AVALANCHE BEACONS - WORKING PRINCIPLES, SPECIFICATIONS AND COMPARATIVE PROPERTIES†

David A. Lind and W. R. Smythe*

Abstract.--The most widely used personal avalanche beacons operating at 2.275 kHz or 457 kHz frequency depend on the magnetic coupling of the sender and receiver units. The sensitivity depends on the separation distance, r, as the function r^{-6} and in a complex manner on the relative orientation of the sender and receiver. A discussion of the performance and strategies for optimum use is given. Means to establish standards of performance will also be suggested. Finally, remarks concerning interference and spurious signals are made along with suggestions for improving directional and quantitative response.

INTRODUCTION

This paper grew out of the realization that most users of avalanche beacons should have an elementary understanding of the principles of operation. There exist a variety of avalance search devices using the principles of electromagnetic induction or propagated wave reflection and reception. This discussion is restricted to devices for personal use employing the inductive princple. Other more sophisticated devices employing microwave transmitter-receiver or microwave reflectometer combinations are not considered. With a good understanding of the principles comes the possibility for modified use strategies, for example the use of directional information.

There are extensive discussions of avalanche beacons, search strategies, and estimates of survival probability in the European mountain safety literature, along with performance estimates of specific manufacturers.[1] Avalanche News[2] recently reported qualitative field tests on the most widely used personal beacons. There are, however, no definitive standards of performance. In addition, there is also a controversy regarding the preferred frequency.[3]

Four frequencies are in use: 2.275 kHz, 457 kHz, 156.842 MHz and 915 MHz. The latter two frequencies use propagating signals and are not considered here. 2.275 kHz was first used by the Skadi unit and then adopted by others. At 2.275 kHz and 457 kHz only the near field signal is significant. However, devices operating above 10 kHz must satisfy U.S. Federal Communications Comm. regulations.

There is no set of specifications available for testing the performance of beacons. Most beacons provide only an audio signal at 2.275 kHz and have a range of roughly 100 ft or about 30 meters. Receiver sensitivity and signal to noise ratio are not specified. There is little or no documentation available for the devices.

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* David A. Lind, Professor (Emeritus) and W. R. Smythe, Professor, Department of Physics, University of Colorado, Boulder, CO 80309

1. Literature and discussions of techniques, equipment and field experience are found in proceedings of Austrian, Swiss and Italian mountain rescue associations. See for example papers by various authors in Avalanches published by Fondation Internationale Vanni Eigenmann (1975) or G. Gidl, Investigation of the Range of Inductive Transmission with Regard to Instruments for the Location of Avalanche Victims, Thesis Technischen Hochschule Graz. Graz 1975 available at the World Hold Data Center for Glaciology, University of Colorado, Boulder, CO.

2. Avalanche News (P. Schaerer Ed) No 13, October 1983, 4.

3. For discussion of these questions see paper of R. Faisant in these proceedings.

INDUCTIVE MAGNETIC DIPOLE COUPLING

To understand the operation of a beacon it is useful to have a clear picture of the magnetic field of a small current loop, as is shown in Figure 1. In the beacon, the transmitting antenna consists of a pencil sized ferrite rod wrapped with a wire coil in which a 2.275 or 457 kHz current flows. This same dipole field pattern can be seen with a small bar magnet, a piece of paper, and some iron filings.

Figure 2 shows the geometry of the sender and receiver antennas, representing each as a conducting loop. It also defines the unit vectors $\hat{r}$ and $\hat{\theta}$. The plane polar coordinates r and θ are the distance and direction to the receiver from the sender. The magnetic moment of the sender antenna, $M\cos\omega t$, is equal to the loop area, A_s, times the sinusoidal current I(t). The complete Maxwell equations solution for the fields of an oscillating magnetic dipole[4] changes character between the near field zone and the far field zone. The approximate boundary between the zones is a sphere about the sender of radius $\lambda(\lambda = \lambda/2\pi$ = the wavelength/2π). This radius is 21 kilometers at 2.275 kHz and 104 meters at 457 kHz. Thus, in both cases, the region of interest lies entirely within the near field zone. The magnetic field in that zone completely dominates the electric field and may be accurately approximated by:

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

where B is the magnetic induction, μ_o is the permeability of free space, ω is the angular frequency, c is the velocity of light, and t is time. Meter-kilogram-seconds (Mks) units are employed throughout this paper. It is important to note that the magnetic field decreases as the inverse third power of the distance from the sender ($1/r^3$).

The changing magnetic field lines linking the receiver loop induce a voltage in that loop given by:

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

where B_1 is the amplitude of the magnetic field at the receiver, A_r is the receiver loop area, and θ_r is the angle between the axis of the receiver loop and the magnetic field lines at the receiver. It is very important to notice the dependence on θ_r. When the receiver antenna (loop axis) is parallel to the local magnetic field ($\theta_r = 0$), the maximum voltage is induced in the coil. If the receiver is turned so that its antenna is perpendicular to the local magnetic field ($\theta_r = 90°$), no voltage is induced in the coil. It is useful to keep in mind the idea that the receiver signal is a maximum when the maximum

4. See D. Corson and P. Lorrain Introduction to Electromagnetic Fields and Waves, Freeman (1962) pg 477.

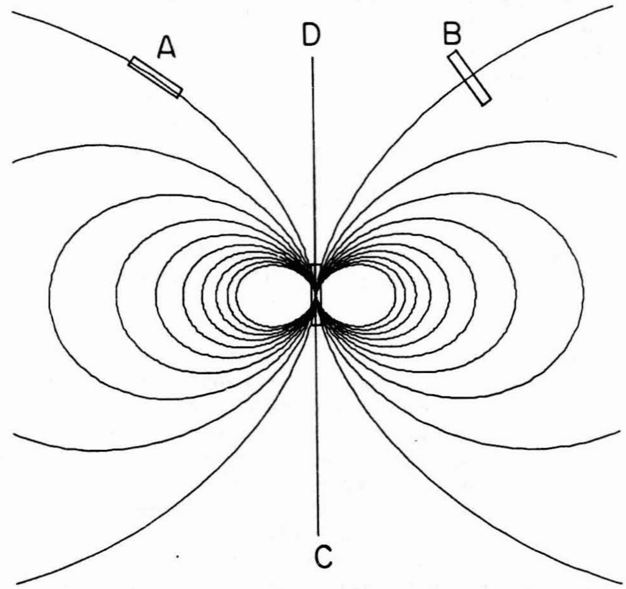

Figure 1. Magnetic field lines of an oscillating magnetic dipole in the near field region. The received signal is a maximum when the receiver antenna is parallel (case A) to the field lines at its location and is zero or a minimum when the antenna is perpendicular (case B) to the lines. The transmitting antenna is located at the center with its axis along the line from C to D.

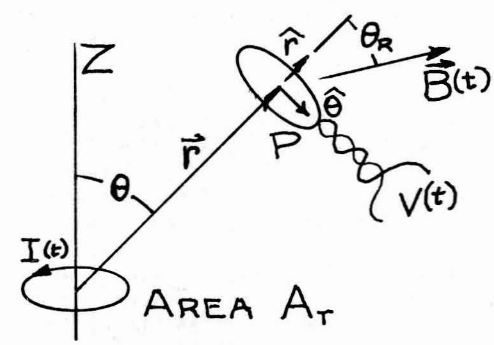

Figure 2. The geometry of the sender and receiver coils separated by the distance $\vec{r}$ is shown. To represent the field at point P orthogonal unit vectors $\hat{r}$ and $\hat{\theta}$, are shown. The magentic field $\vec{B}(t)$ is produced by the sender current I(t). The receiver signal V(t) is induced in that coil by the change in the magnetic field $\vec{B}(t)$.

number of magnetic field lines link the receiver loop and that the signal disappears when the receiver is turned so that the field lines do not link the loop.

For a 2.275 kHz beacon, the signal induced in the receiver antenna can be amplified and applied directly to the earphone. To conserve energy and to take advantage of the increased sensitivity of synchronous detection by the ear, the sender is usually pulsed on for only 0.2 seconds each second. It is worth noting that the energy received is proportional to the square of the induced voltage, and thus varies as the inverse sixth power of the distance between the sender and receiver. This extremely strong variation with distance is a unique property of the near field zone, where these beacons are always used. In fact, the two coils act like the primary and secondary coils of a transformer, rather than as a radio transmitter and receiver. When the magnetic flux of one optimally links the other the signal is a maximum, while the signal is zero if no magnetic field lines link the receiver coil.

Reviewing these facts, the receiver signal depends on just three factors: the distance, r, from the sender; the orientation of the receiver, θ_r, with respect to the local magnetic field; and the orientation of the sender, θ, with respect to the direction to the receiver. That this last effect is less important is shown by Figure 3, which shows that the surfaces of equal signal strength are almost spherical surfaces centered on the sender. Experiments in mountains of weathered granite with soil depths of 0.5 to 2 meters and a snow depth of approximately 0.7 meter have shown a measurable distortion of these surfaces at 2.275 kHz, which was judged not to be significant from an avalanche rescue point of view. The contours of Figure 3 were calculated from the expression for the square of the magnetic field amplitude:

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

It is now apparent that the dominant properties of these beacons are: 1) the dependance of the receiver signal on the orientation of the receiver with respect to the local magnetic field, and 2) the very strong $1/r^6$ dependance of the signal strength of the sender-receiver distance. In practice it is recommended that the receiver antenna be oriented for maximum signal by rotating it in the horizontal plane about a vertical axis. When a maximum is reached, it should then be rotated in that vertical plane, about a horizontal axis to see if a larger maximum can be found. Once the optimum orientation is found then translations can be explored, moving the receiver always parallel to itself, looking for the direction of translation which increases the signal most rapidly. Periodically translation should be stopped and the orientation should be reoptimized.

Figures 4, 5, and 6 show the calculated variations in signal strength as the receiver is moved past the sender under various conditions, always oriented in a fixed direction in space. Figure 4 shows the sound level variation as the receiver is moved past a buried sender on the same path with three different orientations. Figure 5 shows how the degree of localizability gives information about the burial depth. Finally, Figure 6 shows that the orientation of the sender may have a slight offset effect on the localizability.

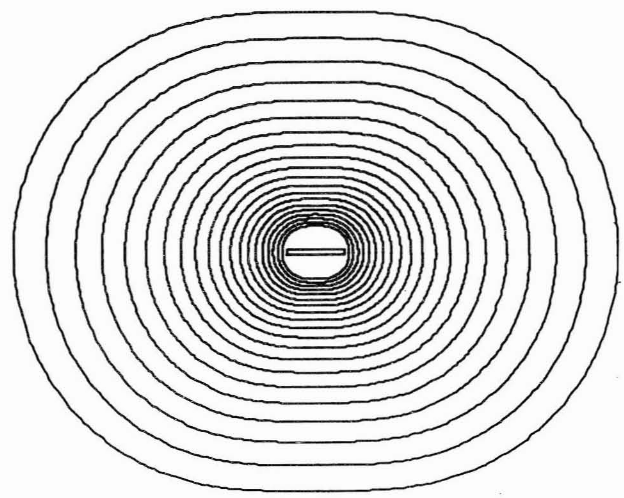

Figure 3. A contour map showing lines of equal signal intensity near an oscillating magnetic dipole. The signal intensity is proportional to the square of the magnetic field. The signal intensity doubles from one countour line to the next as you move towards the source. Moving directly towards the source, the signal intensity doubles when you move 11% of the distance towards the source. In this diagram it is assumed that the receiver is always oriented for maximum signal. If the transmitter were oriented vertically instead of horizontally (as shown) the contour map would consist of concentric circles with similar spacing.

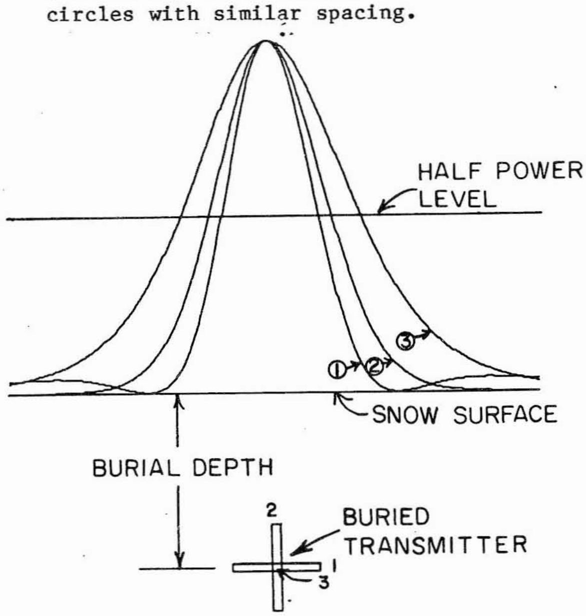

Figure 4. Calculated variation of signal intensity during horizontal scans over a buried transmitter for three mutually perpendicular transmitter orientations. The receiving antenna is assumed to be maintained parallel to the transmitter antenna as it is moved along the horizontal line at the snow surface. The distance between the half power points is less than or comparable to the burial depth. Thus it is usually possible to locate the buried transmitter to an accuracy which is a fraction of the burial depth.

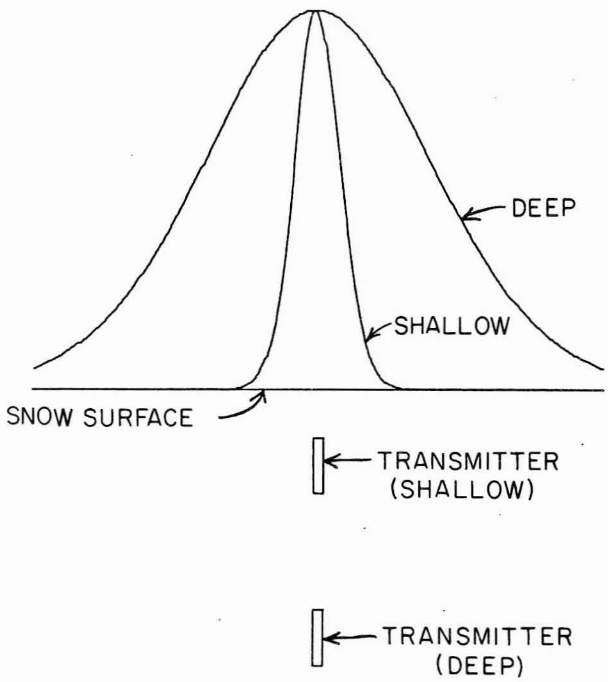

Figure 5. Correlation of localizability with burial depth. The calculated signal intensity is plotted as a function of horizontal position as the receiver is moved along the snow surface for two different transmitter burial depths. It is seen that the signal has a very localized maximum in the case of shallow burial. Both antennas are assumed to be vertical

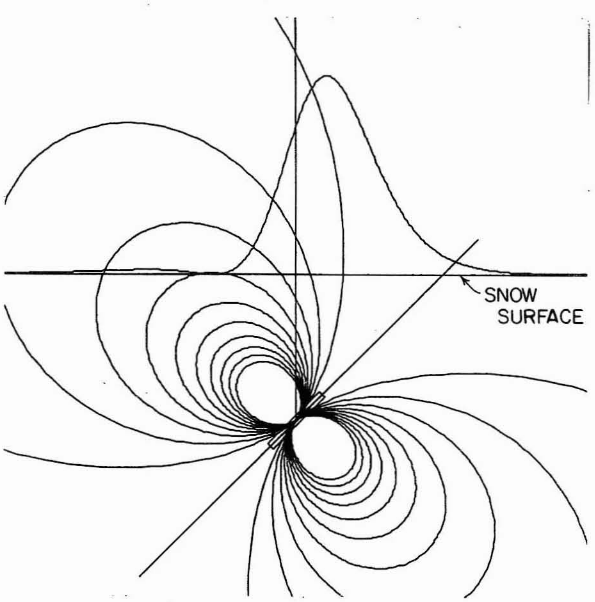

Figure 6. A more general case. The buried transmitter has its antenna at a 45° angle to the vertical. The receiving antenna is held vertically and scanned across the snow surface. It is seen that the position of maximum signal is offset by about 25% of the burial depth. This situation makes clear the importance of using the receiver in the hole frequently after excavation is begun.

SEARCH STRATEGY AND OTHER CONSIDERATIONS

Every manufacturer has supplied rather simplified intructions which generally involve moving in a rectangular grid with the receiver orientation fixed in direction. Since there is also a controversy on the optimal effective range we may discuss that point first.

In practice the range of devices appears to be adequate considering the transverse size of most slides. Except for massive collection basins the flow channels for avalances are of the order 30 to 50 meters wide. Only for victim recovery in a massive slide would a longer range device be more useful. In professional use and in back country use the observations of safely positioned personnel can have much to do with first scan survey success. In fact, rapidly pin-pointing the excavation site is most important, since digging is a time consuming operation.

When a signal is found with the audio receiver, reorient the receiver to maximize the signal. Thus the local field direction is defined. The sender unit is supposed to be worn on the body (usually near the chest) so the antenna is oriented along the body axis. Furthermore, the most probable orientation of an elongated body in the slide debris will be parallel to the slope and the least probable will be with an orientation perpendicular to the slope plane. Thus the initial search should be made with the receiver oriented parallel to the slope and also pointing along the fall line. The lines of flux (see Fig. 1) will lie nearly in the slope plane.

If the sender is oriented normal to the slope the field lines will everywhere be almost normal to the slope and a search in the direction of greatest intensity change will lead directly to the sender. No successive reorientations will be needed.

As an alternative strategy one can orient the receiver for maximum signal and proceed in the direction that the antenna points, reorienting as needed. This may be difficult, since the ear cannot detect slight changes in intensity. It is much more sensitive to a null point in the signal. Alternatively one can orient the receiver to zero signal and move along the receiver axis. One will follow a curve orthogonal to the field lines and approach the sender in its equatorial plane. Of course one may move away from the source; this situation may be detected by physical observations or by signal intensity changes.

This strategy was checked briefly in the field but not under realistic avalanche conditions. Such tests need to be made. One point of warning is that very near the sender, the field is no longer a clean dipole configuration and thus a null cannot be found so one must use the intensity variation alone to pinpoint the site. This situation exists out to about 2 meters from the source.

Without consideration of the other physical terrain factors, if the audio signal strength varies as $S = C/r^6$. Then $\Delta S/\Delta r = -6C/r^7$ and $\Delta S/S = -6(\Delta r/r)$. The ear can discern about a 12 percent change in intensity so $\Delta r \approx 0.02$ r or at 30 meter $\Delta r = 0.6$ m (2 ft) to make a barely perceptible change in loudness. If, however, a visual indicator of signal strength were incorporated then improved localization might be achieved.

At this point we note that the ear responds to audio power intensity with a threshhold level that varies with frequency. A frequency of 2 kHz is the optimum for perceived loudness. At other frequencies a larger audio power will be required. Likewise the perceived loudness for a given power as a function of frequency will be a maximum at 2 kHz also. The important relation, however, is that the perceived loudness L is related to the intensity or audio power about as

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

Thus an eight fold increase in intensity makes but a two fold increase in loudness. The intensity, I, is proportional to B^2 or to r^{-6} so the loudness varies as r^{-2}.

In summary the ear is not a good detection element for accurate localization based on intensity alone because large changes in signal strength are required to make perceptible changes in audio signal as perceived by the ear. A sensation other then audio intensity is needed which will be more sensitive as well as quantitative.

After we recognized the audio limitations of the human ear, we also realized that the ear is very sensitive to pitch (frequency changes). One has no difficulty detecting a change of one whole note (9%). Since voltage to frequency IC chips are available, it is a simple matter to take the receiver output signal to the earphone and convert it to a tonal pitch which depends on the signal strength. Assuming one can perceive a 5% change then a change $\Delta r/r$ of about 2% should be detected even with spurious noise (most of which is filtered by the conversion). Now we noted in Fig. 3 that an 11% change in distance doubles the intensity and the contours of equal intensity are nearly circular about the source. Thus determining the direction of steepest gradient will define the direction to the source once any signal is found. This idea has been incorporated into a prototype circuit.

Some discussion of interference and false signals is needed. The near fields of the sender are predominately magnetic. The field pattern can be perturbed only by the presence of magnetic material or conducting media in the vicinity. Since there are no propagating wave fields, reflections as occur at microwave frequencies do not occur. Furthermore, snow, rock or timber debris have no magnetic properties. Even at frequencies as high as 457 kHz conduction of snow or ground is so low that no eddy current effects occur. At low frequencies the eddy current penetration depth in ordinary metallic conductors; aluminum, copper, brass are large so that shielding will be present but not excessive. Because iron has a large magnetic permeability, it can affect the signal markedly if the sender is near iron objects. None of the effects of propagating microwave signals reflecting from snow layers, soil or other objects occur. The low frequency signals will be less affected by metallic objects than the higher frequency induction signals.

DEVICE SPECIFICATIONS AND TESTING

Since the first Skadi was designed and introduced by Lawton in 1965, a number of devices have appeared (almost exclusively based on designs and studies from the Tech. Univ. of Graz.). The first devices used a frequency of 2.275 kHz since the ear is most sensitive to that frequency. Subsequently a series of devices using a modulated carrier of 457 kHz were introduced as well as units using both frequencies. The idea prevailed that by using a higher frequency, advantages of the propagated field as well as higher sensitivity in the near field would improve the range and hence performance.[5]

Table I lists the devices known to us and their relevant characteristics but without comment on their technical design. We noted that little or no use of modern integrated circuit technology is made and that units are often potted for protection against moisture and vibration. Potting makes repair of these beacons difficult or impossible. Were the market for these devices larger, significantly higher performance at a lower cost ($50-100) could be acheived. Most of the dual frequency devices are reasonably compatible with other dual or single frequency units; however checks should be made to verify compatibility and to check effective range.

No generally accepted test procedures have as yet been developed for these devices. Therefore, we suggest a scheme to measure oscillator field strength and receiver sensitivity. Receiver noise levels are best measured as audio noise power level on the most sensitive scale in db relative to the standard of aural threshold sensitivity.

To test the sender, its absolute magnetic field on the antenna axis at a distance of 1 meter is measured by a calibrated receiver coil. Since the field at any distance can be calculated from the r^{-3} distance dependance, the sender performance is thus specified. The equivalent circuit is shown in Figure 7a. The induced EMF in the coil, $\mathcal{E}(\omega t)$, will be observed as a voltage V_L given by

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5. A discussion of the relative merits of 2.275 and 457 kHz is given by H. Schlögel in Sicherheit in Bergland Jahrbuch 1983 (Osterreichisches Kuratorium für Alpine Sicherheit) pg. 236-242.

TABLE I

PERFORMANCE CHARACTERISTICS OF AVALANCHE BEACON DEVICES

Device Name	Frequency kHz	Controls	Range	Comments
SKADI	2.275	S,R+SV	30 M	Rechargeable NiCd Earphone
PIEPS II	2.275	S,R+SV	30 M	2 - 1.5 V AA cells Earphone
PIEPS III	2.275 & 457	S,R+SV	>30 M	2 - 1.5 V AA cells Earphone Send-receive compatible with 2.275 & 457 KHz devices.
ORTOVOX	2.275 & 457	S,R+SR	>30 M	2 - 1.5 V AA cells Earphone Send-receive compatible.
ECHO & ECHO S	2.275	S,R	>30 M	9V cell earphone Electronic compression of audio response. S model has switch to enhance distance response.
AUTOPHON	457	S,R+SV	>30 M	2 - 1.5 V AA cells Case speaker
RUF	2.275 & 457	S,R	30 M	4 - 1.5 V AA cells Case speaker

S = Send R = Receive SV = Switched Volume

$$V_L = \frac{R_L}{[(R+R_L)^2+\omega^2L^2]^{1/2}}\,\mathcal{E}(\omega t)$$

$\mathcal{E}(\omega t)$ is the induced signal in the coil and is given as

$$\mathcal{E}(\omega t) = \omega NA_{eff}\, B(\omega t)$$

NA_{eff} for the coil can be determined by a variety of methods. Thus the sender strength (proportional to $B(\omega t)$) for each unit is absolutely determined.

Using the same coil and a signal generator in the circuit of Fig. 7b, the magnetic field at any point $P(r,\theta)$ is given by

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

where M, the dipole moment, = $i_s NA_{eff}$, and $i_s = \frac{\mathcal{E}_s}{Z_T}$ and $Z_T = [(R_s + R)^2 + (\omega L)^2]^{1/2}$. A correction for the stray capacitance of the coil is necessary. With this sending circuit the equivalent magnetic field strength necessary to yield an audio signal of intensity equal to noise intensity level of the receiver would be obtained and thus the range of sensitivity with any transmitter could be specified.

Some measurements of this kind have been made for individual models of the Skadi, Pieps, Ortovox and Echo lines. The significant point is that an absolute transmitter-receiver sensitivity parameter is determined so the performance of any pair of units is specified. Further details regarding the calibration proceedure are available but not given here since they are concerned with the testing process itself.

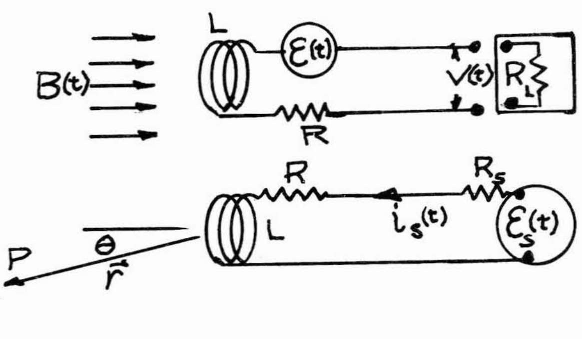

Figure 7. a) The equivalent circuit use of the standard dipole antenna coil when used to measure transmitter sensitivity. b) The equipment circuit of the same coil when it is used as a sender to check receiver sensitivity.

CONCLUSION

The operation of the personal avalanche beacon depends on the magnetic coupling (tranformer effect) between the sender and receiver antenna coils. Because the output signal is converted to audio power and because the ear compresses the power range to provide acceptable loudness range, the device in the usual operation mode is less than optimally sensitive to field strength changes. Some suggestion for search strategies are made. In addition a proposed modification to convert the output signal to a proportional frequency to achieve directionality is given. A better understanding of the operating principles will enhance the effectiveness of the device and improve the localization of the buried victim.

Proceedures for quantitative sender-receiver testing in terms of field strength measurements are also suggested.