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Operation of Magnetometers and Gradiometers at Very Low Dip Angles

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Abstract
Cesium magnetometers flown at very low dip angles have at times been a problem for operators. This is to a large extent a problem of visualization and is also due to misconceptions about how to mount the magnetometers relative to the aircraft axes. At all dip angles, the allowable attitude envelope for a magnetometer is important because for good magnetic interference compensation, calibration manoeuvres should cover the full range of the envelope. For high to moderate dip angles, the envelope is easy to visualize in two dimensions. For very low dip angles, I present a 3-Dmodel to delineate the attitude envelope. At these dip angles, there is a restriction to the heading envelope, which can be overcome by using a feature of the magnetometer.

INTRODUCTION

The operation of optically pumped magnetometers at earth field dip angles below about 20° has often given problems to operators. The problem is in part one of visualization and also the fact that procedures for comprehensive compensation of aircraft magnetic interference, if done properly, are somewhat more complicated than for the higher dip angles. This paper addresses these problems. The discussion is limited to cesium vapour magnetometers, which are currently the industry standard. Helium magnetometers have not proven themselves in exploration because of higher instrument noise and other problems. Recently-developed potassium vapour magnetometers are based on a locked oscillator, as opposed to the self-oscillator principle employed for cesium. Potassium has the potential for very low noise, but a number of design compromises are required in the tracking loop and it would be unfair to base this discussion on the results of early model testing (Hardwick & Onno, 1992). Furthermore, this paper considers only cesium magnetometers operating in airframe-fixed or “strap-down” mode, as opposed to sensors oriented to the earth’s field vector, which are much more costly, complex and were never readily available.

A quick review of the operation of an optically pumped, self-oscillating cesium magnetometer is useful by way of introduction. It consists of an RF-excited cesium vapour lamp that transmits very narrow bandwidth optical energy to a cesium vapour cell. This light causes the cell’s cesium electrons to be “pumped” to align their spin states with the ambient magnetic field. A coil referred to as H_1, whose field is parallel to the optical axis, “de-pumps” the electrons to their normally allowable spin states. With the spin states aligned, the energy absorption of the cell is high and light transmission through it is at a minimum, while in the de-pumped state, it is at a maximum. A photodiode senses the transmitted light, its signal is amplified and suitably phase shifted, and then fed to the H_1 coil to form a self-oscillating system. The frequency of self-oscillation, called the Larmor frequency, is proportional to the ambient magnetic field (Bloom, 1962). However, there are eight spin states for cesium 133, giving rise to eight Larmor frequencies separated by just a few Hz., producing a composite resonant frequency. The probability of any one frequency or group of frequencies predominating to form the composite is a function of the angle between the ambient field and H_1. Thus, changes in the sensor’s orientation with respect the earth’s field, H_e, could cause small errors in the field measurement. It was for this reason that early cesium magnetometers were oriented to keep a constant angle with respect to H_e.**WITH THE ADVENT OF THE SPLIT-BEAM LAMP (YABUZAKI, 1974), ORIENTATION BECAME UNNECESSARY AND THE STRAP-DOWN MAGNETOMETER BECAME POSSIBLE. IT WAS FOUND THAT CESIUM LIGHT PASSING THROUGH A RIGHT-HAND POLARIZING FILTER PRODUCED A PARTICULAR BEHAVIOR OF THE EIGHT CESIUM LINES, WITH A CHARACTERISTIC RESPONSE TO CHANGES IN SENSOR ORIENTATION. LEFT-POLARIZED LIGHT PRODUCED COMPLEMENTARY OPPOSITE EFFECTS. THUS, BY CAREFULLY ADJUSTING THE PROPORTION OF EACH TYPE OF LIGHT STRIKING THE CELL, A LARGE DEGREE OF ORIENTATION INDEPENDENCE COULD BE ACHIEVED. CURRENT SPECIFICATIONS CALL FOR AN ERROR ENVELOPE OF ABOUT 0.5 NT OVER AN ORIENTATION ANGLE OF 65°. SALES BROCHURES MAY MENTION AN ENVELOPE OF 70° OR MORE, BUT BEYOND THE 65° DEGREES, THE INSTRUMENT NOISE INCREASES SIGNIFICANTLY. THE EXAMPLES THAT FOLLOW ARE BASED ON THE 65° ENVELOPE.**

THE MANOEUVRE ENVELOPE, HIGH AND MEDIUM DIP ANGLES

Optimum pumping is achieved when the optical axis of the sensor is aligned with H_e, while for optimum de-pumping, H_1 is aligned with H_e. Thus, optimum orientation of the sensor is at a compromise angle of 45° to the ambient field. Figure 1 shows the magnetometer mounted for operation at dip angles from 90° to about 70°. The 65° nominally flat zone is shown in blue and the area is centred 45° from the optical axis for the reason given above. As long as the H_e vector stays in this zone, the magnetometer will operate correctly. As the aircraft manoeuvres, the zone will move with respect to H_e, but it is often easier to visualize H_e moving with respect to the zone. With this perspective, in the figure, as the aircraft pitches nose down, H_e (the solid vector) moves towards point B. When it reaches OB, that is the pitch-down limit for the North heading. It can be seen that for pitch up, the envelope is virtually unlimited for North. It is important to note that the flat (active) zone is really a three-dimensional cone of revolution about the OZ axis and the magnetometer can operate with H_e anywhere in this solid cone. Thus, on a South heading, H_e would be as shown dotted, and pitching *up* would move H_e to the OA limit. It should be noted that H_e stays within the cone for all headings. (It is a different story, however, for dip angles below 20°, as we shall see.)

For all dip angles from 20° to 90°, only two magnetometer mounting orientations in the aircraft are recommended. They are a) for high dip angles, the optical axis 45° to the aircraft's nominal horizontal (or vertical) axis, as shown in Figure 1, and b), for mid-range dip angles, 90° to the horizontal axis. Other mounting angles will allow larger manoeuvres on certain headings, but they will be proportionally reduced on the reciprocals of these headings. Figure 2 shows the maximum pitch and roll envelopes for all dip angles, using the 45° and 90° mountings. The regions of overlap should be noted.

The attitude envelope would not be so important if it were just a question of flying straight and level in a survey, but compensation has to be considered. Fortunately, the so-called heading error, the magnetometer's orientation error over the flat zone, can be taken out quite effectively by conventional compensation (Hardwick, 1984 a). However, for good compensation of the aircraft interference, a "robust" set of compensation coefficients is required, otherwise there can be residuals in the magnetometer signal that will change with heading and with large changes in total field. The necessary robustness is achieved through the compensation (or "calibration") manoeuvres used to solve for the interference coefficients; the vector between H_e and any axis in the aircraft should sweep through as wide a range as possible during calibration. Expressed another way, this implies a rich diversity in the direction cosines of the aircraft axes with H_e and to achieve this, the manoeuvres should extend to the attitude limits of the solid cone of revolution. The recommended procedure is comfortable pitches, rolls and yaws on any four orthogonal headings with turns between headings at maximum roll angles appropriate for the dip angle.

THE LOW DIP ANGLE CASE

For dip angles below 20°, imagine Figure 1 rotated 90° clockwise and the cone produced to a solid by 360° rotation about the OZ axis. The plexiglass mockup shown in Figure 4 aids this visualization. The magnetometer (black cylinder) is in the 45° mounting. The amber cone, whose half-angle is 12.5°, represents the 12.5° dead zone around the optical axis in Figure 1. The other side of the active zone is represented by the "Chinese hat", whose apex half-angle, α_{hat}, is defined from Figure 1 as 65°+ 12.5° = 77.5°. Thus, the apex angle, is 155 °. The space between the hat and the amber cone is the active zone. H_e (yellow) is in the straight-and-level X-Y plane of the aircraft, i.e. at 0-degree dip angle, and is offset in this plane from the X-axis by 45° of heading.

It can be seen that since H_e is roughly parallel to the aircraft X-axis, as the aircraft rolls around its X-axis, it is close to rolling about H_e and thus, the roll envelope is almost unrestricted at 0° dip. If H_e is swung horizontally in each direction until it touches the "hat" at the red lines, it will have swept out an angle of 144.4°. This is the heading envelope; unlike for the high dip angle cases, it is *not* unrestricted here. The heading envelope half-angle, ψ_{max}, is given by

$$\cos \psi_{max} = \alpha_{hat} / \cos \theta \qquad (1)$$

where θ is the mounting angle (-45 °)

As the aircraft pitches up to 32.5°, H_e meets the inner cone. This is the pitch envelope limit, although the aircraft can pitch down to a very large angle.

At dip angles slightly above 0°, say 10°, H_e is 10° closer to the inner cone, thus limiting pitch up to 22.5°. If this is considered too restrictive, the mounting angle θ can be depressed by the amount of the dip, 10° in this example, from –45 ° to –55°. This will restore the pitch-down limit to the full 35.5°, while reducing the heading envelope, but only slightly. From Equation 1, the half-angle heading limit would then be 67.8°, for a full heading envelope of 135.7°, as opposed to 144.4° without the depression. (The low-dip envelope of Figure 2 is for the basic –45° mounting; it does not show the possible relaxation of the pitch envelope).

In any case, for an aeromagnetic survey, the heading envelope can easily include two orthogonal headings, say a North survey line and an West tie line. For this, the mounting of the magnetometer would have to be rotated about the vertical (heading) axis of the aircraft 45°, as shown in plan view, Figure 3.

But what about the other two survey headings, South and East? By reversing the polarity of the H_1 coil, the cone and the hat can be "turned inside-out", like an umbrella caught in a gust of wind. The configuration is shown in Figure 5. Using this technique, the headings of any survey can be accommodated by offsetting the heading of the magnetometer the appropriate angle from the heading axis of the aircraft, using Figure 3 as a guide. The H_1 switch is done through operator-controlled logic in the Scintrex CS-2 magnetometer and is done automatically in the Geometrics G-822A.

The implications for compensation are as follows: For each heading "hemisphere", a separate compensation is required. In each hemisphere, on three or four headings, the basic pitches and yaws should be done, with large (unrestricted) rolls between the headings. A coefficient solution is obtained for each hemisphere and these two solutions can be combined into a single, robust solution for all survey headings. This technique should not be confused with that of doing a separate compensation for each heading of a survey, as is employed in certain compensation systems. The coefficients produced by such a method are certainly not robust, especially when it comes to gradiometry.

It should be noted that there are actually two “flat” hemispheres for a cesium magnetometer, arbitrarily labelled “North” and “South”, one *almost* the mirror image of the other. In theory, a second pair of orthogonal headings could be flown in the second hemisphere, as has been suggested at times by magnetometer manufacturers. However, there are good reasons to stay with one hemisphere. First of all, the “flat” error envelope has to be carefully tailored when the magnetometer is set up and one hemisphere is usually flatter than the other. The error envelopes, even if small, are never identical. Thus, even though the portion of the coefficients relating to aircraft interference can be combined linearly for the two hemispheres, the portion due to magnetometer error cannot be.

There is another possible mounting that is sometimes suggested by one manufacturer, namely with the sensor in the horizontal plane of the aircraft. Here, with the sensor suitably rotated, one orthogonal pair of headings can be covered, or four such headings if the second hemisphere is used. The disadvantage is that between the headings, H_e has to go through the inner cone (dead zone) and it is not possible to collect as rich a set of compensation manoeuvre data as when the heading envelope covers somewhat more than two orthogonal headings as described above.

GRADIOMETERS AT LOW DIP ANGLES

Gradiometry is always a bigger challenge than total field measurement from the standpoint of instrumentation, particularly when it comes to compensation. There are recommended guidelines that have proven themselves over the years (Hardwick, 1984 b). At low dip angles, there should be no special problems if the magnetometers involved are installed as suggested in this paper and if the manoeuvre envelopes are observed. A simple test to ensure that the magnetometers are tracking each other is to fly a full 360° circle, recording magnetic heading, at a roll angle of 30°. With automatic H_1 switching, for each magnetometer there will be an obvious jump in level corresponding to the switch point; there should only be two of these around the circle and they should occur in each magnetometer at roughly the same heading. With operator-controlled H_1 switching, the pattern has to be thought out in advance, but the criteria are the same.

CONCLUSIONS

There are several choices for mounting magnetometers in the low-dip environment, but because good, comprehensive compensation requires a large manoeuvre envelope, the 45° mounting with possible small adjustments to match the dip angle, is recommended. Visualization of the envelope is very helpful and observation of its limits is important for compensation. If the procedures outlined in this paper are followed, provided that magnetometers are working to specification, there should be no impediment to operating successfully in the very low-dip angle regime.

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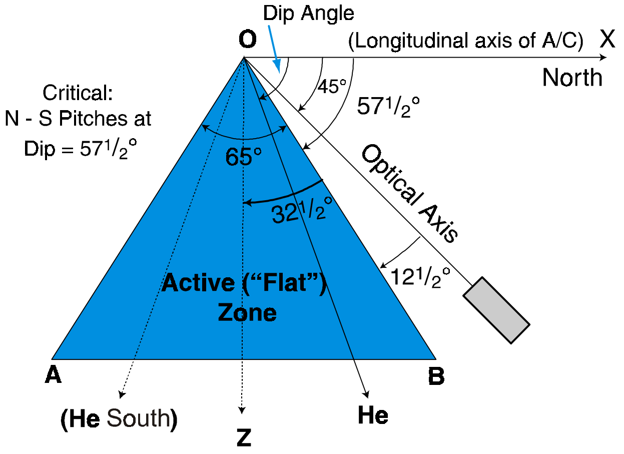

Figure 1. 45° Mounting, For High Dip Angles

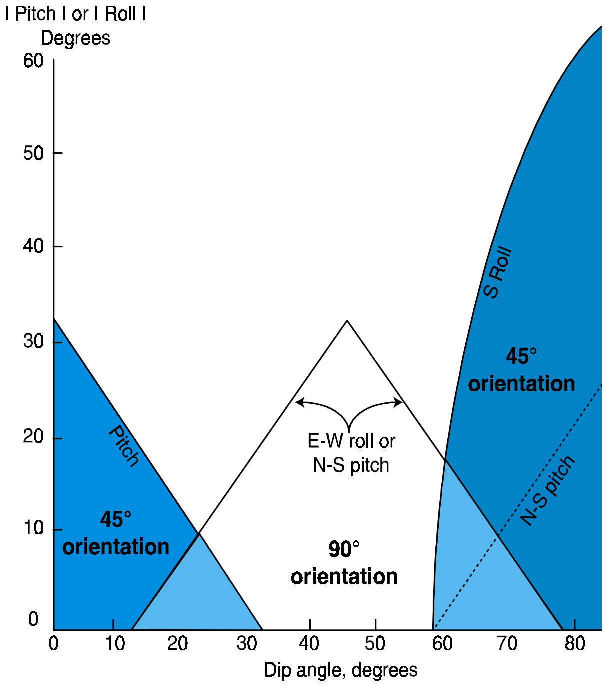

Figure 2. Manoeuvre Envelope, All Heading

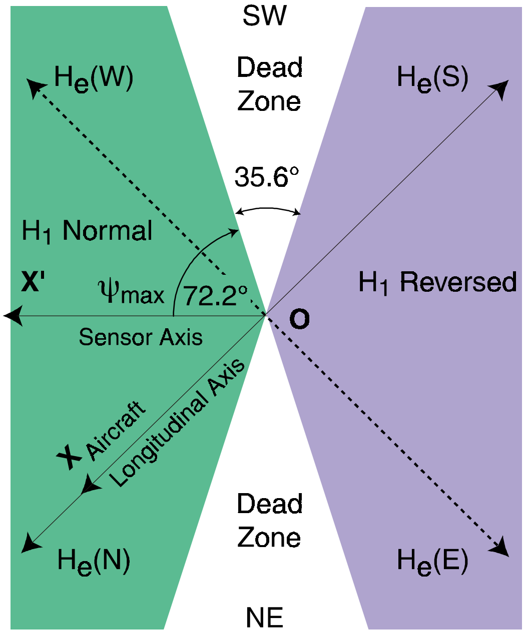

Figure 3. Low-Dip Angle Heading Envelope (Plan View)

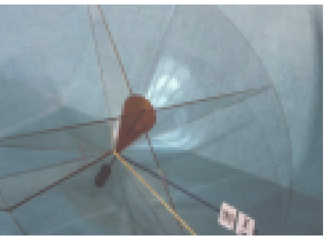

Figure 5.
H_1 Coil
Reversed

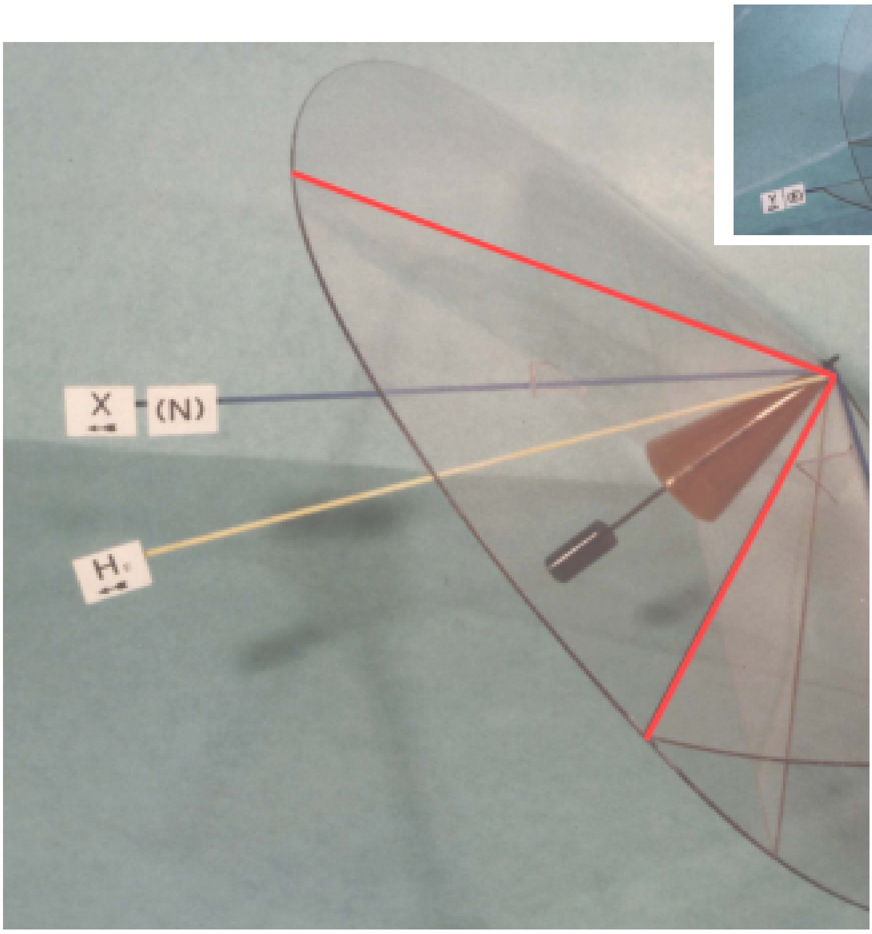

Figure 4.
0° Dip Angle