Magnetic Compass Error Explained

WE ANDS they know, do UNOS?

Daniel Sullivan 12/14/20

You take the written exam – the answers to the 'compass error due to motion' questions are memorized:

WE ANDS – traveling West or East, Acceleration (causes the compass to turn) North, Deceleration South

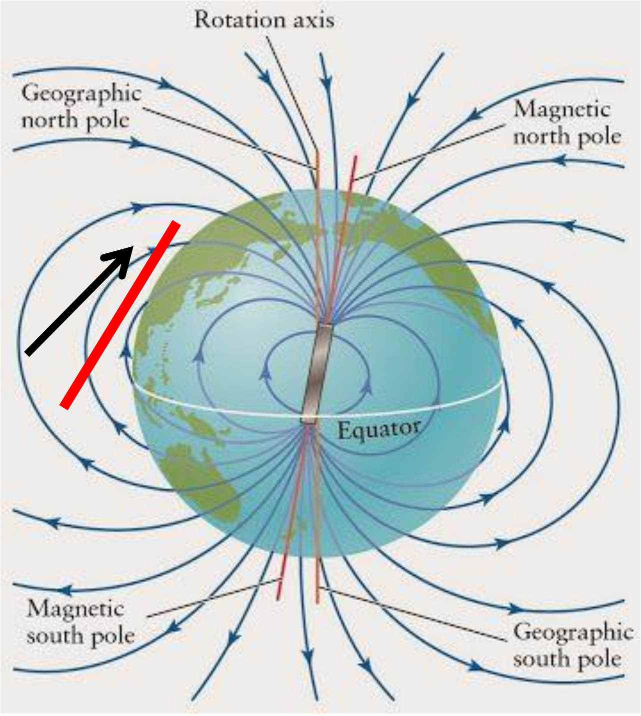
UNOS – Undershoot North: Start your rollout early because the compass lags when turning towards (or initially away from) North. Overshoot South: Let the compass go beyond your intended heading because the compass leads when you are turning towards (or initially away from) South.

We deduce the answer to other questions that might be a variation on the theme and hope we get them right. That is probably the first and last time we use these 'rules'. We hope. No one has ever gone partial panel, right? This article from AvWeb on Petite Panel IFR might give you pause. And having been trained in the northern hemisphere heaven forbid you go partial panel in the southern hemisphere.

So why are there compass errors in turns and acceleration in an aircraft? The question phrased in such a way as to beg the question – Don't you get the same error if you are in a car or being pushed around in a shopping cart? Nope. (Or, maybe more correctly – it depends).

The reason that is usually given is because the magnetic field that surrounds the earth is curved (with respect to the earth's surface) except where it crosses the magnetic equator. The reason sometimes said as "because of magnetic dip" which does not help much in my opinion. True – but only part of the reason. But let's cover the curved magnetic 'dip' field thing first.

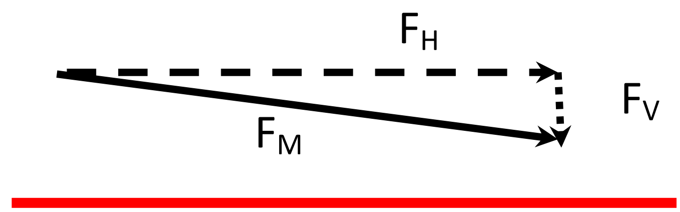
Thanks to TET SUCCESS KEY for this illustration –

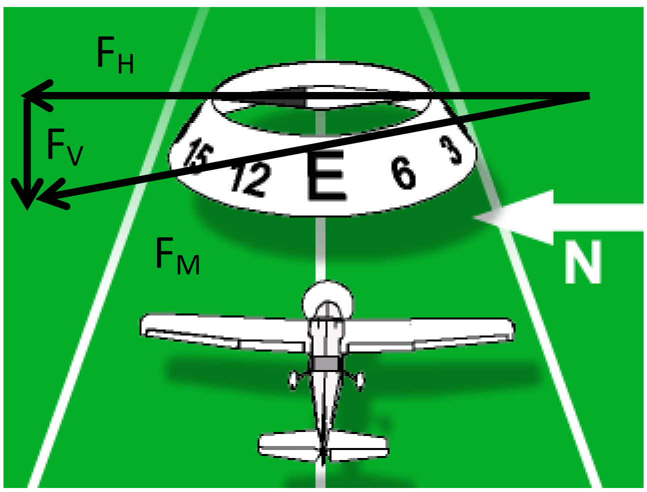


The red line is tangent to some location in the northern hemisphere. Doesn't matter where – let's say Manhattan, Kansas (AKA "The Little Apple"). The black arrow is pointing towards the magnetic north pole and is tangent to the magnetic force line (the line of magnetic flux) that runs through Manhattan. You can see that with respect to the earth's surface the line of magnetic flux is pointing not only towards magnetic north but also downward. It is the downward (vertical) component of the magnetic force ("attraction", if you will) that is of interest to us.

If we view the line of magnetic force with respect to our local spot on earth it looks like this:

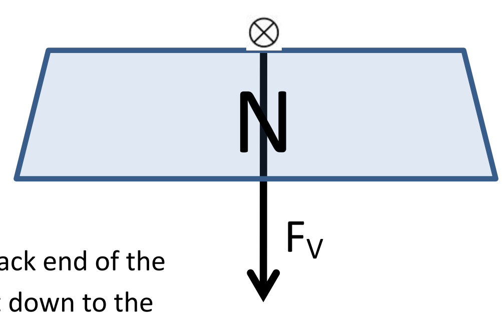
The red line represents the earth – and you can also say that the red line represents a tangent to a path of flight above the earth. F_M is the total magnetic force. F_H and F_V are, respectively, the horizontal and vertical components of the magnetic force with respect to the earth (or the path of flight above the earth).





To illustrate how the two force components act on a 'whiskey' compass card with the help of an illustration from the AvWeb article – the magnetic force (attraction) - makes the compass move in the direction of magnetic north points to the magnetic north pole as shown at left. It is the horizontal force that makes the compass align with magnetic north. Looking east that makes the compass align as shown – but the vertical component of force should make the compass card tilt down to the left, shouldn't it?

Well, it should. But because the compass card is mounted so it's center of gravity is low (the same principle that gives a tightrope walker balance by using a down-sloping pole) *and* because most compass cards have a small weight at the point labeled with the 'N' (which is really the opposite side – the 'south end' - of where the needle is pointing – more on that in a little bit) the amount of tilt is minimized. Aircraft manufacturers adjust the amount and (for aircraft in the southern hemisphere) location of the weight for local consumption. Viewed with the compass card exactly at eye level, looking north we see:

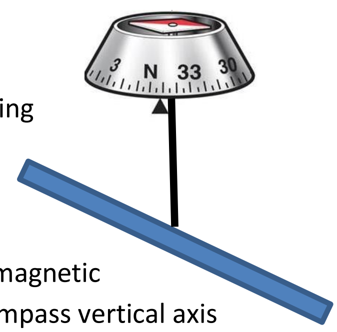


This symbol ⊗ represents the end of the horizontal force vector F_H in the illustration at the right. From this perspective you are viewing the horizontal component of the magnetic (attraction) force from the back end of the vector arrow. The vertical component F_V is as shown – pointing straight down to the earth. We will see that it is the vertical component that cause the turning and acceleration errors. Remember that the examples and illustrations for this phenomenon are based on what happens in the northern hemisphere. The opposite occurs in the southern hemisphere.

For completeness sake I will mention that when you are on the magnetic equator (which does not coincide with the physical / geographic equator of the earth) there are no turning or acceleration errors because there is no vertical component of the magnetic attraction force. Lines of magnetic flux are ‘flat’ at the magnetic equator (parallel to the earth’s surface) so there is no vertical component of force. In contrast, within about 300 miles of either magnetic pole a standard ‘whiskey’ compass should not be relied on because the errors are so extreme. Close to the magnetic poles the vertical component of force is so large that it renders the compass essentially worthless.

Before going further into the reason behind the turn and acceleration errors it is important to remember that the error occurs because of the nature of the ***forces on objects in an airplane during a coordinated turn***. If you built a tilted table as shown on the right with a compass installed on it like this

where the compass was free to tilt and turn on the top of its post then the low center of gravity plus any additional balancing weights would keep the compass level since gravity is working straight down in spite of the table being tilted as would the wings of an airplane in a turn. If you walk around the room (or hold the table tilted and drive around the street) if you keep the compass level it will turn to show the proper direction without any North/South turn or acceleration error because the vertical component of magnetic attraction is aligned with the vertical axis of the compass. It is when the compass vertical axis tilts that the magnetic ‘dip’ produces a vertical component of magnetic (attraction) force and the ability to cause turning and acceleration error. And, in a coordinated turn the compass (or you might say more specifically, the compass card) tilts with respect to the surface of the earth (even though to our eye it appears to be straight in the compass case).



Straight and level everything looks – well, straight and level.

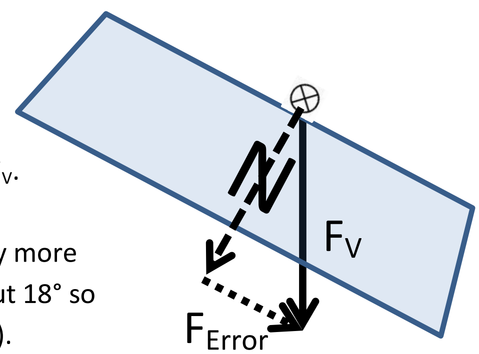
But in a turn even though the compass card appears level in the aircraft the compass is actually tilted with respect to the earth. You can see that this is the case by comparing the top of the glare shield with the horizon line in the distance. The compass stays level because the net forces in a coordinated turn are directed straight down to the floor (parallel to the vertical axis of the aircraft). If you are not sure about why this is the case then the article on the web site [The Most Elegant Aircraft Instrument? The Magic of the Ball] might provide some help.
It is the physics of a coordinated turn in an aircraft plus the magnetic dip that cause the errors.

And one more thing that you need to remember. When you are looking at a whiskey compass you are viewing it from the 'back' – that is, if your aircraft is facing north the compass needle is attracted to the north (the far side of the compass itself) but you are seeing the 'south end' of the compass – even though it has a big 'N' on it, that is the side with the south end of the compass needle. So, when you are going north, east is of course to your right. But, if you look at the right side of the compass card that can be seen inside the compass housing what you see are numbers that represent westerly headings.

A compass always points north. So if (using the above image) you turn right (to the east) the compass itself does not turn (putting aside turning error for the moment). Instead, the compass continues to point to the north and you (your aircraft) turn underneath the compass, moving the viewing window to the left revealing easterly heading numbers. This is important to keep in mind when considering turning errors and how those errors appear to the pilot.

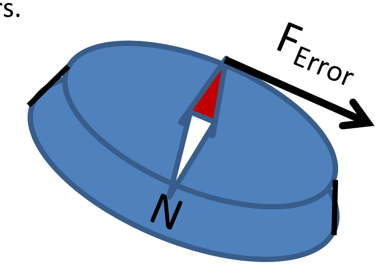
In a coordinated turn to the right (to the east) from a northerly heading the compass is tilted (with respect to the earth) to the right in a coordinated turn. However, the vertical component of the magnetic (attraction) force remains vertical (Why would it ever change? The magnetic field has nothing to do with the position of you aircraft).

With the compass tilted the vertical (with respect to the earth) component of magnetic force has two components with respect to the compass itself. These are shown as the dotted and dashed lines, together represent the two vectors that when summed are F_V.



The normal force is nearly as big as F_V so the compass tends to stay more or less level when you turn (compasses can tilt in their hosing about 18° so a little bit of tilting while turning does not affect compass function).

The component of the force we care about is F_{Error} – called that because this *is* the component of vertical magnetic force (the 'dip) that causes all of the turning and acceleration errors.



But remember – we are viewing the compass from the back and the forces of the magnetic attraction are applied at the front (at the north end of the compass needle) so viewed from the top the error force F_{Error} causes the compass card to rotate clockwise.

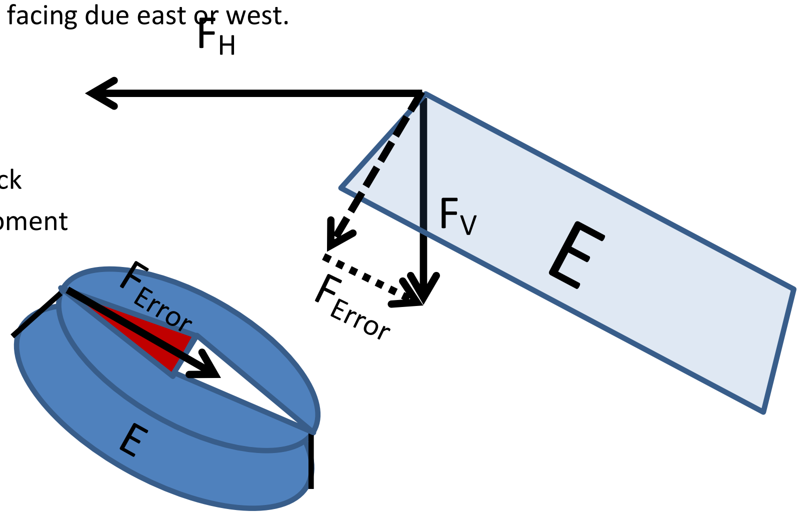
Viewed from the back, a clockwise rotation appears as a turn to the west (if banking to the right, turning to the east). The card itself rotates clockwise (as viewed from the top) revealing westerly heading values so it appears that as you start your turn to the east the compass turns (initially) in

the opposite direction (to the west). The error component of vertical force turns the compass card clockwise (as viewed from the top) but it is the ‘reverse numbering’ that makes the turn look westerly.

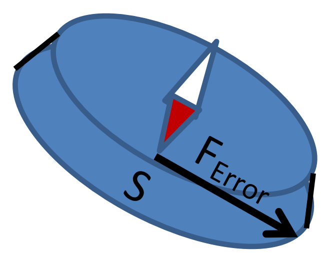
Turning to the left (west) the tilt is to the left so F_{Error} is to the left, causing the compass card to rotate counterclockwise revealing easterly heading numbers – again creating the appearance of a turn in the opposite direction.

The error gradually decreases as the turn progress to the east (or west) and is zero when the aircraft is facing due magnetic east (or west) because the tilt (of the compass card) is now directly towards north, so the vertical component of the magnetic attraction force is acting straight down at the tilted side of the compass card. So, the moment arm (the turning “leverage” of the force) of F_{Error} gradually diminishes as the aircraft turns and is zero when facing due east or west.

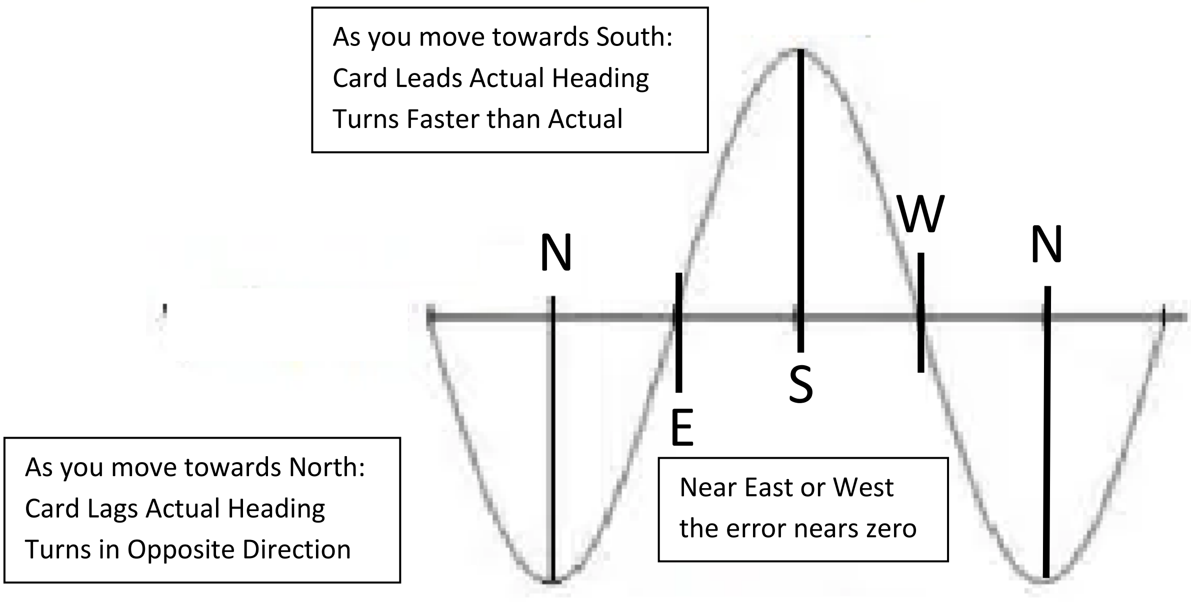
Yes – there are still an F_{Error} component of the vertical force *with respect to the compass card* but when due east (or west) it points directly back to the pivot point of the compass card so the moment arm is zero rendering the turning moment zero.



As you continue the right turn from north to south, once you are past east the F_{Error} force component causes the compass card to rotate counter-clockwise. This is the ‘lead’ error when turning past east or west towards south or turning from south in either direction. F_{Error} is still in the same direction but now the north end of the compass needle which is pointing at us (and at the label ‘S’) because we are viewing the compass card from the back now creates a counter-clockwise turning of the card.



So, continuing the right turn past east to south then towards the west results in the error force turning the compass card faster than the aircraft is turning (under it) so the compass card arrives at ‘south’ before the aircraft actually is pointing south. Or, in the case of starting a right turn from a south heading the compass will initially lead the turn (indicate a heading more westerly than you actually are). Turning left (east) from south causes the compass to lead the turn in that direction also because the compass card is tilted to the left with the error force then causing an additional clockwise rotation that leads the actual aircraft heading, this time to the east.



As noted previously – when turning through (or from, or even near) east or west the turn error moment arm goes to zero so the error goes to zero, as shown in the graph above. Turn error is greatest when near north or south and the error when near north is opposite of the error when near a southerly heading.

Acceleration error is caused by exactly the same force, but the tilt is caused by acceleration (or deceleration, to avoid having to deal with a plus or minus acceleration), not by the bank of the aircraft. Since the compass card's center of gravity is below its pivot point acceleration causes the bottom-heavy compass card's bottom side to swing forward (much like a donut on the dashboard of your car slides into your lap when you accelerate away from a traffic light). So if you are facing east and accelerate it is the same as making a right turn – the bottom of the card comes toward you and the error force is the same as a right turn from the north causing a clockwise rotation of the card. Looking east, the card appearing "backwards" with regard to the heading labels (the north 'N' is on the right side of the card) a clockwise rotation of the card reveals the northerly heading values so acceleration gives the appearance of a turn to the north. Facing west, acceleration tilts the card in the same way (the bottom of the card swings up towards you) but this time it looks like a left turn from the north. Looking at the west side of the card the northerly headings are now on the left and the counter-clockwise rotation of the card due to the error force reveals the northerly headings, again making the appearance of a turn to the north when accelerating. So – accelerate north, decelerate south.

Deceleration causes the bottom of the card to swing forward, like your jelly donut on the dashboard slides forward when you slam on the brakes, leaving a mess on the inside of your windshield. This causes the opposite tilt compared to acceleration, so the forces act opposite to those described above (for acceleration when facing east or west). This turns the compass card towards the southerly headings which gives the appearance of a turn towards the south when decelerating.

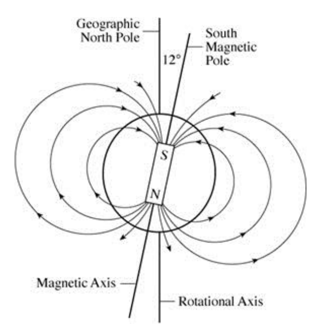
Conclusions and Some Things You Should Know

(At least things you should know so you can pass the written exams, and maybe an oral exam or two)

1. Although this may be the most confusing explanation of why an aircraft's compass is subject to turning and acceleration error it may have provided you with a look at this issue that is a bit different from some of the other explanations you have seen and in doing so might have helped provide a little bit of insight into the cause of compass errors.

2. None of this gives much in the way of easily remembered points or 'tricks' that your brain will immediately latch onto instead of focusing on the strange sensation of oozing warmth in your pants when you are in IMC and your instrument panel suddenly goes dark. So, WE ANDS and UNOS are probably what you are going to fall back on when you're partial panel. I hope that only happens during your Practical test – simulated, of course.

3. Everything described above happens in exactly the opposite if you are in the southern hemisphere. This is because (south of the magnetic equator) a tangent to a line of magnetic flux points upwards in relation to a line tangent to the earth below vs. downwards in the northern hemisphere, as diagramed in this paper. You might say that 'magnetic dip' – the downward component of the magnetic flux vector described above – is actually a 'magnetic rise' in the southern hemisphere (although I guess you could say that the dip is towards the South Pole when in the southern hemisphere).



4. Magnetic directions are defined based on the instrument's (north) pole. So, the 'north' facing needle of a compass is actually attracted to a (magnetically) south pole of the earth's magnetic field although we consider this the magnetic north pole because that is the way the compass points.

5. The magnetic and geographic poles are not the same so you must correct for magnetic ***variation***. Magnetic Heading = True Heading + Variation: Remember MTV. (No, really, do you remember MTV?). Variation is positive if west (so add) and negative (so subtract, the same as adding a negative) if east. Unlike all the other compass stuff above this is the same in both the northern and southern hemisphere.

6. Compass ***deviation*** is different than *variation*. It is the difference between the actual magnetic heading and what the compass reads. It is caused by metal, radios and other magnetic field-generating stuff in an aircraft and the amount and direction (plus or minus) of deviation is different for different headings within the same aircraft. There are questions about this on the FAA written exam. Compass deviation is provided on the compass deviation card usually mounted just below (sometimes above) the compass as shown in the picture from

boldmethod.com. The process of establishing compass deviation is called "swinging the compass". Since this is not a routine maintenance procedure it must be done by a certified aviation mechanic. But, it is not a bad idea to have this done if you decide to add a fancy new batch of headsets or a new iPad to your aircraft since this could change the original or most recent compass deviation determinations. Adding any electronic equipment or making a modification that involves ferrous materials is also a good reason to verify the current compass deviation. Swinging the compass after a lightning strike or passing through a severe electrical storm is also a good idea as is anytime you suspect the compass might not be accurate.

7. Gyroscopic directional heading indicators ('gyro compass') do not have the turning and acceleration errors that a magnetic compass is subject to. However unless they have an electronic compensation system (known as a flux gate) they do drift and need to be reset based on the magnetic compass reading – the recommended interval is every 15 minutes. But, be sure that you read the magnetic compass in straight and level, un-accelerated flight (for the reasons talked about in this paper). Gyroscopic heading indicators are subject to drift (and the math that describes the drift rates is itself very interesting) so without a flux gate to provide a reference north they need to be reset periodically.

8. A vertical compass card magnetic compass can be confused with a directional gyro (gyroscopic heading indicator). It is a magnetic compass and subject to the same errors as a standard floating magnet 'whiskey' compass although most have electronic damping and compensating systems that lessen the errors. The principle advantage of the vertical magnetic compass is that it presents the compass card with headings in the same direction as would be expected (vs. the whiskey compass that has the heading numbers 'reversed' from the pilot's point of view).

9. Whiskey compass – the term comes from the old days when the suspension liquid was alcohol. Not anymore. So, if you are forced down on a chilly winter day and you are looking for something to warm you up don't drink the compass liquid. Instead, use it to start a fire. Today's liquid-suspension compasses use kerosene (cue Miranda Lambert).

10. Remember the acronym A TOMATO FLAMES? Yep – a magnetic compass is required equipment for powered aircraft. 14 CFR § 91.205