Compass Errors

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All airplanes are required by FAR (23.1303(c)) to be equipped with a magnetic compass. An ideal compass would always indicate the correct *magnetic heading* of the airplane, which is defined as the angle between the direction the aircraft is heading and local Magnetic North.

1 Variation

Magnetic North is the direction of the horizontal component of the earth's magnetic field. Except near the poles, this direction is approximately true north. The angle between the direction of local Magnetic North and True North is called variation (also declination). It varies from place to place and also slowly in time, and is charted on both VFR and IFR navigation charts. "East" variation means that magnetic North lies to the East of true North, so that directions are related by:

$$\text{Magnetic Direction} = \text{True Direction (-E/+W) Variation} \tag{1}$$

as illustrated in Figure 1.

The fact that even ideal magnetic compasses reference direction to magnetic North should not be thought of an *error*. Nevertheless it needs to be accounted for if one is interested in obtaining true headings.

2 Deviation

A magnetic compass mounted in an airplane is not only affected by the earth's magnetic field, but in addition by any magnetic fields created by the airplane itself. These include permanent and induced magnetism in any iron and steel airframe components and field produced by nearby DC electrical circuits. (Older Mooneys can have problems from structural steel tubing getting magnetized, and the original Grumman AA5A had a panel mounted compass that was strongly affected by the turn coordinator.)

Much of this *deviation* error can be cancelled by adjusting the two compensating magnets mounted on the compass. After the errors have been minimized

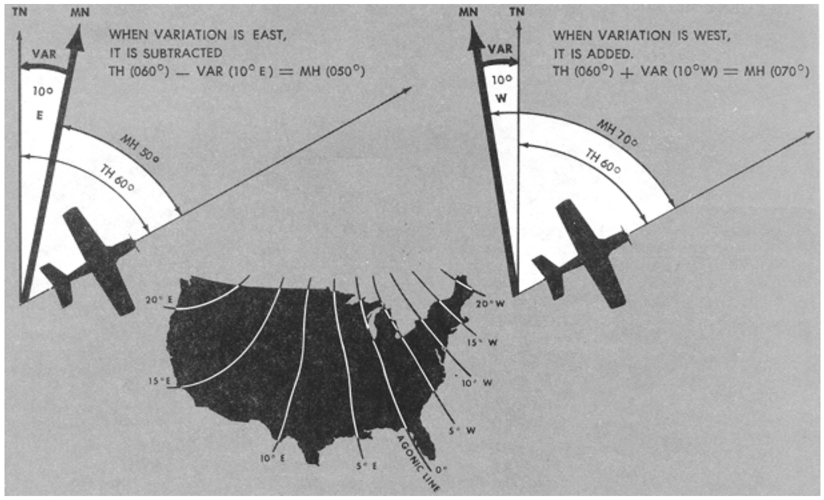

Figure 1: Relation of True and Magnetic headings

to the extent possible, the remaining deviation is documented on the compass correction card mounted under the compass.

This is usually in the form of a table of MH vs. CH. The best way to make use of this in flight is to refer to it when setting the DG (assuming you have one!). The procedure is:

- Stabilize the airplane wings level, constant airspeed.
- Read the magnetic compass - averaging the oscillations if any.
- Using the compass heading, refer to the deviation card to obtain the magnetic heading, interpolating as required.
- Set the DG to the magnetic heading obtained.

The DG is then corrected for deviation. If this is not done, apart from the inaccuracy, the DG will appear to precess when turning to new heading on which the deviation differs from that on which the DG was set! More than one perfectly good DG has been replaced for this!

3 Dip errors

Only near the equator is earth's magnetic field parallel to the earth's surface. In the Northern hemisphere the field lines have a downward component and in the Southern, upward. The angle that the magnetic field makes with the horizontal is called the *dip* angle, and like variation, it varies from place to place and slowly with time. Charts of dip and variation can be found on the net and or can be computed using published formulae. (As implemented in my on-line calculator .)

If the needle of the compass were mounted so it could pivot freely about its center of gravity in three dimensions, it would align with the magnetic field, pointing down (or up) at the dip angle in the direction of local Magnetic North. Since the dip angle is not of navigational interest, the compass is constructed so that is constrained to rotate essentially only in the horizontal plane.

In an aviation compass, this is done by lowering the CG below the pivot point and making the assembly heavy enough that the vertical component of the magnetic force is too weak to tilt it significantly out of the horizontal plane. The compass can then work effectively at all latitudes without specific compensation for dip. However, close to the magnetic poles, the horizontal component of the earth's field is too small to align the compass, and the compass becomes of little use for navigation.

Because of this constraint, the compass only indicates correctly if its card is horizontal. If it is tilted out of the horizontal, it will be affected by the vertical component of the earth's field. This gives rise to two distinct errors.

3.1 Northerly Turning Error

In a coordinated turn, the compass, like the occupants of the airplane, feels an effective gravitational force down the vertical axis of the airplane, which banks the compass card with the airplane, out of the horizontal.

Suppose for instance, an airplane (in the Northern Hemisphere) is in a coordinated turn, as illustrated in Figure 2, which depicts the situation where the airplane is currently heading North or South. In each case, because of the dip, the north seeking end of the compass swings downward, so that the compass no longer indicates North or South respectively.

The resulting error, the so-called *Northerly Turning Error*, depends on the heading, the direction of turn, the angle of bank and the dip angle. One sees from the figure, after some thought, that the error is such that, in a turn the *compass leads the airplane on southerly headings and lags on northerly headings*[1].

On East or West headings[2], one can see that there is no error caused by dip.

By calculating the components of the earth's field in the (banked) plane of the compass, one can derive the relation between compass heading, H_C, magnetic heading, H_M, bank angle, θ[3] and dip angle, μ[4]:

$$H_C = \text{atan2}(\sin(H_M)\cos(\theta) - \tan(\mu)\sin(\theta), \cos(H_M)) \tag{2}$$

Figure 3 shows the required lead (lag) as a function of magnetic heading, for a sequence of bank angles (0, 10, 20, 30 degrees corresponding to curves A, B,

[1] The opposite is the case in the Southern Hemisphere, where the dip angle is negative
[2] if the bank angle is not too large, see later
[3] right bank positive
[4] down positive

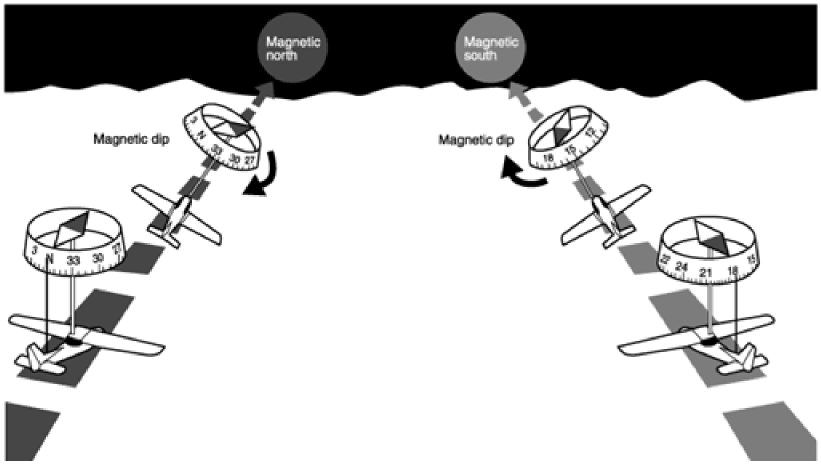

Figure 2: Northerly turning error

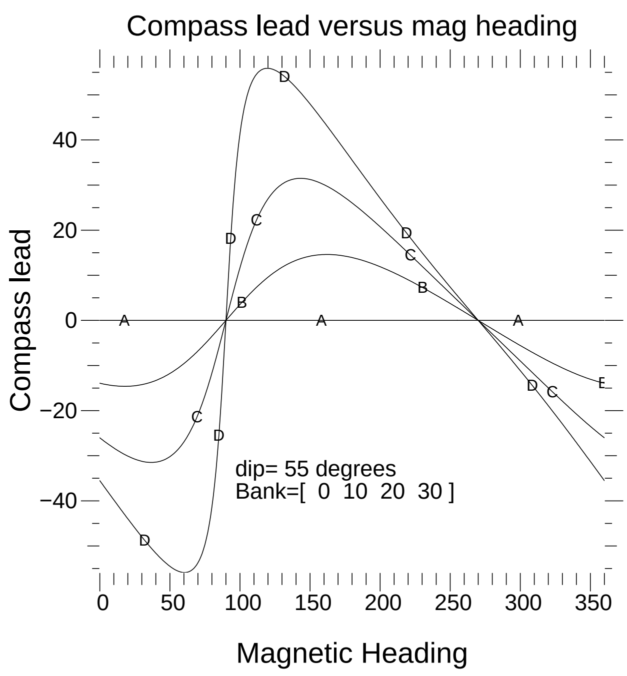

Figure 3: Northerly turning error graph

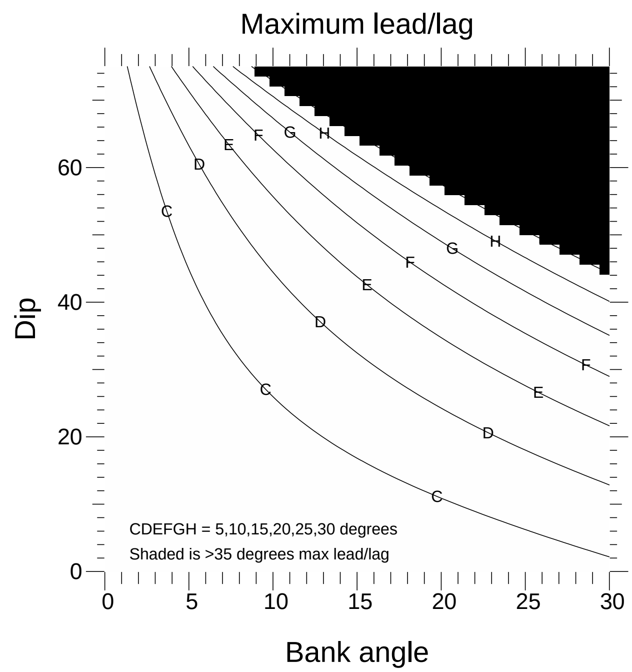

Figure 4: Contours of max lead/lag

C and D.), computed for a location where the dip is 55 degrees down (typical of mid-latitude US).

For standard rate turns at 100-140 kts, requiring bank angles of 15-20 degrees, we see that the maximum lag or lead is about 20-30 degrees, when the *compass heading* is approximately North or South, respectively.

This forms the basis for *partial panel standard rate turns to a heading* in latitudes where the dip angle is not too extreme.[5].

- Determine (in advance) an appropriate maximum lead/lag for your location and standard rate bank angle. (See Figure 4)
- Roll into a steady standard rate turn using the turn coordinator.
- Figure the lead/lag for the desired heading (max for N/S, zero for E/W, guesstimate in between). *A*nticipate *N*ortherly headings, *D*elay *S*outherly headings.[6] (mnemonic *ANDS*)

The method works best for longer turns where you can get the compass stabilized and where timing turns gets less accurate. It works less well as the required bank angles get steeper and/or the dip angle gets larger, because of

[5]half standard rate should be used at higher speeds to avoid excessive bank angles
[6]reverse in S Hemisphere

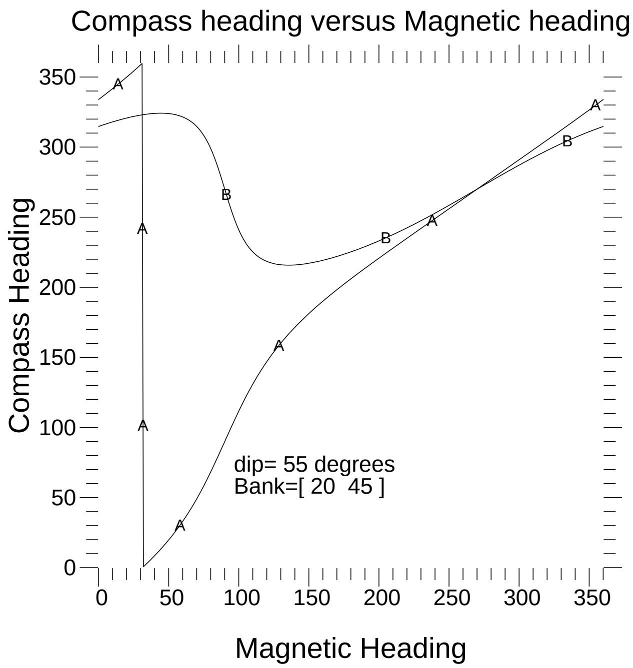

Figure 5: Compass heading vs. magnetic heading for two bank angles in a right 360 turn

the large error that has to be corrected for. For short turns, timing is typically more effective.

For steep turns, where the sum of the dip angle and bank angle exceeds 90 degrees, the compass will "hang up". The compass will refuse to turn through 360 degrees as the airplane makes a complete circle.

It's easy to see why. Imagine being on a heading of East in the Northern hemisphere, and gradually increasing bank angle to the right. Initially, the north seeking end of the compass needle will point exactly North, towards the left wing tip. However, as the bank angle increases, a point is reached where the magnetic field becomes parallel to the airplane's vertical axis. Beyond this point, the compass needle will swing 180 degrees to point to the lower, right wingtip and the compass then indicates West instead of East! So it is not quite true to say there is no Northerly turning error on headings of East and West. Beyond the critical bank angle (equal to 90 minus the dip angle), the compass lags by 180 degrees when the airplane is banked toward the equator.

For turns with bank angle exceeding this critical bank angle the compass is close to useless. As an illustration of this, refer to Figure 5 where we plot compass heading versus magnetic heading in a 360 degree right turn.

In curve (A), the bank angle is 20 degrees, less than the critical $90 - 55 = 35$ degree bank. The compass and magnetic headings approximately agree, with the

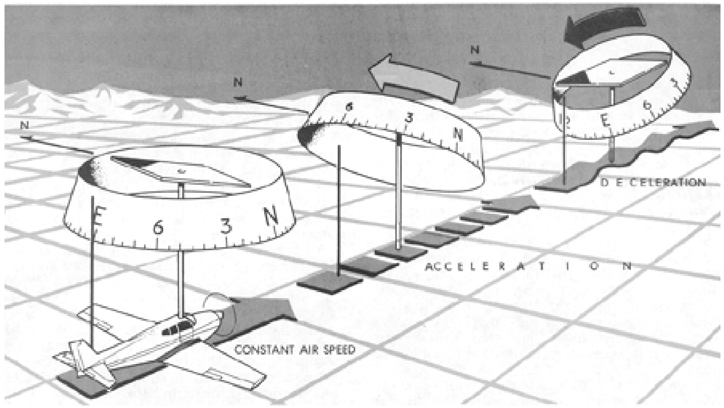

Figure 6: Compass response to airspeed changes on an East heading

compass heading lagging about 30 degrees through North and correspondingly leading through South, while reading correctly passing through East and West.

In curve (B), the bank angle is now 45 degrees, exceeding the critical 35 degree angle for the 55 degree dip angle. The compass oscillates around 270 while the airplane makes a 360. The compass appears to be mechanically "stuck", but in reality its needle is just pointing down towards the low wing, attracted by the downward component of the earth's field. In the limiting case of a 90 degree bank, the compass would indicate 270 degrees throughout the entire turn!

3.2 Acceleration Error

A second way to tilt the compass card out the horizontal plane is to accelerate or decelerate the airplane. With the card mounted with its CG below the pivot, acceleration causes the card to tip forward. In the Northern Hemisphere where the magnetic field has a downward component, this causes the north-seeking tip of the compass needle to swing downward.

This is illustrated in Figure 6 for an airplane heading East. It shows that *a*cceleration swings the compass toward the *N*orth, and *d*eceleration towards the *S*outh. The same mnemonic *ANDS* can be used to remember this.

For completeness, one can derive the relation between the compass and magnetic headings for a given acceleration. Call the acceleration a, measured in g's. Then:

$$\lambda = \text{atan}(a) \quad (3)$$

$$H_C = \text{atan2}(\sin(H_M), \cos(M_H)\cos(\lambda) + \tan(\mu)\sin(\lambda)) \quad (4)$$

where, as before, μ is the dip angle and H_C and H_M are the compass and magnetic headings, respectively. In Figure 7 we plot the compass error vs. magnetic heading for the case of a 55 degree dip angle and accelerations of 0.1g and 0.2g. There is no error on North and South headings, the error is negative

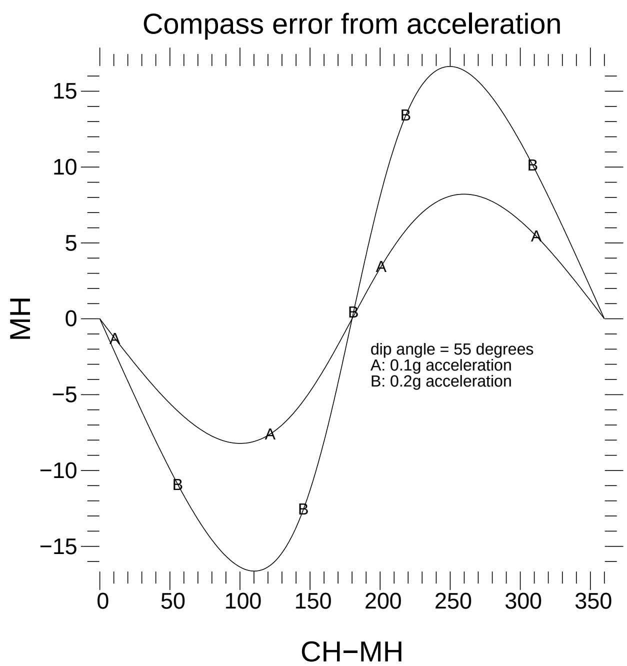

Figure 7: Compass error vs. magnetic heading while accelerating

for Easterly headings and positive for Westerly ones. As expected these are errors towards the North.

It's hard to imagine attempting to compensate for these errors. If you want the compass to read accurately, keep your airspeed constant!

List of Figures

Figures 1, 2 and 6 are taken from the FAA's "Instrument Flying Handbook", (AC 61.27C) which has good material on this subject. Note that the new FAA-H-8083-15 has some bogus information on "dip compensating weights", which are not used in standard aviation compasses.