Understanding the Avalanche Beacon for Best Performance

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This presentation will attempt to clarify the basic principles in the design and operation of the avalanche beacon. It will deal also with the reasons for the upcoming changeover to the single frequency 457 Khz operation mode. The nature of the electromagnetic fields generated by the transmitter unit with particular emphasis on the variation with distance from the unit and how they may be oriented will be presented. How the received signal can be used to determine information on the orientation of the transmitter even when the location is not yet determined will be shown. Of special significance is the power level of the detected signal and how that is modified by the location and surroundings of the sender. From an understanding of the performance some appreciation of the current suggested modes of field use may be gained and users can then adapt their maneuvers for the best overall performance.

Introduction

This paper will serve to remind users of avalanche rescue beacons of the basic principles of operation. It is not intended to be a comprehensive comparison and documentation of the various units available. That information will be available in other papers at this meeting. Most of the discussion which I give here has already been presented at an earlier meeting of ISSW (1). The family of skiers and professionals who use beacons as a practice are not keenly aware of how they operate and hence are not able to optimize the field performance. It is useful now to go over the basic physics upon which the device operates as a refresher, but also to point out and emphasize how such understanding may improve the field performance.

International agreement on the properties of personal avalanche beacons has now been achieved so that starting in 1996 only single frequency beacons will be used world wide. At present some people have units working at the old 2.275 kHz frequency; dual frequency 2.275 kHz and 457 kHz units are more widely used, and conversion to the single frequency 457 kHz mode must be anticipated. A brief history of the reasons for this evolution will be given, but a full discussion of the issues is available (2).

I will not discuss higher frequency and microwave responder types of equipment. In general they require complex instrumentation and even helicopter assistance for effective usage. First, all the higher frequency systems which operate in the propagating electromagnetic wave domain have generally much longer ranges, >1000 ft. They suffer because the detection receiver equipment is not portable and must be called to the scene with considerable time delay. The power requirements and cost of such systems is large also.

When John Lawton produced the first Skadi in 1968, he selected the frequency of 2.275 kHz because that is the frequency at which the average ear has the greatest sensitivity. The concept worked on the principle of a simple transformer in which a magnetic field is produced by the 2.275 kHz current in a coil on a small ferrite rod. A second identical rod and coil system in a receiver module picks up the oscillatory magnetic field and generates a voltage which is detected by an earphone. The signal is keyed on for about 0.2 sec every couple of seconds, so the listener hears a string of audio beeps. The intensity of the signal depends on the magnitude of the magnetic field at the receiver and whether it is coupled into the receiver coil. If the receiver ferrite rod lies in the direction of the field coupling is a maximum; if it lies at right angles to the field, the signal vanishes. One cannot know to start whether the field is too small to give an audible signal or whether the orientation is incorrect. It is also difficult to determine how to move the receiver in which a minimal signal has been found in a direction toward the source of the magnetic field which is the buried transmitter. Given the limitations of electronic circuits and the level of atmospheric electromagnetic noise which is also picked up by the receiver coil, the maximum range of the low frequency device is about 30m or 100ft.

Soon after the use of the 2.275 kHz units became widespread, it was realized that over a broad snowfield an effective range of 100m was required to make search times of the order of 10 minutes. For other reasons it was desirable to preserve the magnetic field coupling mode of operation rather than use a propagating field principle. Hence the frequency had to be set high enough to give an acceptable range and also conform with international radio frequency band allocations. The frequency of 457 kHz was chosen because it falls in a low frequency AM band set aside for maritime communications and at least out to 100m the devices would operate in the so-called near field region. The meaning of near and propagating field regions is discussed in the next section. With 457 kHz as a carrier modulation by the 2.275 kHz frequency is necessary. The electronics is more complex but performance is improved because of greater detection sensitivity and lower atmospheric radio noise.

From field tests the superiority of 457kHz units was clearly demonstrated by 1984 (2). In the next couple of years details of licensing and performance standards were worked out for the US and European government regulations. Dual frequency units were manufactured to make all users compatible. By 1996 only 457 kHz units with a minimum usable range of 100m will be available. Future improvements will lie in reducing power consumption and improving reliability. The greatest improvements will be in the nature of the output response so the user may effectively fix the source location. Because the device does not behave like a radio beacon, the user must understand the spacial configuration of the magnetic field of the transmitter coil and how the receiver coil couples to generate the signal.

Inductive Magnetic Dipole Coupling

The system consists of a small loop carrying the oscillating transmitter current. At some distance a similar receiver loop intercepts the magnetic flux generated by the transmitter to produce a voltage used to generate the output signal. The geometry is shown in Figure 1. The sender coil if fixed as shown; the receiver coil may have any orientation at the vector distance $\vec{r}$. The direction of the magnetic field at the receiver position P is given in terms of the unit vectors $\hat{r}$ and $\boldsymbol{\Theta}$ by the expression Eg. 1.

1 $$\vec{B} = \frac{\mu_o M}{4\pi r^3}(2\cos\Theta\ \hat{r} + \sin\Theta\ \hat{\Theta})\cos[\omega(t - \frac{r}{c})]$$

B is the magnetic induction; μ_o is the permeability of free space; M is the magnetic dipole moment of the sender given by $I(t)A^t$. To increase the effectiveness of transmitter and receiver loops they are wrapped on ferromagnetic ferrite rods. ω is the angular frequency; c is the velocity of light, and t is the time. This expression gives only the near field behavior. Other terms depending on r^{-2} and r^{-1} are not shown, but Eq. 1 gives the dominate field terms out to a distance $r=c/\omega=104$m for 457kHz signals. Terms that depend as r^{-1} are the propogating field terms, but are too small to be considered.

The changing magnetic field coupled through the loop of the receiver coil induces a voltage V(t) given by Eq.2.

2 $$V(t) = A_r B_1 \omega \sin[\omega(t-\frac{r}{c})]\cos\Theta_r$$

A_r is the receiver loop area, and Θ_r is the angle between the axis of the loop and the field direction at P. The loop may be oriented in any direction other than that shown. The signal will be a maximum if the loop is oriented in the direction of the local magnetic field. If the receiver is turned at right angles (Θ_r=90°) to the field the signal becomes zero. It is useful to keep always in mind the idea that the receiver signal is a maximum when the maximum number of field lines link the receiver loop and that the signal disappears when the field lines do not link the loop. This idea will be discussed later as a means to enhance the effectiveness of search proceedures over the conventional instructions for beacon use. Note also that the signal voltage in the receiver coil depends on the frequency ω. Thus the signal for the same field at 457 kHz is about 200 times that for the 2.275 kHz.

Figure 2 shows the pattern of the magnetic field lines around the oscillating magnetic dipole represented by the alternating current in the sender loop. The loop is oriented as in Figure 1 along the line C-D. A and B represent orientations of the receiver loop for maximum and minimum signal respectively. The axis of the ferrite core in a current loop represents the orientation of that loop. From expression Eq. 1 at the same distance from the sender loop the field on the axis is two times that in the plane at right angles to the loop. The magnitude of the field falls as the distance, r, to the minus third power.

The propagating field is very much smaller in magnitude for the same current so higher current and thus higher power consumption is needed. It is also much more subject to absorption and reflection in the surroundings so that in spite of the directivity information a false location may be indicated.

In the receiver coil it is not the voltage signal that one detects but the power generated by that signal. The power that can then be used to generate an audio response or to operate a threshold indicator will be proportional to the square of the magnetic field at any point. The signal in the detector varies then as the inverse sixth power of the distance. The expression for the square of the magnetic field amplitude given by Eq. 3 is to be used to estimate the detector response.

3 $$B^2 = [\frac{\mu_o M}{4\pi r_3}]^2(1 + 3\cos^2\theta)$$

This expression is used to generate Figure 3 where the contour lines of constant B^2 differ by a factor of two in the intensity. The rod at the center indicates the orientation of the sender dipole, and the line on the axis indicates the orientation of the receiver dipole for that position. At every point around the contour line of equal intensity the receiver dipole must be oriented to achieve the maximum signal. That orientation is determined by reference to Figure 2 where A shows the detector orientation for optimum signal. On the axis and at 90^o it must be parallel to the sender dipole. A change of 12% in the distance, r, doubles the value of B^2.

If the sender dipole is oriented so one moves around it in the equatorial plane, the contours will be circles separated by 12 % in radius for a factor two in intensity. These are the limiting cases for the variation in intensity with radius, and will be used to think about the most effective search routines using a device which has an adjustable detection threshold indicator besides the audio output.

Reference 1 gives further details on the performance on the dependance of the surface signal as a function of orientation of the buried sender and the depth of the sender. These are of importance when the detector is almost directly overhead and one wishes to pinpoint the location for excavation. The signal profile will be narrowest in space if the sender is parallel to the surface and parallel to the search direction, and widest if the search is at right angles to the orientation of the sender. A shallow burial depth will give a sharper detector response, but if the sender is tilted relative to the surface, the maximum of the surface signal will be displaced relative to the position of the sender. By keeping in mind the basic pattern of Figure 2 for the magnetic field of a dipole and the fact that as one moves the optimum orientation of the receiver should change, one can interpret and compensate for the observed response.

From the behavior of an elongated body caught in avalanche debris, the body would with greatest probability come to rest lying in the plane of the slope. It is assumed that the sender dipole is fixed to be more or less parallel to the body axis if it were worn against the chest. Thus the field intensity pattern of Figure 3 is applicable. Once one has a signal and any idea of the horizontal location one may estimate the orientation of the sender dipole by rotation of the receiver dipole. Rather brief checks of this kind may determine the optimum search procedure; some of these strategies will be discussed.

It is useful to determine the local magnetic field orientation as follow: See Figure 4. Rotate the receiver one complete turn around any axis. At two orientations given by the line N-N' the signal must vanish because the receiver is at right angles to the field line B. Rotate 90^{o} from N-N'and then rotate about N-N' to a signal maximum. From the geometry this direction must coincide with the direction of B.

To conclude this section on technical performance it is sufficient to restate that only units operating at 457 kHz carrier frequency amplitude modulated at about 2.275 kHz and keyed on about once per second will be available in the near future. The effective detection range will be at least 100m. Units may differ in the output and controls. All will have an audio output sensitivity ranging for detection. Some may have adjustable signal level threshold indicators for a preset signal level.

Search Strategies and Other Considerations

Let us discuss the factors that may disturb the response first. The carrier frequency is near the marine communication band. It is possible that such voice communications will be detected near sea coasts, but is not likely. At 457 kHz the conduction of ground, ground cover or snow is too small to affect the signal by eddy currents. Good conductors such as an aluminum shovel near the sender will markedly influence the fields. Ferromagnetic materials near-by may short circuit the external magnetic field and thus act as a very effective shield. Everyone is urged to check out at home the effect of shovels, metallic camp gear or other equipment and then be sure to wear the sender appropriately fixed to the body.

The primary detector output is an audio signal. Realizing that the signal power levels vary from that at 100m to 1m and that the dependance goes as the distance, r, to the sixth power, the audio power level will vary as 10^{12} from the far to near range. Some kind of power level ranging is absolutely required. An important physiological relation for the perceived sensitivity of the human ear, L, to the actual audio power level, I, is given by Eq. 4

4 $$L = 445\, I^{0.33}$$

With such an intensity compression in the ear, if the intensity, I, varies as r^{-6}, the loudness varies only as r^{-2}. The ear is certainly not a good detector except to make very crude intensity measurements.

It does however have a very useful characteristic; it can discern the presence of the 2.275 kHz signal which cannot otherwise be seen in background radio or electronic noise. Thus at the limits of detection sensitivity the ear will confirm the signal. This means that for orientation of the receiver it is much better to find that orientation for which the signal is zero, and then rotate the receiver 90° perpendicular to the axis of the receiver. One will have the direction of the local magnetic field precisely determined. Since all magnetic field lines must pass through the core of the sender coil, one could inevitably follow a field line to the sender. Refer to Figure 2. One may take the short path or the opposite direction or long path. For an experienced user this method might be useful in some cases.

If the receiver is provided with a definable intensity threshold level adjustment, there is a better method. One has a well defined signal and by moving to and fro triggers the threshold indicator. Refer to Fig. 3. One is at some point on one of the contours, and he can rotate the detector to achieve optimum sensitivity so the detector is oriented along the field line. Now move the detector sideways a few steps and then at right angles or in the direction the detector is pointing to get a new threshold position. The line between these two positions is tangent to a curve of Fig. 3, so walking perpendicular to that direction toward greater intensity automatically carries one almost directly to the source. Since the contours in Fig. 3 are not circles a correction must be made in the same manner as one approaches the source. If the source orientation is perpendicular to the plane of the search field, the intensity lines are true circles centered at the source. One should be able to move directly to the center while monitoring the increase in the audio signal. This method should work for any orientation of the sender coil. As mentioned above some idea of the orientation of the sender is possible from the orientation of the magnetic field in or out of the search plane.

For very close determination of the best point for excavation rely only on intensity measurements. The very near fields may be disturbed by surroundings so the field direction is unreliable.

Another variety of proportional response is given by a device fitted with a voltage to frequency converter so the pitch of the audio signal measures the field strength. The ear is very sensitive to pitch so small changes in intensity could be discerned. Automatic ranging would be necessary to keep the pitch within a reasonable audio range. No unit has been built with this feature.

Conclusions

Within a very few years only devices working at the single 457 kHz frequency with an effective range of 100m or more will be available. Dual frequency units may still be used but 2.275 kHz units should be discarded. Units with signal threshold detection will be much more effective for rapid location. In every case an understanding of the fields around a magnetic dipole will improve the efficacy of the search routine used.

References

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2 Faisant, R.D., Frequenzsalat-Toward Uniform Frequencies for Various Types of Avalanche Victim Locators, ISSW Proceedings, pg. 54-57, Aspen 1984.

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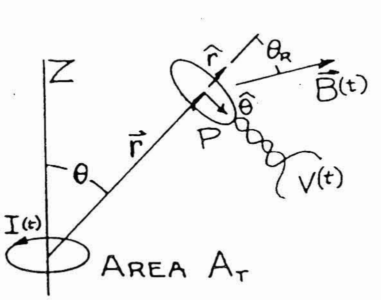

Figure 1. This figure shows the geometry of the sender and receiver coils separated by the distance $\vec{r}$. The unit vectors $\hat{r}$ and $\boldsymbol{\theta}$ shown at the point P serve to define the field $\vec{B}(t)$ produced by the current I(t) in the sender coil. The receiver coil voltage V(t) is generated by the time variation of the magnetic flux which links the receiver coil.

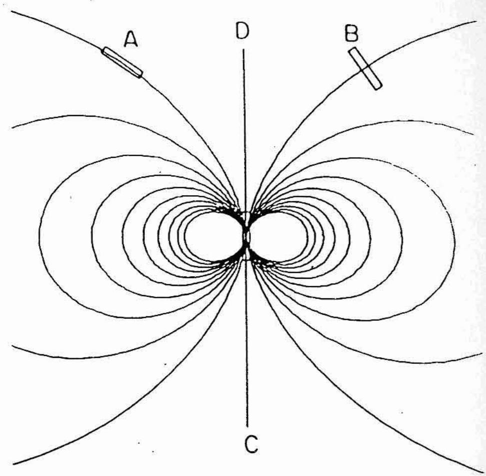

Figure 2. Magnetic field lines are shown ab the oscillating sender magnetic dipole orien along the line C-D. A receiver coil at A i oriented for maximum field linkage and henc maximum signal. At B it is oriented for a n signal. The sender and receiver coils wrapped on a ferrite rods to enhance the magnetic field produced or collected. In this figure the respective rod orientations shown.

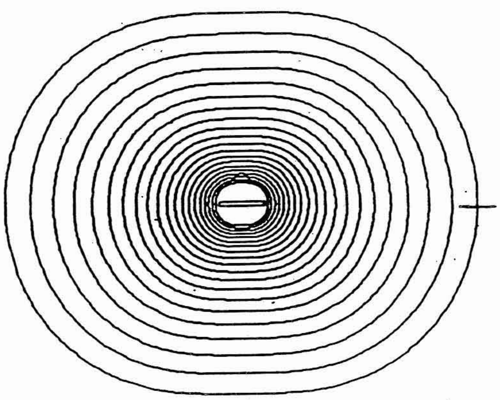

Figure 3. This contour map shows the lines of equal magnetic field intensity B^2 about a sender oriented as shown at the center. The receiver coil oriented for maximum signal on the axis is shown at the right edge. Moving from on contour line to the next toward the sender represents a change in intensity of a factor of two. These contour lines are given by the expression in Eq. 3. Since B^2 varies as r^{-6}, a 12 percent change in r results in a factor two change in intensity. If the sender were oriented vertically instead of horizontally as shown, the contour lines would all be circles with the same spacing.

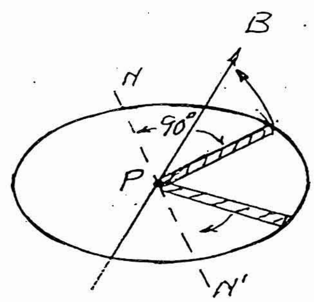

Figure 4 To determine the orientation of the magnetic flux B at the point P, rotate the receiver around any fixed axis. Two n signal points N and N' will be observ Rotate in the original circle 90° from the direction N-N' and then rotate about N-N' to a signal maximum. The receiver must now be the direction of B.