A SYSTEMATIC APPROACH TO OPTIMIZE AVALANCHE BEACON DESIGN FOR MINIMUM SEARCH TIME

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ABSTRACT: The time required to search a buried person using an avalanche beacon contributes significantly to the overall rescue time. This paper investigates the technical requirements and psychological demands with respect to minimal search time. The earlier ones define a beacon's technical specification, the latter ones the design of the user interface. The first search phase is mainly characterized by the search strip width defined by receiver sensitivity. Even the time required to get the beacon ready to receive is subject to optimization. Once the first signal is detected, confusion caused by multiple transmitters costs valuable time. Hence a reliable and user-friendly multi-burial detection and signal isolation is crucial. Pin-pointing finally imposes the highest mental workload on the searcher. An intuitive user interface freeing the searcher from the need to compare numbers promises the largest gain here. For multi-burial accidents the influence of these beacon characteristics on search success and search time is discussed. This analysis includes numerical simulation of multi-burial search as well as a qualitative discussion of user interface requirements based on the accident reports and statements of the persons involved. The results may serve as a starting point for the development of a more generalized framework.

KEYWORDS: Avalanche beacon, safety, multi-burial

1 FORMULATION OF THE PROBLEM

During the past few years, the development in avalanche beacon technology showed a strong tendency towards increasing complexity and additional functionality. Manufacturers' marketing efforts as well as comparative tests published in magazines drew the users' attention more and more towards isolated technical features like vertical antenna reach, multi-burial detection etc. In turn, beacon developers may be tempted to optimize beacons rather for benchmarks and test scenarios but for the real case.

1.1 *The Real Case*

However, the one and only legitimate development goal for a beacon design is to

maximize the probability to survive for a buried person!

Since there is a strict and aggressive relation between the time a person is buried in the snow and her probability to survive, this can be immediately translated into the requirement to

minimize the time required to rescue a buried person!

1.2 *Trade-Offs*

This time is composed of search time and shoveling time. Since both times add, each single action within the whole process is subject to optimization. Moreover, recent results indicate a strong variance in shoveling time depending on the skill level of the rescue team (Ortovox 2008). Together with more complex and capable beacons, this might justify a shift in training from searching to shoveling.

1.3 *The Overall Design Goal*

This said, the overall design goal for a modern avalanche beacon is to

minimize the time it takes an average user to locate one or more buried persons!

The view of the user and the beacon as a team plays a key role in understanding this design goal. A beacon has to be designed for the average user, with an average (or below average) level of skills, experience and training, exposed to enormous stress and time pressure.

In the sequel, we will derive more detailed technical criteria from the overall design goal and review how current technology hypes support this goal.

2 MAN AND MACHINE – THE TEAM

Our overall design goal emphasizes the interaction between searcher and beacon. The other way round this means that the requirements for

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the beacon depend on the searcher's skills. An experienced searcher with well-trained auditive capabilities using a classic beacon with pure acoustic output will often perform better than a beginner using a digital beacon with distance readout and direction indicators.

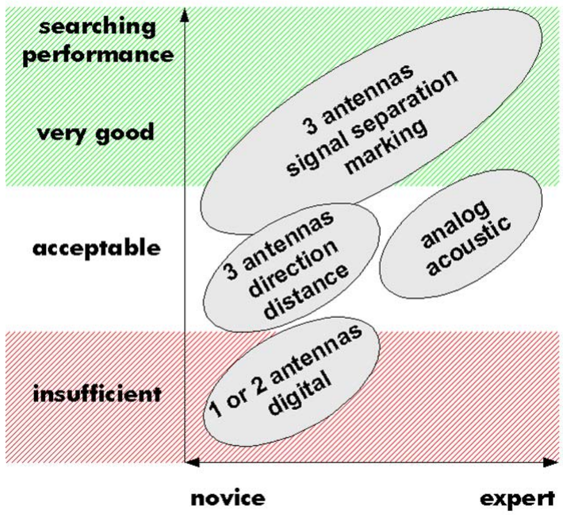

Figure 1: The searching performance depends on the skills of the searcher and the capabilities of the beacon. While experts can achieve very good results with conventional acoustic beacons, a novice should choose at least a digital 3-antenna beacon.

Clearly, from the average user we cannot expect regular training and highly skilled auditive capabilities. At best, this user has taken part in an avalanche training several years ago. At best, he read his beacon's user manual right after he had bought the beacon several years ago. We cannot expect the average user to refresh his knowledge on a regular basis (although he should!).

2.1 *Switching From Transmit to Receive Mode*

The real case starts with fondling the beacon out of its pocket and switching it to search mode. Firstly, the user must manage this process at all, and secondly, the searchers should be able to perform this action as quickly as possible.

Even successfully switching from transmit to search mode is not a trivial task. This is sadly documented by an accident near the Heidelberger Cottage in the Swiss Alpes (Swiss 1990). There three of a group of four were killed in an avalanche. The fourth person not affected by the avalanche failed to switch her beacon to search mode.

If there is a group of searchers, time counts. As long as at least one searcher's beacon is still operating in transmit mode, the others will most likely see his signal as the strongest one. The search cannot start before all searchers have accomplished the mode switch (Frema 2001).

Obviously, the operation of the transmit/search switch has to be (i) *intuitive*, (ii) *easy* and (iii) *unambiguous*.

Intuitive: Switching the beacon to search mode must be possible for anybody without reading the user manual. This is usually not the case if you *need to know* that you have to press a certain knob for a certain time.

Easy means, operating the knob or slider must be possible even with gloves, cold fingers and in a hostile environment. In simple words: The knob or slider has to be large enough.

It is *unambiguous* if the transmit/search switch does not have a second function, e.g. power on/off. The widely used slider off – transmit – search does not fulfill this requirement. Most likely searchers will frequently switch off the beacon instead of setting it to search mode – especially when exposed to mental stress.

Figure 2: The flip case: an intuitive, easy and unambiguous concept for the transmit/search mode switch.

A concept complying with all three requirements is a flip case (fig. 2). In the closed state, the beacon is transmitting. In the open state, it is in search mode. This concept is intuitive, because it is clear you need to open the case in order to use the display. It is easy, because the manual operation for opening a flip case is well known from mobile phones. It is unambiguous, since open and closed are two clearly different states, and it is obvious which one is used for searching.

Switching a beacon from transmit to search mode must be an intuitive, easy and unambiguous task.

2.2 The Mental Coach

In an athletics competition the audience often cheers for the athletes to maximize their performance. On contrast, in a real accident, nobody will cheer for firemen to work faster. The rescuers have to stay calm, control themselves and work rationally. The same is true for the search for buried comrades after an avalanche accident.

In the real case all communication of the beacon with the searcher should be designed to becalm the searcher, help him concentrate and efficiently use his time and his energy. While flashing displays and shrill beeping sounds look good in trial and training scenarios, they are mostly counter productive in the case of a real accident. In such a situation there is absolutely no need for the beacon to cause the searcher to produce additional adrenaline!

A calm and wary course of action is especially important during pinpointing. The searcher should move the beacon slowly, since distance readings cannot be updated faster than the pulse rate of the transmitter, which is usually between 0.7 s and 1.3 s. Moving the beacon too fast and hectically will decrease the precision of pinpointing and increase the time required to find the minimum.

In the real case, the role of the beacon is that of a coach who becalms the searcher and helps him to efficiently use his energy. The user interface of the beacon should never induce additional bustle.

2.3 Use the Play Instinct

A “good” user will buy a modern beacon, carefully read the manual, get acquainted with her beacon, visit a training, and regularly practice searching. This is the ideal case. Our average user will buy the beacon, skim through the manual, try the beacon a couple of times, and then use it for years without refreshing her skills. In the case of an accident the average user will have to remember what she found out playing with her new beacon years ago. While this is hard enough in everyday life, it can become a real challenge in a life or death situation.

From a beacon design point of view, there are two answers to this challenge. Firstly, using the beacon in search mode should be intuitive and easy. This has already been discussed above.

Secondly, the beacon itself can motivate the user to use it more frequently and keep some level of familiarity. The best mechanism to achieve this is to use the play instinct of the user. If the beacon offers additional – to some degree – “sexy” functions, the user will more often play with these functions. Note: The simplest and most effective way to learn is play!

While the applicable standards are restrictive concerning additional functionality in a beacon, it should be possible to open access to functionality that is required for the search process itself. For a modern beacon this can be a compass (used to track movements of the beacon during search) and a slope meter (used to compensate the compass once the beacon is not held exactly horizontally). Of course, a responsibly designed beacon will block access to those “play and learn” functions long before battery level goes low.

Providing “play and learn” functions motivates the user to use her beacon more frequently. The user will become more familiar with her beacon and feel more certain about the beacon's operation in the real case.

2.4 The Real Case: Focus on the Essentials

While using the play instinct can be a good strategy for training purposes, in the real case the user needs full concentration on the search process without any distraction by additional functionality.

Moreover, the beacon can actively support the searcher in various phases of the search process. Simple as is, at the start of the search a graphical display depicts a searcher moving along search strips. For an untrained, nervous user this can be a good anchor point to remember what he once had learnt.

Later on in the search process, the user must change his strategy moving from fine search to pinpointing. While during fine search he follows the magnetic field line, in pinpointing he strictly retains the orientation of the beacon and just moves slowly forth and back, left and right. The user interface of the beacon should clearly indicate this change of behavior!

During search, the communication of the beacon with the user should be reduced to the essential. However, the beacon should guide the user through the various phases of the search process.

3 MULTI-BURIAL SUPPORT

3.1 On the Relevance of Multiple Burials

In the past, accidents with more to many buried persons gained attention (e.g. Bauer 1989, Tiroler 2000) and led to the development of beacons actively supporting search in the presence of many transmitters. Very recently, Stopper (2007) raised doubts whether such situations really play a significant role. On the one hand, Genswein (2008) revealed several conceptual flaws in Stopper's study. On the other hand, we can simply state that adequate technology to resolve a multi-burial situation exists and works reliably in most situations. It is pretty hard to argue one should not use an existing technology just because it is said to be *unlikely* you really need it. Hopefully it is fairly *unlikely* you ever need your avalanche beacon at all.

3.2 <u>On the Relevance of Signal Separation</u>

Once multiple persons are buried, their beacons are simultaneously transmitting the typical pulsed 457 kHz signal. Randomly, the pulses from various transmitters will overlap in time. In signal theory this is known as interference (fig. 3).

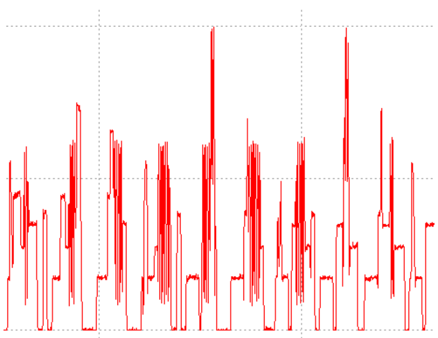

Figure 3: The effect of interference: Depending on the phase of the interfering signals, the total amplitude can be anywhere between the difference and the sum of the interfering signals' amplitudes. Two interfering signals of same strength can even extinguish each other!

Once two signals interfere at a receiving beacon, the measured amplitude (= distance) and phase (= direction) are influenced by both transmitters. If one signal is dominant (near) and the other is weak (far), this is not a problem and the interference can merely be ignored.

Due to the pulsed nature of the 457 kHz signal, pulses only interfere if they overlap in time. This frequently happens, and – even worse – such an overlap state (in rare cases) can last for several minutes (Lund 2007). A state-of -the-art beacon with signal separation will measure the individual signals while they do not overlap or overlap only partially. In periods of full overlap it will inform the user to stop and wait until the overlap state resolves. Although just standing and waiting is among the most unsatisfactory proposals a beacon can make to the user, it is the most efficient, time and resource saving action that can be taken in such a situation.

Conventional beacons not employing signal separation will take measurements regardless of any overlap and interference state. Those measurements will start to jump in distance and direction when the received signals amplitudes (field strengths) reach a ratio of 8:1 or less. The measurement will become completely useless if the amplitude relation reaches 2:1, i.e. the stronger signal has only double the strength of the weaker signal. Which part of the search process will be influenced by such an interference?

In fig. 4 the ratio of the stronger to the weaker signal is depicted for two transmitters located 7 m apart. The first transmitter's antenna is oriented parallel to the x-axis, the other one in an angle of 45°. The searcher would start at the upper left margin (at 0 m on x and y axes).

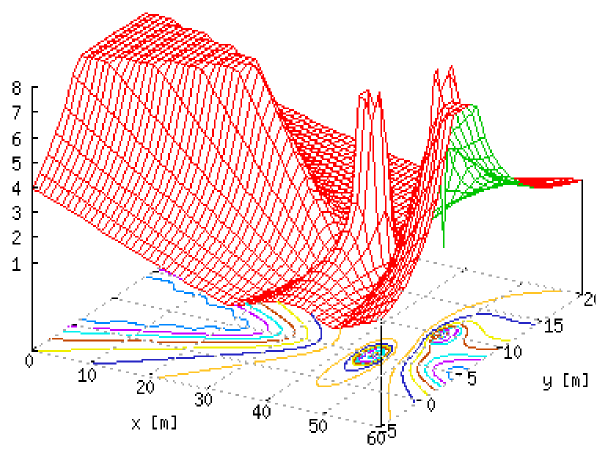

Figure 4: Amplitude ratio of the received signals of two transmitters located at (45m, 5m) and (50m, 10m). Ratios smaller than 8 lead to a noticeable flurry of distance and direction, 2 or less render the readout completely unusable.

Obviously, only a small area at the beginning of the search and the immediate proximity of the two transmitters are free of noticeable interference (dark shaded area in fig. 5; ratio strong : weak > 8). During the vast majority of the search a user of a beacon without signal separation will have to cope with misleading and randomly jumping distance and direction indications. Especially in a range of about 10 m around the transmitters interference is very high (light gray to white areas in fig. 5; ratio strong to weak < 2) and distance and direction readouts become useless during overlap.

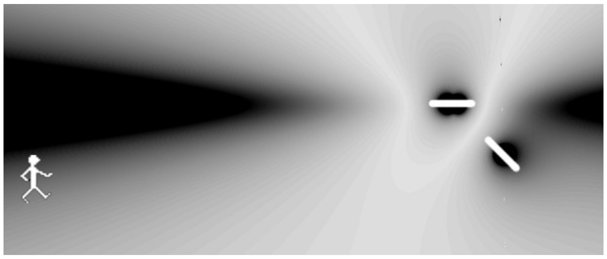

Figure 5: The two transmitters and the orientation of their antennas are marked on the right. Only the dark areas are free of noticeable interference. A searcher starting at left will have to cross large areas of significant interference. The graph spans 60 m horizontally.

In the dry words of an accident report (with two killed) this reads “*They had some trouble initially with the double signals but eventually were able to ...*” (Heinecken 2000). Bottom line this means that valuable minutes passed by while the rescuers tried to interpret unclear beacon readouts caused by interfering signals.

3.3 <u>Worst Case?</u>

The relative angles of the transmitting antennas in fig. 4 and 5 were chosen arbitrarily. A full investigation of the areas with and without interference for all possible antenna directions is beyond the scope of this paper. However, just turning the second antenna by 45° makes a remarkable difference, cf. fig. 6.

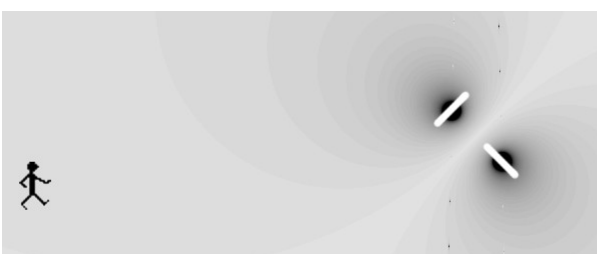

Figure 6: Now the second transmitting antenna is turned by 45°. The entire search area – except the immediate vicinity of the transmitters – is exposed to severe interference.

We can conclude that already two transmitters are sufficient to cover a large percentage of the search range with interference. Users with conventional beacons will have to cope with ambiguous, unstable distance and direction readouts. Following our machine-man team view, the beacon should give as much as possible support to clarify such a situation.

For an average-trained user, signal separation can significantly reduce confusion in multi-burial accidents and save valuable time.

3.4 <u>Marking</u>

Beacons capable of signal separation provide the ability to hide the signal of a buried person after she has been found.* So the searcher can concentrate on the remaining transmitters (fig. 7).

Using a simple beacon without signal separation, after pinpointing the first transmitter the searcher has to follow some (hopefully previously learnt) strategy. Usually it is recommended to walk away from the transmitter until the signal from the next buried person becomes stronger and the beacon 'locks' onto this stronger signal. Firstly, depending on the position and orientation of the transmitting beacons, several attempts might be necessary until a stronger signal is found and the searcher is no longer guided back to an already found one. Secondly, the searcher has to practice this strategy on a regular basis.

Figure 7: *Left* – The transmitter is pinpointed at 0.9 m depth. The user presses the MARK key. *Center* – The device acknowledges the MARK function. *Right* – The current transmitter is hidden, the next two buried persons in 8 m and 15 m distance, resp., are shown.

Signal separation with marking is able to shift the workload during the search process from the searcher towards the device. It helps even untrained searchers to successfully and quickly solve a multi-burial situation.

The marking function disburdens the searcher from applying a time-consuming strategy. It enables the untrained searcher to solve multi-burials using the same technique as used for single burials.

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* Other than Lund (2007) states, modern beacons can reliably mark a transmitter even during signal overlap. Lund's remarks are true for the first beacon available with marking capability only.

4 PINPOINTING

Pinpointing is the most time-consuming part of the search and deserves special attention.

4.1 User Interface

As stated before, pinpointing is very different from fine search. A beacon considered being part of a man-machine team should advert the searcher to this change in behavior as explicitly as possible.

Pinpointing means to move the beacon slowly in a strained posture, while observing the display and accordingly changing the direction of movement. This is a complex and – mentally and physically – demanding task. Viewing searcher and beacon as a team, the beacon should carry as much of the workload as possible in this phase.

Figure 8: Example of a pinpointing display with analog and numeric indication.

It is a well-known phenomenon that observing an analog display like a speedometer conserves different cognitive capacity than following a digital readout (e.g. Walter 1989). This is the main reason that speedometers in automobiles are still analog in the vast majority of cars. A graphical display in the beacon allows to support the searcher's cognitive system by a symbolic, analog representation of the remaining distance to the buried person.

Figure 8 shows an example of a combined analog/numerical display. The outer circle represents the current distance to the transmitter. It shrinks with decreasing distance. The inner circle stands for the smallest distance already reached. The four arrows in the corners show the tendency. Pointing outwards means increasing distance, pointing inwards decreasing distance. This concept offers communication elements for different cognitive types. Depending on his preferences, the user can work either with the numeric readout alone, or the symbolic indicators alone, or combine both pieces of information.

Pinpointing imposes high mental workload on the user. The beacon should offer assistance and support for different types of cognitive reception.

4.2 Antenna Orientation of a Buried Transmitter

Pinpointing a beacon buried in a depth of 2 m or more is a technical challenge. Other than in coarse and fine search, the three dimensional nature of magnetic field lines can no longer be neglected. For this reason, all state-of-the-art beacons are equipped with 3 antennas – two (x and y) for directional orientation during fine search, and a perpendicular one (z) to measure the vertical field component. Unfortunately, the strength of horizontal (x, y) and vertical (z) components depend heavily on the buried transmitter's vertical angle.

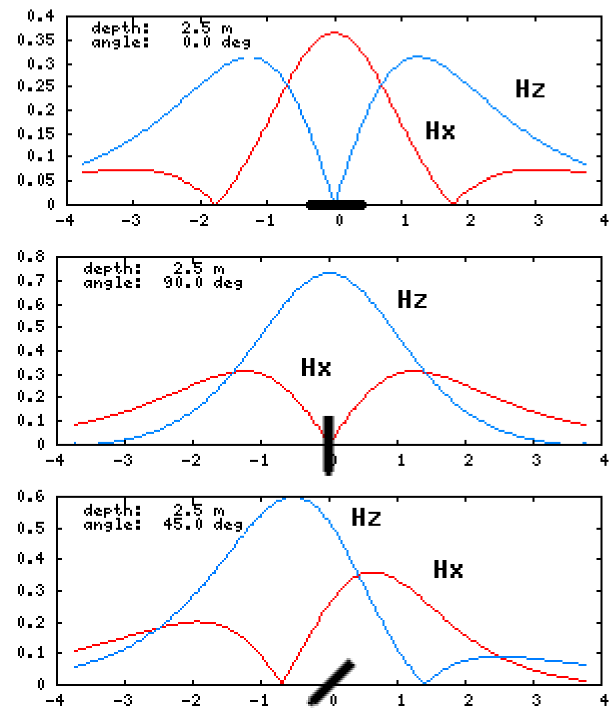

Figure 9: Horizontal (Hx) and vertical (Hz) field component while moving the receiver over the buried transmitter. The transmitter is at coordinate 0 in a depth of 2.5 m with an angle of 0° (top), 90° (center) and 45° (bottom).

While for a *horizontally* transmitting antenna the *horizontal* field component at the receiver shows its maximum exactly over the buried transmitter, for a *vertically* buried antenna the *vertical* field component exhibits a maximum at the same position (fig. 9, top and center). Conventional beacons with one or two antennas receive the horizontal field component only and leave the interpretation of minima and maxima to the searcher.

For any angle other than 0° or 90° it is a complex, but solved, task to compute the real distance from the searching beacon to the transmitter and hence find the correct position to start probing. The more accurate the position is determined by pinpointing, the less time is required for probing. Modern beacon technology allows to identify the position of the transmitter nearly independent of the transmitting antenna's orientation.

In pinpointing mode, the beacon should indicate the true position of the transmitter as accurate as possible, regardless of the orientation of the transmitter's antenna.

5 CONCLUSION

Avalanche beacons are safety devices and need to be optimized for the real case. For an optimum search result it is important to view the searcher and the beacon as a team. Even if a good training level of the searcher is highly desirable, we cannot take it as a prerequisite. As an important part of the team, the beacon's task is to disburden the searcher from whatever task possible, to becalm him and to coach him through the entire search process. State-of-the-art beacon technology like 3 antennas and signal separation shift workload from the searcher to the beacon. There is no reasonable argument to preclude searchers from available technology. A well-designed intuitive, easy to understand and unambiguous user interface helps even untrained and overly nervous users to accomplish complex search tasks.

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