Then climb while accelerating to V_Y just as in the normal takeoff .
- If, however, there are obstacles, it is better to remain in ground effect until the speed approaches V_X, then raise the nose and climb out while maintaining V_X as in the obstructed-field takeoff (section 13.3).

You may be surprised at how well soft-field procedure works. Just after liftoff, the airspeed is extremely low. In ordinary conditions of flight, your airplane might well have a negative rate of climb at that airspeed --- yet in this case it not only maintains altitude, but accelerates. The special ingredient in this case is ground effect: a wing produces very little induced drag while it is in ground effect (that is, roughly, within one wingspan or less of the ground) for reasons discussed in section 3.12.4.

Just after liftoff using this procedure,

1. there is no rolling friction because the wheels are not touching the ground;
2. there is very little induced drag because you are in ground effect; and
3. there is very little parasite drag because you are moving slowly; and
4. no power is being used for climb because you are moving horizontally.

The engine is producing full power, so if none of it goes into drag and none of it goes into climb, the airplane will accelerate like crazy.

There are many situations where this procedure is useful.

- If the runway is covered with mud, tall grass, sand, or snow, there can be troublesome amounts of friction against the wheels. Soft-field procedure allows you to transfer the airplane's weight from the wheels to the wings as early as possible, decreasing friction and improving acceleration.
- If the runway is rough and bumpy, the problem is not so much friction, but rather damage from hitting a bump at high speed. The sooner you lift off, the less harm to the airplane. Remember, the force involved in hitting a bump goes like the square of the groundspeed.
- Suppose the runway is perfectly smooth and firm, but very short --- and suppose it is surrounded by open fields with lots of bumps but no serious obstacles. You can become airborne over the runway, and then accelerate in ground effect over the fields.
- Suppose you are attempting an ordinary takeoff from an ordinary field, but due to a gust (or perhaps even a lapse in pilot technique) you become airborne at a too-low airspeed. The best strategy is to accelerate in ground effect; you don't want to re-contact the runway (especially if there is a crosswind) and you don't want to try climbing at the too-low airspeed.

In all cases you must be careful to remain in ground effect until you have accelerated to a proper climb speed. If you try to climb at the liftoff speed you will have a big problem: in many cases, you will be unable to climb out of ground effect. That is, as soon as you climb to a height where ground effect is no longer significant, the induced drag will become so large that you will be unable to climb *or* accelerate.

* Brief the Passengers

If you have passengers aboard who haven't seen a soft-field takeoff before, give them the courtesy of an explanation. Otherwise, they may find the procedure extremely disturbing.[5] Just tell them you will lift off at a low airspeed and they fly horizontally for a few moments while you accelerate to the optimal climb speed. Tell them that (a) this is standard procedure for getting best performance, and (b) it minimizes jolts to the passengers.

* Maneuver by Reference to the Edge Line

Whereas in a normal takeoff you can guide the airplane by looking out the front, in a soft-field takeoff the nose will block your view during most of the maneuver. Therefore you must use the *edge* of the runway as your reference. Practice this skill during taxi. You will need this skill for landings and for soft-field takeoffs, but those aren't the best times to be learning it.

13.5 Crosswind Technique

There is not a "crosswind procedure" that you would use *instead* of normal procedure, soft-field procedure, or obstructed-field procedure. Rather, you use crosswind technique *in conjunction with* such procedures.

A crosswind takeoff is not as tricky as a crosswind landing, but it does call for some special care. Consider the following scenario: You are trying to take off in gusty conditions using the (over)simplified techniques of section 13.1. You've already rotated, and are accelerating toward liftoff speed with the wings level. As the speed increases, the wings produce more and more lift, lightening the load on the main wheels. The wind is still blowing against the side of the fuselage as strongly as ever. The ability of the wheels to provide a sideways force to resist the wind is proportional to the downward load on the wheels.[6] If you keep the wings level, there will necessarily come a point --- prior to liftoff --- where the wind overpowers the wheels and blows the airplane to the side, scraping the tires across the runway.

So, here are the correct techniques for handling a crosswind takeoff.

Regarding rudder usage: To counteract the airplane's weathervaning tendency (section 8.11), you must press on the downwind pedal to keep the plane going straight. Before rotation, both the rudder and the nosewheel contribute useful steering. In the period after rotation but before liftoff, with just the main wheels on the runway, weathervaning continues, but the rudder has to do 100% of the steering. Therefore you can plan on applying a little additional pedal deflection during this period. Once you are fully airborne, there is no weathervaning tendency.

Regarding aileron usage, there are two options:

1. A possible but uncommon method is the reverse of an ordinary crosswind landing. That is, during the takeoff roll, deflect the ailerons into the wind, to place more weight on the upwind wheel. The ailerons create force in proportion to airspeed squared, so at the beginning of the

takeoff roll you will need *full* aileron deflection. As the airspeed builds up, gradually reduce the deflection. Rotate normally, maintaining appropriate aileron deflection, so that the downwind wing comes up while the upwind wing remains down. Keep the upwind wheel firmly planted, so that it can provide friction to resist the wind. Now the airplane is in a bank, trundling down the runway on one wheel; the sideways lift of the wings serves to counteract the force of the wind on the fuselage. As the load on the remaining wheel decreases to zero, the airplane will lift straight up.

Since the ailerons are deflected one way and the rudder another, you are commanding a slip. Indeed, the moment before liftoff you are (as desired) in a nonturning slip. The moment after liftoff you want to get rid of this slip. Yaw the nose to windward (to align it with the airflow), and level the wings.

2. The much more common method is the reverse of the special "737-style" crosswind landing discussed in section 12.9.5. That is, you deflect the ailerons into the wind, but not as much as in the previous method. The idea is not to transfer all the weight to the upwind wheel, but merely to equalize the weight, counteracting the wind's tendency to flip the airplane over onto the downwind side. To keep the wind from pushing you sideways, you keep weight on *both* wheels, delaying rotation until you have almost 100% of flying speed (rather like the obstructed-field takeoff procedure, section 13.3). You then rotate and fly away. This method is not optimal for soft or bumpy runways, because it involves driving along the runway at high speed.

   Again, immediately after liftoff you must make a heading change to establish a crosswind correction angle, so that the fuselage is aligned with the airflow.

Note that in both cases, the heading change that occurs right after liftoff is *not* a normal, coordinated turn. The motion of the center of mass is already aligned with the runway, so you do not want to change the direction of motion, just the heading. Use the rudder, not the ailerons.

After you have lifted off, you must take care not to settle back onto the runway. Since the airplane's heading is no longer aligned with the runway, re-landing would cause a severe sideways force on the landing gear.

As you climb out, you should expect that the crosswind will be stronger at altitude than it was near the ground. To compensate, make the appropriate heading changes.

13.6 Multi-Engine Takeoff

In a multi-engine airplane, an engine failure shortly after takeoff is a very critical situation. It places considerable demands on the pilot. Make sure you know what to do; brief yourself in detail before the takeoff. Engine failures and related procedures are discussed in section 17.1.

Early in the takeoff roll, verify that both engines are developing the same amount of power. If the aircraft is trying to pull to one side, you've got a problem. Also, check the engine gauges to make sure (a) you've got the normal RPM on both engines, (b) you've got the normal manifold pressure on both engines, and (c) you've got the normal fuel flow on both engines. The instruments that measure these three quantities are usually a single gauge with two needles, so if you notice that the needles are *split* you've got a problem.

If anything funny happens while there is runway remaining ahead of you, close both throttles immediately and stop straight ahead. Even if you are airborne, close the throttles and re-land if there is sufficient runway available. Indeed, even if the remaining runway is not quite enough, you might want to land on it: Suppose that because of density altitude or whatever, your aircraft has poor single-engine climb performance. You will sustain vastly less damage if you land and run off the end of the runway at low speed, rather than making an unsuccessful attempt to climb out on one engine.

You really don't want to be airborne at a speed below V_{MC}, i.e. at a speed where you can't maintain directional control on one engine. In many aircraft, you should aim for a lift-off speed of V_{MC} plus 5 knots. To make sure you do not lift off too soon, you can delay rotation until reaching V_{MC}. You can semi-rotate earlier if you want; just make sure you don't rotate to a pitch attitude that will cause liftoff below the desired airspeed. After liftoff, climb while accelerating to V_{Y} (which ought to be greater than or equal to V_{YSE}).

In many twins, V_{MC} is essentially equal to the stalling speed. In others, however, it is considerably higher, which makes soft-field takeoffs problematic. You don't want to lift off at "the lowest possible airspeed" (like you would in a single) since if you lost an engine at that speed you'd have a big problem: uncontrollable yaw. It would be a lot safer to lift off at V_{MC} or higher, even if this means staying away from soft, bumpy fields.

13.7 Planning and Decisionmaking

The most important thing a pilot can do to promote aviation safety is to know when to leave the airplane tied down. Don't pressure yourself --- or let others pressure you --- into making a questionable flight.

I advise all my passengers explicitly:

A flight can be delayed or diverted for many reasons, including weather, mechanical trouble, pilot fatigue, et cetera. If you feel they have to go or return at a particular time, you should make alternate arrangements.

Different takeoff situations call for different takeoff techniques. You have to ask yourself:

- Should I be making this flight at all?
- Is there a significant crosswind?
- Is the runway long enough?
- Is the runway firm and smooth, as opposed to soft and bumpy?
- Is the area free of obstructions?

Use a takeoff checklist that is appropriate to the particular aircraft you are flying (not a generic substitute). See section 21.6 for more on this. Some airplanes require the fuel boost pump on for takeoff, while others require it off. A C-152 requires 10 degrees of flaps for short-field takeoff, while a C-172 requires zero.

Make sure you have enough runway (section 13.7.1 and section 13.7.2). Make sure you have a plan for avoiding obstacles in the departure area (section 13.7.5).

13.7.1 Monitoring Takeoff Performance (wrong)

Predicting takeoff performance, beyond what is covered in the POH, requires knowing a tremendous amount about your airplane. It is a challenge for professional engineers and test pilots. It's possible, but the details are beyond the scope of this book.

When planning your takeoff, do not trust the so-called Koch chart. It purports to predict takeoff and climb performance as a function of altitude and temperature. It says it applies to “personal” airplanes, whatever that means. The bottom part of the chart is fairly accurate but useless, because better information is available in your POH. The upper part of the chart, *if it were accurate*, would be informative in situations not covered in a typical POH, such as takeoffs from airports high in the mountains. But it is not accurate. For one thing, it is based on the assumption that all “personal” airplanes have the same absolute ceiling at standard temperature. That’s nowhere near true. Even for a specific airplane, you can increase the absolute ceiling by operating at a reduced gross weight. Ceiling can have an infinitely large effect on takeoff performance, as will be discussed in conjunction with figure 13.5, yet the Koch chart doesn’t take it into account. In some conditions the chart is absurdly pessimistic, while in other conditions it is dangerously over-optimistic. Other simple extrapolation schemes are just as bad.

I sometimes hear statements which are even worse, such as:

- Statement #1 (wrong): “On any runway, if you have attained 70% of your takeoff speed before you have used up 50% of the runway, then you will have 100% of your takeoff speed by the end of the runway.”

People even claim to “prove” statement #1, using physics plus a number of hare-brained assumptions, including:

1. Assuming friction is negligible. In fact, friction is much more important in the second half of takeoff roll.[7]
2. Assuming the engine puts out constant thrust. Although constant thrust might be a fair approximation for jets or rockets, for piston engines (especially ones with constant-speed props) constant *power* is a better approximation. Therefore we expect considerably less thrust in the second half of the takeoff roll.
3. Assuming zero wind. This might be true sometimes, but it’s certainly not safe to assume this in general. With a strong enough headwind, you can attain 70% of flying speed with no engine power at all.

The following modified version is also wrong, and even more dangerous:

- Statement #2 (wrong): “On any runway, if you have attained 70% of your takeoff speed before you have used up 50% of the runway, then the takeoff will be successful”.

A little thought shows this cannot possibly be correct in general. It cannot even be repaired by changing the percentages. As shown in figure 13.5, consider a very, very long runway and a density altitude slightly above the airplane’s absolute ceiling. You will able to reach 100% of flying speed before you have used up even 10% of the runway. You will be able to take off and climb a few feet, but you will never be able to climb out of ground effect, no matter how long the runway. Therefore:

> Forget any X% --- Y% rule you may have heard.

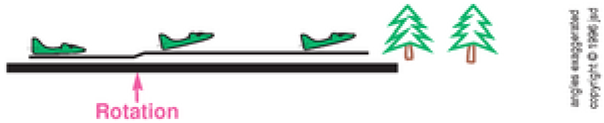

Figure 13.5: Takeoff Failure despite plenty of airspeed and runway

13.7.2 Monitoring Takeoff Performance (right)

Suppose that you are on your takeoff roll, and several subtle things have gone wrong: (a) you have underestimated the density altitude; (b) for various reasons (see below) the engine is only producing 80% as much power as it should, even at this altitude; (c) the parking brake is partially stuck so the brakes are dragging; (d) you didn't notice a shift in the wind, so you now have a few knots of tailwind; (e) you didn't notice that the runway has a slight up-slope; and (f) your mother-in-law has stowed away in the back seat, so the airplane is 15% heavier than you planned for. You may not be able to complete the takeoff safely. The question is, can you somehow notice the performance deficit in time to abort the takeoff?

If you are familiar with the airplane, you should know how the engine is supposed to sound; if it sounds rough, have it checked. Similarly, you may know what engine RPM to expect early in the takeoff roll; if you get less, abort the takeoff and investigate.

Unfortunately, if you are not intimately familiar with the airplane, it can be very difficult to notice a performance deficit until it is too late. Careful planning and checking is required, as we shall see.

Using the Pilot's Operating Handbook (POH), calculate the takeoff ground roll distance that is expected for your takeoff conditions. Also calculate the landing ground roll distance for the same conditions. Choose a runway that is at least as long as the two distances *combined*, plus a suitable margin for error. Observe and note well what part of the runway should be consumed by the takeoff roll.[8] Then commence your takeoff. If you are not airborne by the predicted point, close the throttle and apply the brakes immediately. Taxi back to the hangar and figure out what's wrong.

Do not attempt to use "extra" runway length to salvage the takeoff if there is a significant performance deficit. If you've got a deficit, you should figure out why, and the takeoff roll is no place to be doing complicated figuring.

Now let's consider the annoying situation where the available runway is just a little shorter than the aforementioned "takeoff plus landing" ground roll distance. The POH tells you that a takeoff should be possible, if everything goes right, but it does not tell you how to make a timely determination that you've got a problem. In such a situation, there are three possibilities. One is to change the situation; that is, you can offload some fuel, toss out some payload, wait for cooler air, and wait for more headwind --- so that you can attempt a takeoff using the procedure described two paragraphs ago. The second possibility is to figure out how much runway your airplane should consume reaching various speeds *less than* flying speed, so that you can have earlier opportunities to abort the takeoff. This is a job for a test pilot; the typical POH does not provide such information, and takeoff performance is notoriously hard to predict accurately. Please do not try this; playing "amateur test pilot" is like playing Russian roulette. The third possibility, if you have any remaining doubts about your airplane's performance, is to stay home.

13.7.3 Causes of Diminished Power

There are dozens of things that could go wrong with an aircraft engine.

- One of the exhaust valves could be burned or stuck, so it won't fully close.
- One of lobes on the camshaft could be worn, so a valve won't fully open.
- The magneto timing could be not quite right.
- There could be a bird's nest in the air intake.
- et cetera.

Such problems are not particularly rare; I have personally experienced the first four items in this list.

If some such thing goes wrong, the engine will usually *not* stop cold. It will continue to run, producing a fairly large percentage of its normal power. In flight, this resilience is clearly an advantage.

During takeoff, this resilience is a two-edged sword. Because the engine continues to develop lots of power, you might not notice the degradation. You might be tempted to take off with such an engine. This could lead to big trouble, especially on an obstructed-field takeoff.

13.7.4 Plan & Practice Rejected Takeoffs

There are many types of problems that you may not notice until you have begun your takeoff roll. Early in the takeoff roll, scan the airspeed, engine RPM, manifold pressure, and fuel flow to make sure you're getting reasonable readings.[9]

You should *always* plan your takeoff. This includes planning for a rejected takeoff, for reasons discussed in section 13.7.2.

Be sure you practice this. The first few times the rejected-takeoff situation arises, your expectation of a normal takeoff will be so strong that it is difficult to accept the situation and close the throttle. A rejected takeoff is psychologically at least as difficult as a go-around. Actually, most single-engine pilots find it *more* difficult than a go-around, if only because it isn't given as much emphasis during training.

Instructors: here's an instructional technique: During preflight, brief the student on the procedures for rejected takeoff. Choose a runway that is plenty long. During the takeoff roll, wait until the airspeed is about half of the liftoff speed. Then slap a suction cup on the airspeed indicator and say, "simulated airspeed indicator failure".

If something seemingly minor happens early in the takeoff roll, reject the takeoff. The rationale is that during the takeoff roll you don't have time to make an intelligent decision about what is minor and what is not, so (assuming there is plenty of runway remaining) the safest thing is to stop now and think later. See also section 15.3.

13.7.5 After Liftoff: Departure Climb

Obstacle clearance is a particular problem if you are operating VFR at night at an unfamiliar field. I recommend you don't attempt such operations, unless you can remove one of the risk factors. That is, get familiar with the field and its environs before operating at night ... or adhere to the IFR procedures. I'm not saying you need to file IFR or even have an instrument rating, but if you really want to depart an unfamiliar field at night, you should have a copy of the approved Terminal

Procedures and know how to use them.

In most cases that's remarkably easy. The Terminal Procedures can be purchased in booklet form, and/or you can download them from the web. There is a particularly simple "default" procedure that is approved for a great number of airports. It can be summarized as 35 feet, 400 feet, and 200 feet per nautical mile. That is, you must cross the departure end of the runway at least 35 feet above field elevation. You must climb straight out along the extended centerline until reaching at least 400 feet above field elevation, then you can turn at your discretion. You must maintain a climb gradient of at least 200 feet per nm all the way from liftoff until reaching a safe enroute altitude.

Such a procedure should be well within the capabilities of the ordinary pilot and the ordinary airplane. The required climb-out slope is less than two degrees. That should be no problem unless you have an impaired rate of climb, an unusually high airspeed, and/or a huge tailwind.

At some other airports, the procedure is only slightly more complicated than the default -- for instance, it might require a slightly steeper climb gradient.

If you find an airport where the approved departure procedure is complicated, you should assume it's complicated for a reason. There are probably nasty obstacles in the area.

Don't try to invent your own procedures. You don't have enough information. The VFR chart will tell you about *some* nasty terrain and *some* obstructions, but it is easy to find examples where it doesn't tell you enough. The Airport/Facility Directory will usually tell you about the 50-foot tree near the end of the runway, but it may not tell you about the power lines on the hill half a mile away. The only thing that tells you what you *can* do safely is the IFR Terminal Procedures book.

See section 12.1.3 for an analogous discussion of approaches. See section 21.4 for a discussion of general decisionmaking issues.

13.8 Other Elements of the Takeoff

At a tower airport, you will need to get approvals and clearances before taxiing or taking off.

During the takeoff roll and climb-out, you will need to apply right rudder to compensate for the helical propwash, as discussed in section 8.4.

In an aircraft with retractable landing gear, you have to decide when to retract them. It is *not* a good procedure to retract them the instant you become airborne. The reason is that sometimes things go wrong in the first seconds after liftoff, and you don't want to foreclose the option of re-landing on the remaining runway. Therefore the usual procedure is to retract the gear when it is no longer possible to re-land on the departure runway. You should say aloud the checklist item: "No more useful runway; gear coming up".

On a really, really long runway, it's OK to reduce drag by getting the gear up somewhat before you've flown all the way down the runway. However: (1) it's usually not worth the trouble, and (2) make sure that you're high enough that, in the event you *do* want to land immediately, you have time to re-extend the gear.

When ATC gives you a takeoff clearance, supposedly nobody but you should be on that runway. This applies to the runway itself, not to the airspace, so as soon as you are airborne, you are 100% responsible for seeing and avoiding other traffic. Even on the runway, it pays to keep your eyes open;

there's always a chance that ATC has made a mistake, and an even bigger chance that some other pilot has made a mistake and is encroaching on your runway without a clearance.

Very early in the climb, pick a landmark somewhere a few miles along your intended flight path, so you can maintain direction of flight primarily by outside references. The upwind leg of the traffic pattern is supposed to be an extension of the runway centerline. Similarly, note the pitch angle relative the horizon, so you can maintain the proper angle of attack and detect any windshear. You can cross-check direction, pitch angle, and angle of attack using the directional gyro, horizon gyro, and airspeed indicator, but you don't want to spend more than a tenth of your time looking at gauges. You need to be looking outside to check for traffic.

Upon reaching a comfortable altitude, say 500 feet AGL, there are a number of things that might need doing: If your aircraft has cowl flaps, check them. On a normal takeoff they will already be open, but on a go-around you will have to open them. This is also be a good time to throttle back to normal climb power, which is less than takeoff power on most aircraft with controllable-pitch propellers. This is also a good time to retract any remaining flaps. Finally, this might be a good time to accelerate from V_Y to a nice cruise-climb speed.

You should not mess with the cowl flaps or other items until you are several hundred feet up. Turbulence might cause a pitch or bank excursion while your attention is distracted, or you might bump the yoke. At low altitude, basic aircraft control should get your undivided attention.

In some aircraft, the fuel-boost pumps should be turned off at 1000 AGL; in other aircraft they stay on throughout the initial climb. Other aircraft don't use boost pumps at all.

13.9 Summary

Four of the most-common takeoff procedures are related in a fairly logical way, as summarized in table 13.4.

	Unobstructed	Obstructed
Well-paved	Semi-rotate early. Fully rotate at V_R. Climb while accelerating to V_Y.	Rotate at V_X. Climb at constant airspeed: V_X.
Soft	Hop into ground effect just above V_S. Accelerate horizontally (1 foot AGL) to V_R. Climb while accelerating to V_Y.	Hop into ground effect just above V_S. Accelerate horizontally (1 foot AGL) to V_X. Climb at constant airspeed: V_X.

Table 13.4: Basic Takeoff Procedures

Additionally, in each of the four cases, you must take into account the crosswind if any.

Proper planning is important. A wise "no-go" decision could save you a lot of trouble. Make sure you know the proper procedures, including the critical airspeeds. Make sure you know how much runway you will need. If, during the takeoff roll, it looks like you are getting less performance than you should, stop and figure out what's wrong. Practice rejected takeoffs.

Make sure you know what angle of climb you should expect. You need this to check obstacle clearance. This also affects your choice of initial pitch attitude.

When choosing an initial pitch attitude, remember that pitch attitude is not the same as angle of attack. See section 2.9 for information on the right (and wrong) ways to handle cases where the correct pitch attitude differs from what you expected.

Keep the aircraft properly trimmed and fly with a light touch. Don't forget the after-takeoff checklist.

1
: In your Pilot's Operating Handbook, this is probably called "short-field takeoff". However, as we shall see, this is definitely not the right procedure for a short unobstructed field --- it actually uses more runway than a normal takeoff. If you have a really short but unobstructed field, consider using soft-field procedure (section 13.4).

2
: I like to avoid running the engine at high power when the airplane is not moving at all, since this tends to suck up rocks, damaging the propeller. If you are moving, by the time the rock gets off the ground you will be somewhere else, possibly escaping damage.

3
: I wouldn't do this except in an emergency, because it would imply operating without adequate safety margins.

4
: ... but you shouldn't be looking at the airspeed indicator. It doesn't provide any useful information at these speeds.

5
: Imagine how it looks: The airplane is airborne but not climbing, and you are flying directly toward the bases of the trees at high speed. Just when they're convinced they're about to die, you pop the nose up and climb out.

6
: Most types of friction behave this way.

7
: Indeed, if friction were negligible, airplanes would fly much faster and would use much less fuel.

8
: There are several good ways to do this. (a) Some runways have standard markings every 500 feet. (b) Sometimes the required takeoff distance is a half or a third (or some other convenient fraction) of the total runway length. (c) Sometimes you can pace off the distance between runway lights, and then count lights. (d) Sometimes you just have to pace off the whole distance

9
: Other problems you might notice during takeoff include: A door that is not properly latched may pop open as the airspeed builds up. A seatbelt hanging out can cause a very loud, aperiodic banging noise. Neither of these is aerodynamically serious, so don't over-react.

14 Cross-Country Flying

> I'm not lost, I'm just uncertain of my position.

The term *cross-country flying* refers to essentially all flying that takes you beyond the immediate vicinity of the airport.

In cross-country flying, a number of basic skills assume added importance. For example,

- When you stay near your home airport, you can land and refuel whenever you want, but during a cross-country flight you need to plan ahead.
- When you stay near your home airport, you can land immediately if threatening weather moves in, but during a cross-country flight you need to do a lot more planning and a lot more en-route double-checking.
- When you stay near your home airport, you presumably know the length of all the runways and the layout of the traffic pattern, but it can be highly embarrassing to show up at another airport and turn left base when everybody else is using a right-hand pattern. It is also embarrassing to land a little long and a little fast and then discover that the runway is very short.
- And last but not least, you need good navigation. Navigation involves keeping track of where you are and finding your way to the destination. The three primary methods of navigation are pilotage (section 14.1), dead reckoning (section 14.2), and navigation by instruments (section 14.3).

14.1 Pilotage

The term *pilotage* refers to finding your way by reference to landmarks. This is a basic yet important pilot skill.

From the air, things look different than they do from the ground. It will take you a while to learn aeronautical pilotage skills. The rest of this section covers miscellaneous small hints.

14.1.1 Airports Make Good Landmarks

When you are planning a cross-country trip, it is advantageous to plan a route that passes over airports along the way. They make great checkpoints.

Airports make good landmarks.

If you fly over an airport, it is hard to mistake it for something else. Indeed, many airports have their name printed on one of the taxiways in twenty-foot-high letters, which pretty much eliminates all doubt as to where you are.

Even if you are not using the airports as navigational references, it is a great exercise to practice spotting all the little airports along the route. This is not easy; it is an acquired skill. Airports with grass runways can be particularly challenging, since it is hard to distinguish them from the surrounding fields. Hint: Look for the airplanes. If you see lots of airplanes parked on the grass, there's probably a runway nearby.

If you stumble across an airport that doesn't correspond with where you think you are on the chart, it probably means you are off course, but not necessarily. That's because some private strips and military fields are intentionally omitted from the charts.[1]

Spotting airports at night is sometimes a challenge. Non-pilots often have the impression that airports ought to be brightly lit, but in fact they are not. An airport in the middle of a town will be about the darkest thing in town.

Major airports have fairly bright runway edge lights, but the lights are highly directional, so unless you are near the final approach course you may be unable to see them. Also note that the tower has control of the runway lights, and may well turn off all the lights on whatever runways are not being used at the moment.

Most airports have rotating beacons that flash white and green, alternately. However, it is surprising how many airports have no beacons, inoperative beacons, or beacons that are so dim as to be useless.

Airport-spotting skill might come in very handy if you ever need to make a landing on short notice.

14.1.2 Choose Distinctive Landmarks

In parts of the world where there are relatively few lakes and rivers, they make good landmarks. In other parts of the world, there are so many lakes and rivers that it is distressingly easy to misidentify them.

Similar words apply to highways: if there are a lot of them, their usefulness as landmarks is impaired.

In forested areas, highways and railroads have the additional problem that you may not be able to see them unless you are nearly overhead.

Some landmarks (like airports, small towns, small lakes, etc.) are essentially point-like (zero-dimensional). Other landmarks (highways, railroads, coastlines) extend a long way in one dimension. In the latter case, you can readily see that you are *somewhere* along the landmark, but you will need additional information to know *where* along the landmark you are. Suggestion: the intersection of two one-dimensional landmarks makes a fine zero-dimensional waypoint.

14.1.3 Doglegs

When planning your first few cross-country trips, rather than planning to make a beeline from departure to final destination, plan a dogleg course that passes directly over a goodly number of airports and other landmarks along the way.

In general, if there is a long stretch without a 100% obvious landmark, plan a dogleg so that there is. Especially on hazy days, this simplifies life.

Even a rather crooked dogleg (say, 20 degrees off the beeline heading) adds only a few percent to the length of the trip.

14.1.4 Reality-Based Navigation

When you are at home, *planning* a flight, it makes sense to look at the chart and try to pick out a set of convenient, conspicuously-charted objects. This is called map-based navigation: you go from the map to the reality.

On the other hand, when you are in the plane, it makes a lot of sense to reverse the process: Look out the window and find some conspicuous object, and then see if you can find it on the map! This is called reality-based navigation: you go from the reality to the map.

14.2 Dead Reckoning

The term *dead reckoning* refers to navigating by keeping track of time, rate of travel, and direction of travel. To do a good job of dead reckoning, you need three instruments:

- watch or clock,
- airspeed indicator, and
- compass.

In addition, you will need decent estimates of wind speed and wind direction.

Before discussing the theory of this, let's do an example. Let's suppose you are airborne at 5000 feet, cruising at 110 knots (indicated airspeed) on a heading of 090 degrees. At 32 minutes after the hour, you arrive over Hackettstown, New Jersey, and your next checkpoint is Sussex, New Jersey. The "winds aloft" forecast called for winds of 335 degrees at 25 knots. You need to know what heading to fly and how long it will take to reach the next checkpoint. The calculation that follows is a rough estimate that you can do in the cockpit. (Later on we'll see how to do more exact calculations in the peace and quiet of the flight-planning room.)

Figure 14.1: Course Line from Hackettstown to Sussex

First of all, note the time. Write it on the chart near Hackettstown, as exemplified by the red ":32" marked on the chart in figure 14.1. (Use a pencil, so that you can erase and re-use the chart for your next flight.) While you are there, draw a line from there to the next waypoint (Sussex). This line, too, is shown in red in figure 14.1. Look outside, checking for traffic.

14.2.1 Course

Next, you should estimate the *course* from your present position to the next waypoint. To do this in the cockpit, use your hand as follows: put your thumb on your present position (Hackettstown) and your long finger on the next waypoint (Sussex). Now move your hand (without rotating it)[2] until your thumb is at the center of some nearby compass rose. In this case, the Broadway VOR[3] is convenient. Now look along the line from your thumb to finger, and see where it crosses the edge of the compass rose. In this case we find that it crosses at the tickmark that corresponds to 040 degrees, which we take as our approximate magnetic course.

In the absence of other information, this approximate course is your best estimate of the proper heading. This may not be exactly your optimal heading, but it is a reasonable approximation, certainly better than maintaining your previous heading. Turn promptly to your best-estimate heading and maintain it while carrying out the next steps of the calculation. If and when you have information about crosswinds (section 14.2.3) and VOR twist (section 14.4.4) you can refine this estimate. Check for traffic again.

14.2.2 Distance, Time, and Airspeed

When looking for a waypoint, such as your destination airport, it doesn't do you much good to be on course if you have already inadvertently passed the waypoint. Therefore, it is vital to know how far you have progressed along the course. This is just as important as staying on course, and perhaps not as easy. Consider the contrast:

- It is rather easy to notice that you are off-course by half a mile when passing a waypoint.
- It is more difficult to notice that you are a minute early or late when passing a waypoint.

Note that the distance error involved in the second case is many times larger than in the first case.

To say it another way, it is easier to notice an unforecast crosswind that is blowing you left or right of course than it is to notice an unforecast headwind or tailwind that is messing with your progress along the course.

To keep track of distance along the route using pilotage, you need an estimate of your groundspeed. Then, given speed and distance, you can figure out how much time it will take to get to the next waypoint.

The first step is convert indicated airspeed to true airspeed. In this case, 110 K_{IAS} is about 120 K_{TAS}.[4]

The next step is to account for the wind. We need to resolve the total wind into a headwind component and a crosswind component. We will use the face of the directional gyro as an analog computer to help solve trigonometry problems.

Recall that the wind was out of 335 degrees at 25 knots. Since these forecasts always use *true* azimuth, you need to convert 335 true to 347 magnetic. (Notice how the compass roses on the chart are rotated relative to true north if there is any doubt as to the sign and magnitude of the correction.) Now find 347 degrees on your directional gyro. It will be at about your 10:00 position, as shown in figure 14.2. Now we are going to use the circular face of the DG as a map. We choose the scale factor such that the radius of the DG represents the magnitude of the total wind, 25 knots in this case. Imagine a vector from the "347 degrees" point on the DG to the center. This represents the total wind, as shown in red in figure 14.2.

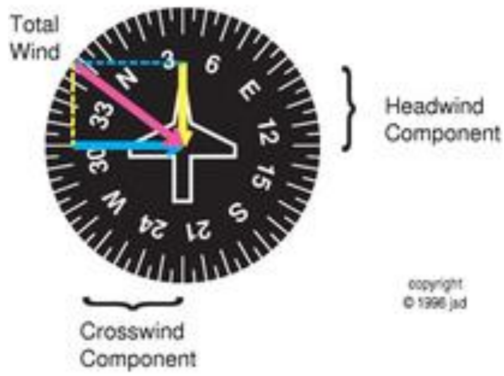

Figure 14.2: Wind Calculation using Directional Gyro

The headwind component is represented by the projection of the wind vector onto a line that runs vertically across the face of the instrument (from your 12:00 position to your 6:00 position), as shown in yellow in figure 14.2. In this case its length is about 3/5ths of a radius, which represents about 15 knots. Therefore your groundspeed is about 105 knots (true airspeed minus headwind component).

Now, we need to estimate the distance of this leg of the flight. There are two ways to do this.

Method one is literally the rule of thumb. The length of my thumb (from the last joint to the end of the nail) corresponds to ten nautical miles on sectional charts, almost exactly. You can calibrate your own thumb. In this case, the required distance is about two and a half thumbs, or about 25 nm.

Method two is sometimes more accurate. Again put your thumb and finger on Hackettstown and Sussex, respectively. Now move and rotate your hand (without changing the distance between thumb and finger) so that you can use the tick marks on one of the north-south grid lines of the chart as a reference. One minute of latitude is one nautical mile.[5] Again the answer is about 25 nm.

It is easy to remember that a groundspeed of 120 knots corresponds to two miles per minute. At that speed, you would be there in 12.5 minutes. However, in this example your groundspeed is about 10% slower than that, so it will take about 10% longer, about 14 minutes. You therefore expect to pass over Sussex at 46 minutes past the hour.

14.2.3 Crosswind Correction

Now we are going to calculate the crosswind component. Again we will use the face of the DG to help solve the trigonometry problem.[6]

Recall that the wind was out of 335 degrees at 25 knots, represented by the red vector in figure 14.2. The projection of this vector onto line that runs horizontally across the instrument (from your 9:00 position to your 3:00 position) represents the crosswind component, as shown in blue in the figure. The length of this component in this case is about 4/5ths of a radius, which represents about 20 knots. That is, we have a crosswind component of about 20 knots, from the left.

To convert the crosswind velocity component to a crosswind correction angle, you can use the information in table 14.1.[7] In the present example, you should turn the airplane 10 degrees to the left of course,[8] that is, to a heading of 030 degrees (heading = course + wind correction).

Groundspeed	Groundspeed	Crosswind Correction
(knots, real)	(knots, pi=3)	(knots per degree)
57	60	1.0
85	90	1.5
115	120	2.0
145	150	2.5
170	180	3.0

Table 14.1: Crosswind Correction Angle

If you are off course, apply an intercept angle (heading = course + wind correction + intercept) as discussed in section 14.3.3. The heading problem is now solved.[9] Check for traffic again.

14.2.4 The Wind Triangle

Concept #1: According to Galileo's principle of relativity, you cannot measure a velocity by itself; you can only measure the velocity of one thing *relative* to another.

Concept #2: Velocity is a *vector*; that is, it has a *magnitude* and a *direction*. (In contrast, something that has only a magnitude, without direction, is called a *scalar*.)

There are three velocities involved in dead reckoning, as illustrated in figure 14.3, and as shown in table 14.2.

Vector	=	**Magnitude**	&	**Direction**
airplane velocity relative to the air	=	airspeed	&	heading
airplane velocity relative to the ground	=	groundspeed	&	track direction
air velocity relative to the ground	=	wind speed	&	wind direction

Table 14.2: Relative Velocities

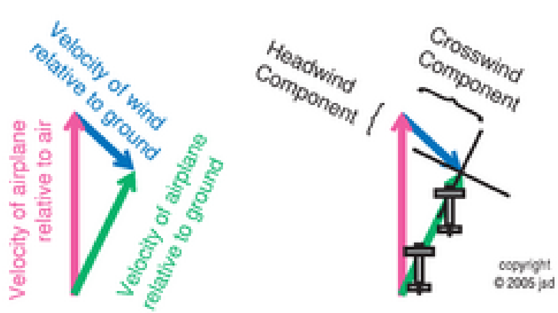

Figure 14.3: Wind Triangle + Headwind and Crosswind

Note that the word *velocity* always refers to a vector, while the word *speed* always refers to the corresponding scalar magnitude; see section 19.1.

If you want to draw an accurate wind triangle, you must be careful to draw the headwind and crosswind components as projections along and across your *course* as is shown on the right-hand part of figure 14.3. (It is a common mistake to draw them along and across your airspeed vector instead.) With the help of such a drawing you can understand why a direct crosswind (that is, a wind directly perpendicular to your course) will slow you down a little bit: even if there is no headwind component, your groundspeed (the base of a right triangle) will be shorter than your airspeed (the hypotenuse).

Also you can see that the airplane is *pointing* into the relative wind but it is *moving* along the course --- which are two different directions.

14.2.5 Discussion

Note that in the scenario presented above (section 14.2) there was basically no alternative to using the quick, approximate dead reckoning techniques (section 14.2.2 and section 14.2.3) for choosing the heading. Consider the possible alternatives:

- Pilotage will never entirely replace dead reckoning. Pilotage was great for determining your position over Hackettstown, but it didn't tell you the outbound heading.
- Radio-navigation instrument will never entirely replace dead reckoning. The Broadway VOR could tell you that you are northeast of Broadway ... but you already knew that. Even if the VOR were on the field at Hackettstown, it wouldn't have told you what outbound heading to use to get to Sussex. A GPS instrument (or a VOR station on the field at Sussex) would have simplified the job of finding the *course*, but you still would have needed to apply a wind correction to find the right *heading*.
- For a general discussion of flight planning techniques, see section 14.8.

Flying involves at least some dead reckoning all the time. Even if you are relying on instruments for long-term navigation, you can't be looking at the CDI all the time, so in the short term you are just using dead reckoning, i.e. just holding a heading.

Even on IFR flights, dead reckoning is important. Sometimes it's merely a convenience, and sometimes it's absolutely required; procedure turns and holding patterns are familiar examples.

14.3 Navigating by Instruments

14.3.1 Don't Be a Gauge Junkie

Navigating by instruments does not relieve you of your responsibility to see and avoid other aircraft.

A seemingly-nice fancy GPS can get you into trouble. It is altogether too common for pilots to spend too much time fussing with the GPS when they should be flying the airplane. Hint: on a typical GPS, 90% of the value comes from 10% of the features, so don't knock yourself out trying to use features you don't really need.

A plain old VOR receiver can get you into trouble, too. It is altogether too common for pilots approaching a VOR to have their heads "down and locked" --- paying vastly too much attention to the Course Deviation Indicator (CDI) needle and not enough attention to other traffic. The more accurately you fly over the VOR, the more likely you are to run into somebody else who is trying to do the same thing.

Keep track of your position on the chart. This will be much easier if you have drawn your course-line on the chart as discussed in section 14.8.

14.3.2 Navigation Systems (Brief Survey)

Navigation systems in common use for cross-country flying include:

- GPS = Global Positioning System. It uses a system of satellites transmitting on approximately 1.5 gigahertz.
- DME = Distance-Measuring Equipment. It uses the frequency band from 962 to 1213 megahertz.
- VOR = Very-high-frequency Omni Range. It uses the frequency band from 108 to 118 megahertz.
- LORAN = LOng RAnge Navigation. It uses the frequency band from 90 to 110 kilohertz.
- NDB = Non-Directional Beacon. It uses the frequency band from 300 to 1600 kilohertz (which includes standard AM radio). The aircraft instrument that receives and interprets the NDB signal is called an Automatic Direction Finder (ADF).

The principles of operation of these systems will not be discussed in this book.

14.3.3 Intended Heading

On cross-country flights, I repeatedly ask my students the following question: “What is your intended heading, and why?”

The answer to the “what” part of the question depends on circumstances, and will be a simple number such as 035 degrees for example. The “why” part of the question is easy; the answer is always the same, so you might as well memorize it right now:

Heading = Course + Wind Correction + Intercept

By way of example, suppose the course is 040, there’s about 20 knots of crosswind from the left, and we’re cruising at 120 knots. That makes a ten-degree crosswind correction, so if we are on course we will stay on course if we fly a heading of 030 (i.e. 040 - 10).

Now suppose we are about 10 miles from the station, and the CDI is one dot off to the right. That means we need to apply about 5 degrees of intercept angle, and hold it for a couple of minutes. Therefore the intended heading should be 035 degrees (i.e. 040 - 10 + 5).

Note: When I ask for the intended heading I want you to tell me your *intended* heading. It has almost nothing to do with the present *actual* heading. You should be able to answer this question immediately ... and without looking at the DG. (If I had wanted to know the actual heading, I would have asked a different question.)

At the earliest opportunity, you should figure out the intended heading for the current leg of the flight. Make a mental note of it. Then from time to time, look at the DG. If you ever see that the actual heading is not equal to the intended heading, promptly turn to the intended heading.

The course is fixed by basic considerations of where you're trying to go. The wind-correction angle is determined by procedures discussed in section 14.2.4. So let's now discuss the intercept angle.

A ten-degree intercept angle is usually plenty. If you are a mile off course, a ten degree intercept angle will get you back on course in less than 6 miles, which should be just fine for typical enroute navigation. As you get better at navigation, you will be able to detect smaller off-course distances (say, half a mile), in which case a smaller intercept angle (5 degrees) will be appropriate. Small corrections are the mark of a pro.

If you are farther off course, say 2 or 3 miles, you can still use a ten degree intercept angle, which will get you back on course in 12 or 18 miles. If for some reason you need to be back on course sooner than that, you can use a larger intercept angle.

Usually, the reason you are off course is because you didn't do a very fastidious job of maintaining the correct heading over the last few miles. In such a case, the solution is straightforward: choose the right heading (course + wind correction + new intercept angle) and maintain it.

In other cases, you might have been blown off course by an unexpected wind. In such a case, you might want to revise your estimate of the crosswind correction angle. Therefore the intended heading will be course + *revised* wind correction + intercept.

14.4 VOR Techniques

Nowadays practically anybody who can afford to have an airplane can afford to put a GPS in it. But you don't want to let your VOR navigation skills atrophy completely.

14.4.1 Off-Course Distance

The *Course Deviation Indicator* on a VOR receiver indicates the off-course *angle* (two degrees per dot). If you know how far you are from the VOR, you have to do a little work to figure out the off-course distance.

In contrast, on a GPS the CDI reads directly in miles and fractions thereof ... which is usually what you care most about.

The simplest way is to look at the chart. If you are ten miles from the VOR, the distance between tick marks on the compass rose tells you immediately what distance corresponds to a five-degree off-course angle. If you are nearer or farther from the VOR, the off-course distance (for any given angle) is proportionately smaller or larger.

The other way is to use arithmetic. Suppose you are 57 miles from the VOR. Since there are 57 degrees in a radian, at this point each degree of off-course angle corresponds to one mile of off-course distance. At this point (57 miles from the VOR), a three dot deflection corresponds to being six miles off course, which is embarrassingly poor navigation. In contrast, suppose you are only a couple of miles from the VOR. Then the same CDI deflection (three dots, which is six degrees) corresponds to being off course by less than a quarter mile, which is perfectly fine navigation.[10]

Bottom line: when you are close to the VOR, do not overreact to small CDI deflections. Conversely, when you are far from the VOR, you must notice and react to rather small CDI deflections.

14.4.2 Approaching the Station

Just because the CDI has super-high sensitivity near the VOR doesn't mean you have to pay super-close attention to it.

By the time you are within a couple of miles of the VOR, you should know how much wind correction is needed. The wind doesn't change at the station! You should know the course to the station, so you should be able to get there (plus or minus a tenth of a mile) by dead reckoning. Therefore take up the correct heading and just hold it. Don't chase the needle. Look outside.

The wind doesn't change at the station.

14.4.3 Progress Along the Course

It is worth repeating what was said in section 14.2.2: When looking for a waypoint, such as your destination airport, it doesn't do you much good to be on course if you have already inadvertently passed the waypoint. Therefore, it is vital to know how far you have progressed along the course. This is just as important as staying on course.

1) You can use distance/time/airspeed to keep track of your progress, as discussed in section 14.2.2.

2) You can also use pilotage: identify landmarks along the course, and put checkmarks on your chart as you pass each one.

3) GPS, LORAN, or DME make it easy to keep track of your progress along the course. VOR and NDB stations, provided they are not directly behind or ahead of you, can also provide progress information. To make use of this information, draw on your map. The navigation receiver will tell you what radial you're on ... then draw the appropriate radial line from the station. The place where that line crosses your course-line is your present position. Another option is to pre-tune the OBS to the radial that corresponds to a point of interest ... when the needle centers, you're there.

The question arises as to *how far* off your course the off-course station should be. If the station is too far away, you may have trouble receiving the signal. Also, the farther the station is away, the less precise will be the information you get from it, just because the same number of degrees will correspond to a longer distance. On the other hand, you don't want the station to be too close to the course. This is because you want the cross radials to cross the course at a reasonably large angle (preferably 45 degrees or more); otherwise accuracy is impaired. Therefore, if you chose a station that is farther from the course its usefulness will extend over a longer portion of the flight.

14.4.4 Twisted VORs

In the region where I usually fly, every VOR is misaligned by several degrees. If you want to fly along an airway that is defined by, say, the 224 radial of a certain VOR, you need to hold a 227 heading in no-wind conditions.

Here's why: In general, the radio-beams that a VOR radiates are not necessarily aligned with the actual magnetic directions. Presumably the transmitters were properly aligned when they were first installed, but some of them have not been re-aligned in over 35 years.

That's significant, because the earth's magnetic field changes over time. A VOR that was aligned with the magnetic directions several decades ago may disagree with the current magnetic directions by quite a bit. The FAA is "supposed" to re-align them, but they've fallen rather far behind. Re-alignment is a lot of work: not only do you need a really big wrench to rotate the transmitter, but you need to revise all the navigation charts.

Your GPS will agree with your compass and disagree with the VOR. That's because GPS receivers have a database that can be updated with the latest map of magnetic variation.

Here are some of the implications:

- If you are using dead reckoning, when you select a course based on the charted airways or compass roses, add the VOR twist to the charted radial before using it to select a course or heading.
- If you are flying by reference to VORs, add the VOR twist to whatever your VOR receiver is saying before using it to select a heading. That is, the nice rule (heading = course + wind correction + intercept) given in section 14.3.3 must be replaced by an uglier rule: heading = radial + twist + wind correction + intercept.[11]
- If you are *not* flying by reference to VORs, but rather using GPS to fly from waypoint to waypoint along an airway, do not be surprised if your GPS indicates a bearing that differs from the charted VOR radial for that airway.
- If you are using a GPS or a landmark to check the accuracy of your VOR receiver at some arbitrary off-airway location, add the VOR twist to whatever your VOR receiver is saying, then compare that to the actual magnetic bearing. Usually, though, it is better to use the GPS to identify a named intersection on a VOR airway or on a VOR approach, and check the VOR against the published VOR radial (not GPS radial) to that point.[12]
- If you simply want to use a VOR to determine whether you are following an airway, or an instrument approach procedure, you do *not* need to worry about VOR twist. The charts conveniently tell you what VOR radial goes from point A to point B.

Here is how you can ascertain the VOR twist: The first step is to obtain the actual magnetic variation in your area. Often the easiest way is to look through the Airport/Facility Directory[13] and find a nearby airport that has been recently surveyed. That will give you the local variation as of a specified date. (Sectional Aeronautical Charts are another source of information about magnetic variation, but you never know how up-to-date that information is.) Also, your GPS may have a mode that tells you the local variation.[14] The second step is to look up the VOR in the A/FD, and see what variation the VOR is aligned to. Subtract the VOR alignment number from the actual variation.

14.5 Combined Techniques

You should not hesitate to combine pilotage, dead reckoning, and navigation by instruments. For instance, you could use a VOR signal to stay on course left/right, and use time and groundspeed to measure you progress along the course. Conversely, you could use dead reckoning to stay on course and use a cross-radial to measure your progress along the course.

The combination of dead reckoning with pilotage is quite powerful. Dead reckoning helps you find your landmarks. Pilotage allows you to establish your position with certainty, so that small dead reckoning errors (which are inevitable) do not accumulate.

Also remember that navigation is not your only task. You still need to fly the airplane, watch for traffic, et cetera. You should run an enroute checklist every few minutes, as discussed in section 21.6.

14.6 Staying Un-Lost

Here are some suggestions to help you keep from getting lost:

1. Keep track of your current position. I know this involves a certain amount of work, but remember: Staying un-lost is easier than getting un-lost. Consider the analogy: don't wait until you have cavities and then start brushing your teeth. By the same token, don't wait until you are lost to start keeping track of your position.
2. Write on the charts. When you pass a checkpoint, write the time on the chart, so later you will know how long it has been since you were there.
3. Choose unambiguous checkpoints. If you think you are heading for Jonesville, make sure you are not heading for Smithville instead. (A water tower with the word "Smithville" in twenty-foot-high letters should make you suspicious.) If your checkpoint is a round lake, make sure there is not another round lake a few miles away.
4. Keep your DG aligned with the magnetic compass. Sometimes a DG will behave nicely for hours or even years. Then, just when you have become complacent, it will start precessing like crazy. Also note that radical maneuvering (steep turns, stalls, takeoffs and landings) can cause an otherwise well-behaved DG to lose a few degrees.
5. Identify the Morse code on each navaid that you use. I've seen lots of students tune up the wrong navaid, or an inoperative navaid, and then blissfully follow the needle. Don't just check that there is "some" Morse code, make sure it is the *right* Morse code.
6. Make the VOR status flag part of your scan. If you lose the signal from the VOR (perhaps because you flew out of range, or perhaps because of a loose connection in your receiver) the CDI needle will settle in the center, making it look like you are doing an excellent navigation job no matter how far off course you are. The easiest defense is to notice that the "To / OFF / From" flag is showing "OFF".
7. Make a habit of getting enroute radar advisories (also known as flight following) from ATC. On my very first cross-country trip after getting my private pilot certificate, I was blissfully following road "A" when I thought I was following road "B". Unfortunately, road "A" was leading right into the middle of a restricted area that was being used for air-to-air missile testing. Fortunately, I was getting advisories. A few miles before the restricted area ATC called me and suggested I make an immediate 90 degree turn. At that point I didn't even realize I was lost, so it took me a while to understand what ATC was saying. Eventually I took the hint and everything worked out OK.

14.7 Getting Un-Lost

14.7.1 Basics

First of all, don't panic. Being slightly lost is usually not, by itself, a big-time emergency. However:

- Being lost and low on fuel is a big problem. Therefore try to get un-lost reasonably promptly, while you still have plenty of fuel.
- Being lost at night in mountainous country is a big problem.

14.7.2 When in Doubt, Climb

Low altitude causes lots of problems, including:

- You might run into obstructions.
- Your ability to see distant landmarks is limited.
- Your ability to receive VOR signals is limited.
- Your ability to use your communications radio is limited.

There are of course exceptions: For instance, you don't want to climb into a cloud layer unless you have current instrument-flying skills and a clearance. Similarly, you don't want to climb into restricted airspace without permission. Still, given the choice between running into a mountain and violating restricted airspace, the latter is preferable.

14.7.3 GPS or LORAN

Most GPS and LORAN receivers have a really nice feature: By pushing a button or two, you can display the name of the nearest airport(s), along with the bearing and distance from your present position to there.

These instruments will also, of course, tell you your latitude and longitude, but usually this is less convenient than the "nearest airport" feature.

14.7.4 VOR Cross Radials or VOR/DME

If you know even approximately where you are (within a few dozen miles), pick a VOR in the area and tune it up. Draw a line on the chart, along the radial that the VOR is telling you. Then pick a second VOR and draw another line. The point where the lines intersect is your position. If the lines cross at a shallow angle, the precision of the fix will be poor, so when picking the second VOR try to pick one that is well off the line given by the first VOR.

Of course, if you have VOR and DME, the job is even easier.

14.7.5 Ask ATC

Here is an exchange I heard on the radio, back when I was a student pilot:

Voice 1: PSA 1705, cleared for visual approach.

Voice 2: Approach, PSA 1705 is unfamiliar with the area, requesting vectors to final.

Voice 1: Roger, PSA 1705, fly heading 350, vectors to final.

I smiled when I heard that. I figured if airline captains could ask for vectors, so could private pilots, and even students.

It's true: you don't need to declare an emergency. You don't need to admit that you're lost. You don't even need to *be* lost. You can just be slightly unfamiliar with the area.

ATC has radars. They can find you real fast, and give you a vector toward wherever you want to go. Even without radar, some flight service stations can find you by doing "direction finding" on your VHF radio transmissions (although this system is slowly dying of neglect).

Don't worry about getting "blamed" for being lost. ATC would much rather have a lost pilot who is talking to them than a lost pilot who isn't talking. You should be embarrassed enough to be motivated to do better navigation next time, but not so embarrassed that you hesitate to ask for help this time.

To contact ATC, if there is any doubt[15] about what frequency to use, call up on 121.5 MHz. Practically every ATC facility can receive and transmit on that frequency. Yes, it is the "emergency" frequency, but it is not so special that you should be the least bit hesitant about using it.

14.8 Flight Planning

Here is a rundown of various flight-planning methods:

1. The dead reckoning methods outlined here --- even though they involve various approximations --- are good enough for most purposes.
2. One very good method is DUAT (Direct User Access Terminal). Its original purpose was to allow pilots to get weather briefing information on-line, but the contractor that provides the service has augmented it with a free flight planner. It will find a route for you automatically, then compute the courses, distances, headings, and times between waypoints. It gets the forecast winds aloft directly from the FAA weather computers. An important advantage of this approach is that you can, with very little effort, try several different routes and several different altitudes. Sometimes it's worth going a little out of your way to pick up a tailwind. Information about DUAT in general and the flight planning features in particular can be found at the DUAT provider's web site.
3. On those rare occasions when I can't connect to DUAT, I have a spreadsheet in my laptop that will calculate headings, times, fuel consumption, et cetera, given courses, distances, winds aloft, et cetera. You can download a copy of the spreadsheet (and instructions) from my web site, as discussed in section 22.1. If you are curious about the details of how to compute wind triangles to high accuracy, you can reverse-engineer the formulas in the spreadsheet.
4. There exists a clever mechanical device called an E6-B which works like a slide rule for adding and subtracting vectors. I haven't used mine in years. When I'm in the airplane, I use the rules of thumb discussed above to estimate headwind components and crosswind components. When I'm not in the airplane, I use a computer.

It is important to be able to solve navigation problems while you are flying the airplane. When you are in the cockpit improvising a flight plan, an approximate solution *right now* is vastly preferable to an exact solution that would require many minutes of careful calculation. There are many reasons why you might want to (or need to) improvise a deviation from your preconceived flight plan. These include:

- The winds-aloft forecasts are never precise enough to allow super-accurate dead reckoning.
- You might want to deviate around some isolated but threatening cloud build-up.

- On an IFR flight, it is quite likely that your clearance will not be identical to what you filed, and it is quite likely that whatever clearance you get will be changed enroute. Oftentimes the controller is trying to do you a favor by offering to shorten your route, and you can save lots of time and fuel by accepting. Other times the controller is trying to do somebody else a favor by changing your route, and you will cause lots of trouble if you can't do a good job of flying the amended clearance.
- One of the advantages of a pilot license is that it gives you more freedom to go where you want, when you want. Being able to improvise a flight plan makes flying more fun.

Almost the only time you need really accurate dead reckoning is when you are taking FAA written tests. You will be allowed to use and E6-B or an "approved" electronic equivalent; a laptop will not usually be allowed. The tests sometimes contain questions where the right answer differs from the wrong answer by a tiny amount. In such cases, you must use the FAA-approved approximations[16] and no others.

On a real trip (as opposed to a written test), if you are planning to rely on highly accurate dead reckoning, such as flying to the Azores without a GPS, then you should probably have your head examined.

As soon as you know your route, draw a line on your chart representing this route. Run your eyes along this line to make sure it doesn't come too close to any obstructions or special-use airspace. At the same time, look at the "sector altitudes" for each box that your course line crosses. If your enroute altitude is above these altitudes, you are assured you won't hit any terrain enroute. If you plan on flying below these altitudes, perhaps because you are flying through a mountain pass, you need to do a whole lot of additional work to select a safe altitude.

Make a column on your flight plan in which you note the minimum safe altitude for each leg.

The sector altitudes on the VFR chart offer very little safety margin. The ones on the IFR chart have much greater safety margins, horizontally and vertically. They are particularly useful for planning off-airways IFR flights ... but I like to use them for VFR planning, too, just because it's an easy way to get a known amount of safety margin. See section 21.4 for additional discussion of obstacle clearance and decisionmaking.

There are of course many cases where it makes sense to fly below the sector altitudes, for instance if you have lateral separation from tall towers or mountain peaks. The point is that above the sector altitude, flight-planning is easy, whereas below the sector altitude the planning is much more intricate and laborious.

1
: ... presumably as a way of discouraging uninvited guests. The legend of the VFR sectional chart claims all recognizable hard-surfaced runways are depicted, but it's not true.

2
: The idea is that the direction from your thumb to finger is the same before and after the move. You may want to practice this skill. Here's a good exercise: find a nice straight Victor airway on the chart. Put your thumb and forefinger on it, twenty or thirty miles apart. Then move your hand to a compass rose that is not on the airway, and read off the heading. Finally, look back at the airway and see what the "official" heading of the airway is. With a few minutes practice, you should be able to get within a couple of degrees.

3

See section 14.3.2 for a list of navigation systems and their acronyms.

4

In many airplanes, there is a device like a circular slide rule built into the airspeed indicator that allows you to calculate the true airspeed, given the indicated airspeed, altitude, and temperature. Otherwise, you could perhaps use your E-6B. Typically though, it suffices to use the simple rule: two percent per thousand feet.

5

That's how nautical miles were originally defined, and that's why aviators use them. A nautical mile is about 1.15 statute miles, or about 1.85 kilometers. A *knot* is defined to be a nautical mile per hour.

6

To practice these techniques on the ground, you can use the compass roses on the chart, in the same way that you would use the DG if you were in the airplane. That is, draw a line from the edge of the compass rose to the center, representing the total wind, and then resolve it into components parallel and perpendicular to your course line.

7

You don't need to memorize the table. You just need to remember that there are about 57 degrees in a radian; then you can figure out the rest at a moment's notice. The figuring is even easier of you approximate π by 3.0 (i.e. 60 degrees per radian). You can speed things up by remembering the conversion factor (degrees per knot of crosswind) that applies at the typical groundspeed of your airplane. Also, you can usually simplify the calculation by comparing the crosswind component to your airspeed (as opposed to groundspeed), unless the headwind or tailwind component is really large.

8

To calculate a more-accurate course, see section 14.4.4.

9

If you want to get technical about it, you should recalculate the crosswind component after correcting for the crosswind, but you will find that this is almost never a significant correction.

10

... enroute navigation, that is. In contrast, if you are performing an instrument approach, you might want to do better, but that is a different subject.

11

If you forget to account for twist, you can drive yourself crazy trying to figure out the winds aloft. Suppose you are following a north/south airway that is twisted by +3 degrees, flying at 120 knots in no-wind conditions. Then your instruments will seemingly indicate 6 knots of "wind" from the east when you are northbound on the airway, and seemingly indicate 6 knots of "wind" from the west when you are southbound on the same airway!

12

This is the most accurate check you can do, but does not quite meet the requirements for the mandatory 30-day receiver check --- unless you check two VOR receivers at the same time and sign it off as a cross-check.

13

The A/FD is published as a small book every 56 days. The same information is also available on the web, which is often more practical. For example, search for "JFK VOR variation".

14

Every GPS has a database of detailed information about variation as a function of location. It needs this so it can calculate your magnetic course based on a sequence of positions.

15

At the other extreme: if you are already talking to ATC on a given frequency, you should undoubtedly use that frequency.

16

In particular, the test-makers apparently believe π = 3 (i.e. 60 degrees per radian). I remember one question where you would be marked wrong if you used π = 3.14 (i.e. 57 degrees per radian).