457 KHz ELECTROMAGNETISM AND THE FUTURE OF AVALANCHE TRANSCEIVERS

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ABSTRACT: The standardized frequency for avalanche transceivers, 457 kHz, presents many interesting, important, and confusing issues, especially related to receive range, flux lines, near field, interference, point sources, receiver design, searching, and specifying and measuring transmit power and receive range. Improved standards and the possible addition of a higher frequency will help in providing a sophisticated, yet uncomplicated beacon in the future for the expeditious rescue of avalanche victims.

1. BENEFITS AND DISADVANTAGES

An advantage of using the (656 m) long wavelength(λ) 457 kHz signal for companion rescue is that there is little attenuation or effect by objects such as snow, the body, metal, trees, and rocks. There is no "multi-path," which means that the signal does not bounce or reflect off of objects in the backcountry, which would present confusion in location systems. [Multi-path is what causes "ghost" images on a television set using an antenna (at about 50 – 200 MHz)].

For a small antenna as used in avalanche beacons, the (near) fields transmitted and received are predominantly magnetic. This is why objects like aluminum shovels don't significantly limit the transmit field strength of a beacon (unless it is placed so closely that it affects the Quality of the antenna and circuitry); the blade may only "block" the small part of the electric field. The earth and its grounding do not attenuate or affect the signal as much. Ferrous objects, however, do have an effect (e.g. steel towers, iron framework).

The boundary between near field and far field is related to the wavelength λ and is $\lambda/2\pi$ (see appendix). At 457 kHz, this distance is at about 100 meters (656m/6.28), so the operation for companion rescue is definitely within the near field. (For reference, the wavelength of a 60 Hz power line is 5 million meters or about 3000 miles and the near-field boundary is 833 km).

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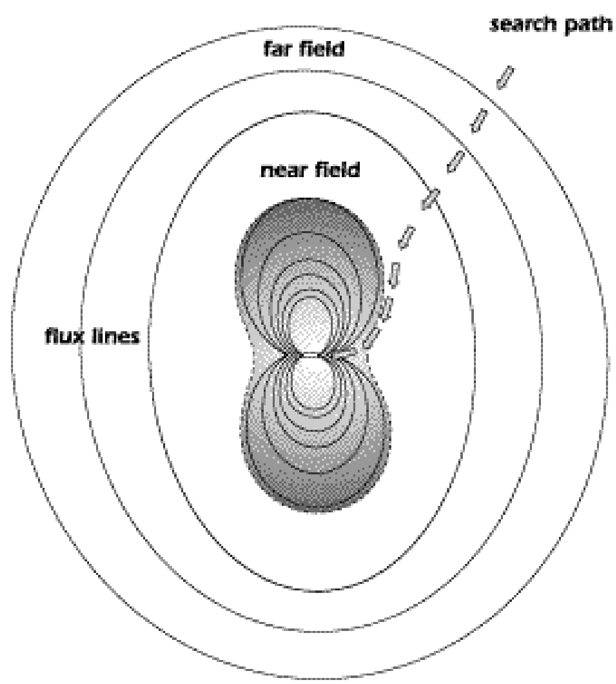
A disadvantage of the 457 kHz frequency is that, in its near-field application, the shape of the signal can be quite complex. In the near field, as compared to the far field, the flux patterns are dependent on the distance (r) from the transmitter, mathematical analysis is very complex, antenna size and type is important, field strength decreases by up to r^{-3} versus r^{-1}, magnetic and electric field dependence varies, and the fields are curved (a far-field application would directly point to the source). This curved shape looks like a figure eight or the wings of a butterfly. Another analogy is that the flux pattern in the near field appears like water coming from a fountain.



Near field/ far field. In the near field, the shape of the signal can be quite complex. A far-field application would point directly to the source.

2. FAR-FIELD EXAMPLES

The question is often raised why GPS (Global Positioning System) technology has not been applied in the field of avalanche rescue. Its frequency is 1.6 GHz, which gives a wavelength (λ) of ~0.19 meters or about 7 inches, which allows for small, efficient antennas. Because of this high frequency, the transmitting satellites need less than 50 Watts to provide usable signals down to earth. There are about 24 satellites in orbit and for the triangulation needed, several satellites are needed. The signals require line-of-sight orientation because the small wavelength signals are blocked by buildings, mountains, canyons, tree, etc. and are severely attenuated or limited by snow. Furthermore, a GPS receiver will tell you where you are, but there is substantial added technology to relay that information to a person searching for you.

Another example of a far-field application is the Recco system currently in use for locating lost individuals. It uses a 1.6-kg transmitter/detector to bounce microwaves at 917 MHz off a special reflector–a thin printed circuit card that doubles the signal frequency–that is attached to an individual's equipment or clothing. One limitation, due to its high frequency, is that the user should always have two reflectors so the body does not interfere with the signal.

3. ANTENNA AND TRANSCEIVER LIMITATIONS

Of course, the avalanche rescue transceiver for companion rescue needs to be a portable product. Therefore, the antennas are electrically small and the (battery) power available is very limited. These are two main reasons, along with the operation in the near field, for little increased range potential at 457 kHz.

For optimum antenna size, its circumference or equivalent height should be one half of a wavelength ($\lambda/2$), or 327 meters at 457 kHz. Therefore, the avalanche beacon antenna is a very small portion of the wavelength. There are things that can be done to increase the effective height of the loop antenna, such as adding a ferrite core and increasing the number of turns of the wire, but the efficiency is still less than 0.1 percent, and this is a limitation with both the transmitter and the receiver.

Transmission power for a beacon is less than 0.1 Watts. Compare this to AM radio stations, which are slightly higher in frequency – they have a power typically greater than 10kW (at least 100,000 times more powerful) – and the transmitting antennas can be hundreds of meters high.

Atmospheric and man-made noise, produced by such things as power lines and weather phenomena, is very high in the region of 457 kHz, and can be aggravated in an urban environment. For all types of receivers, extensive filtering and processing (e.g., mixing) is done to reduce this extraneous noise and to help isolate the beacon's transmission signal, which gets very weak quickly from the transmitter. This partially explains why so-called analog receivers appear to have more receive range: with analog transceivers, this filtering is done by the user's ear rather than the transceiver's microprocessor. Consequently, the usefulness of this weak signal at long range is heavily dependent on the ability level of the user.

This difference in receive range is due exclusively to the noise filtration process of the digital receiver, and has no relationship to the number of antennas used in receiving the signal, as suggested in other literature (Kroell, 2000). On the contrary, the number of antennas actually increases the search strip width. In the case of the Tracker DTS, which uses two receiving antennas, the search strip width is increased by a factor of 15 percent (Meier, 2000). Since search strip width defines the primary search path, not maximum range, this has a stronger effect on the primary search time than a beacon's maximum range.

However, while receive range and search strip width are often perceived as an important product benefit, they may have more marketing value than technical significance. The receive range of an avalanche beacon has no significant effect on the speed of a search or the probability of a live recovery – and can actually prolong the search when performed by recreationists (Atkins, 1999). On the periphery of an analog beacon's receive range, the searcher must cover a relatively large distance before making a determination on signal strength and direction. For recreationists, this can be extremely time consuming, resulting in unnecessary backtracking and signal interpretation. For this user group, it might very well be less time consuming to continue with the primary search until the signal data can be presented with enough resolution to make quick decisions. This is where the signal-to-systems can be seen as a major benefit: it eliminates the "gray area" which can frustrate novice analog beacon users at longer range.

4. ANALOG VS. DIGITAL TECHNOLOGY

A better term for analog beacons would be "audible-based." The human ear is a powerful signal detector out of noise. An example of this is that, in a noisy room it is possible to detect and hear a known voice. It is difficult for a digital signal processing system in the room to detect, recognize, and isolate the speaker, especially if the voice is as loosely defined as it is by the present international standards for an avalanche beacon transmitter. For example, the present broad standard for the on- and off- time may tell a listener or receiver that the speaker in the room is feminine, but a tighter definition would better describe the transmitter's specific speaking characteristics to allow isolation of a specific person.

The greater perceived range of the audible-based transceiver is not due to better design or necessarily better signal-to-noise ratio, but due to the power of the human ear. But the human ear is a very poor judge of loudness (volume) changes. That is why it is difficult to determine the direction of a transmitter based on audio level changes, especially at low signal levels and especially among non-professional users. However, the ear can recognize very fine changes in pitch.

A "digital" beacon can take several forms, but basically it takes the Radio Frequency signal that has been filtered, mixed, and amplified using analog technology and then digitizes this to allow a microprocessor to process it. This provides for many advantages, such as determination of direction (from a dual antenna system), distance calculation, audio interface improvements (such as pitch variation), improved algorithms for signal detection, multiple transmitter isolation and location, automatic sensitivity adjustment, digital filter implementation, and other user interface improvements.

5. STANDARDS

Beacon development is not just limited by electronic technology, but also by down-level standards that do not define the signal characteristics very well, specifically on- and off-times of the 457 kHz carrier. Modernizing these standards could significantly improve the future performance of avalanche transceivers. However, trying to standardize or explicitly define how the beacon should operate is counter-productive. User inferface issues are most efficiently addressed in the marketplace, based on the needs and wants of the consumer.

There is no one international standard. The European standard is ETS 300 718 (currently undergoing revision), with the EN 282 standard still being used in some cases. The only standard for avalanche beacons in the United States is set by the American Society for Testing and Materials (ASTM F1491-93); it sets only the frequency at 457.0 kHz, with no other requirements.

Standards should be modernized so that the signal is better defined to allow better digital signal processing and isolation. Also, product design is challenged by direct tradeoffs between traditional wants and assumptions, "feature bloat," and simplicity. For example, a standard that required a minimum receive range or search strip width might suit the needs of the snow safety professional, but would be counter-productive for the recreational consumer, who generally does not have the skills required to make use of a weak signal at longer range. These conflicts should not be addressed in the standards, but the product developer and (ultimately) the consumer are best suited to determine the best device at the lowest cost.

5. HIGH FREQUENCY AND ID LOCATOR

We propose to significantly improve beacon operation by adding a higher frequency signal to this 457 kHz carrier. With digital technology, this is now more feasible than in the past. This would increase the detection range and would allow giving each transmitter a unique identifier (ID) so that multiple victims can be even better isolated and located.

Since there is more power explicitly in a higher frequency, this would increase the detection range, but without the inherent limitations described above regarding the (non)usability of a weak signal in the near field by the recreationist. Since the operating range would be in the far field, the transmitter could be seen as a point source, initial detection would "point" in that direction, antenna systems could be more optimally designed, and there would be less effect from atmospheric noise. Finally, this higher frequency signal would allow giving each transmitter a unique identifier so that tims could be even better isolated and located. Of course, this frequency would have to be carefully selected based on issues related to snow depth, multi-path, human body effects, radio spectrum allocations, and other considerations.

Adding this higher frequency to the present 457 kHz carrier would not interfere with downward compatibility, or the ability of a newly designed transceiver to detect an “older” transmitter. The higher frequency would “ride” on the 457 kHz signal much like DSL or ISDN data rides on an analog telephone line. The 457 kHz signal would still be used for fine and pinpoint searching in the near field.

5. CONCLUSION

Avalanche beacon design has improved markedly in the past three years, but progress has been limited by the issues stated above. Constraints for future development are not just limited by technology, but by poorly defined standards for the signal and by the need for downward compatibility with existing beacons. Professional use is an important aspect of transceiver design, but one main goal should be to make effective avalanche rescue transceivers accessible to as many users of the backcountry as possible, especially those who are most at risk: recreationists. By leaving user interface issues up to the designers and allowing for a higher frequency in addition to the current 457 kHz standard, transceiver technology could see even greater improvements than the present, yet maintain downward compatibility with the transceivers of the past.

APPENDIX:

REFERENCES

Atkins, D., 1999. Companion Rescue and Avalanche Transceivers: The U.S. Experience. AAAP Avalanche Review, 1999.

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APPENDIX
RF Electromagnetism

There are some essential physics and definitions that help highlight the issues. Electromagnetics entail just what the word says: With any Radio Frequency (RF) signal (which is produced and radiated by a changing, time-varying current through a wire or antenna), there is a magnetic field, **H** – a vector signifying the current density measured as Amperes per meter (A/m) – and there is an electric field, **E**, also a vector quantity that is a voltage density denoted as Volts per meter (V/m).

These fields generate their respective fluxes, or "flow" of electric and magnetic energy. The electric field strength gives rise to the electric flux density **D**, with units of Coulomb per square meter. The magnetic field produces a magnetic flux density, denoted by **B**, with the unit T, for Tesla or volt-second per square meter. Magnetic field strength is independent of the medium, but its flux density, or force field, does depend on the material's permeability. This is true also for the electric field, where its flux is related by permittivity.

For magnetic fields, which the avalanche beacon's antenna mainly radiate, the relationship is **H** = B/μ_o, where μ_o is the permeability of air. Most materials, such as snow, rocks, and trees, all have a relative permeability close to one, or the same as air; i.e., they're non-magnetic. Different permittivities means electric waves may be attenuated, reflected, refracted, scattered, and diffracted by the changes and depth of the media through which the RF signal propagates. The permittivity of snow is about 80 times that of air.

Some essential field vector equations from a predominantly magnetic source for **any** distance, given in spherical coordinates, are:

$$H_\theta = -\frac{\beta^3}{4\cdot\pi}\cdot I\cdot h\cdot\left[\frac{1}{\beta\cdot r}-\frac{j}{(\beta\cdot r)^2}-\frac{1}{(\beta\cdot r)^3}\right]\cdot\sin\theta\cdot e^{-j\beta\cdot r}$$

$$H_r := \frac{\beta^3}{2\cdot\pi}\cdot I\cdot h\cdot\left[\frac{j}{(\beta\cdot r)^2}+\frac{1}{(\beta\cdot r)^3}\right]\cdot\cos\theta\cdot e^{-j\beta\cdot r}$$

$$E_\phi := 30\cdot\beta^3\cdot I\cdot h\cdot\left[\frac{1}{\beta\cdot r}-\frac{j}{(\beta\cdot r)^2}\right]\cdot\sin\theta\cdot e^{-j\beta\cdot r}$$

$$E_r = E_\theta = H_\phi = 0$$

Where:

$$\beta := \frac{2\cdot\pi}{\lambda}$$

λ= wavelength; the distance the beginning of a RF signal covers before the beginning of the next; given by c/f, where c is the speed of light (which is the velocity the radio wave travels (in air or free space)) and f is the frequency.

Therefore, **at 457 kHz**:

$\lambda = c/f = (3X10^8\ m/s) / (457X10^3\ Hz\ (cycles/s)) =$ **656 m**/cycle or over 0.4 miles long

I = electric current flowing through antenna loop

h = equivalent height or area of antenna

r = distance from transmitter

j = imaginary number that is used in defining vectors

Notice that the terms with the coefficients

$$\left(\frac{1}{\beta \cdot r}\right),\ \left(\frac{1}{\beta \cdot r}\right)^2,\ \text{and}\ \left(\frac{1}{\beta \cdot r}\right)^3$$

will all be equal at the distance $r = 1/\beta = \lambda/2\pi$. This distance is defined as the boundary between near-field and far-field.

When $r << \lambda/2\pi$, totally in the near field, only the third term in each equation is significant. The wave impedance or resistance to the field, is the ratio of the electric field to the magnetic field. For a small, loop antenna, the above equations reduce to:

$$Z_w = E_\phi\ (V/m) / H_\theta\ (A/m) = Z_o{*}(\lambda/2\pi r)\ \text{ohms}$$

$$Z_o\ (\text{the free space impedance}) = 120\pi = 377\ \text{ohms}$$

This means that the resistance to the magnetic field, especially in relation to the electric field, is less as one gets closer to the transmitter. The magnetic field is reactive or inductive and is concentrated near the source.

When $r >> \lambda/2\pi$, which is in the far field, only the first terms of 1/r are significant and the field components reduce to:

$$E_\phi := 30 \cdot \frac{\beta^2}{r} \cdot I \cdot h \cdot \sin\theta \cdot e^{-j \cdot \beta \cdot r}$$

$$H_\theta := -\frac{\beta^2}{4 \cdot \pi \cdot r} \cdot I \cdot h \cdot \sin\theta \cdot e^{-j \cdot \beta \cdot r}$$

$$H_\theta := \frac{E_\phi}{120 \cdot \pi}$$

$H_r = 0$

The wave impedance is the constant relationship of Z_0 (120π or 377 ohms), and the fields are orthogonal to each other and produce plane waves. **H_r** reduces to zero, so the curved flux pattern phenomenon goes away. Therefore, the fields would directly "point" to the source. They are radiated fields and their effects extend far from the source. The field strengths fall off as 1/r and the relationship between the electric fields and magnetic fields is a constant.

In terms of power, the relationship at any distance is a Poynting vector, or **E X H** (cross product), and the power density would be $H_\theta^2 {*} Z_w$ [(A/m)²(ohms)]. Therefore, terms are squared: e.g., power roll-off of r^{-6} in the near field.

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