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Survival chance optimized search strip width in avalanche rescue

Manuel Genswein [a,*], Ingrid Reiweger [b], Jürg Schweizer [b]

[a] General Willestr. 375, CH-8706, Meilen, Switzerland
[b] WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland

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ABSTRACT

When using transceivers (or avalanche beacons) to search for fully buried subjects, the search strategy depends on the signal search strip width which influences the search time until the first signal from the buried subjects can be received by the rescuer. The signal search strip width depends on technical characteristics of the avalanche rescue devices, the avalanche scenario as well as the rescuer's behavior. The larger the signal search strip width, the shorter is the search time and therefore the higher the survival chance of the buried subject. However, if the search strip width chosen is too large, the probability to miss a buried subject increases, which makes time-consuming multiple searches necessary — and decreases survival chances. Therefore, the search strip width needs to be optimized. We developed a simulation approach for the optimization of the search strip width which allows considering the many factors that affect the search and making realistic (rather than worst case) assumptions for their values. Our results suggest that the optimal signal search strip width is higher than previously assumed, that is – depending on the type of transceiver – about 1.2 to 1.4 times the realistic maximum range. In future applications, the simulation may be used to optimize a broad variety of search parameters or even entire search systems.

1. Introduction

Today most avalanche victims in Europe and North America are recreationists (e.g. Meister, 2002). When searching for a buried subject in an avalanche, the primary issue is time since survival chance decreases rapidly (e.g. Brugger et al., 2001). To locate fully buried subjects, electromagnetic transceivers are the method of choice, in particular in companion rescue. Organized rescue teams have additional search means, such as secondary radar (e.g. RECCO) or search dogs available. Transceivers allow a fast, reliable and efficient rescue — as they may be used immediately after the event has occurred.

The search strategy on the avalanche deposit depends on factors such as the number of rescuers available and on the range of the transceiver. This was recognized at the very beginning when the first devices that were able to transmit and receive electromagnetic signals were developed in the 1960s (e.g. Good, 1972).

The search strip width which is the lateral distance between individual rescuers, determines the area of avalanche debris that can be covered in a given time — given a certain search velocity. If the search strip width increases, the chances increase that a buried subject will not be detected (i.e. missed) when searching the debris area the first time, but if the subject is found it will be sooner than when using a narrow search strip width. In other words, the point is to optimize the chance of survival by finding an optimal search strip width (given a certain search speed). Therefore, the optimal search strip width is the result of solving an optimization problem.

Good (1972) illustrated the optimization problem with the two following extreme cases:

a) Probability of detection = 1: time → ∞: chance of survival = 0.
b) Chance of survival → 1: time → 0: probability of detection = 0.

It becomes obvious that the probability of detection cannot be 100%, since this would require a very narrow search strip width and therefore will increase the search time very much. In fact, all buried subjects would be found — but most likely dead.

In summary, the search strip width needs to be chosen to maximize the chances of survival. Some thoroughness needs to be sacrificed in order to decrease the search time. Consequently, there is no need to determine the minimal range which tends to be zero (see below) with the consequence that the chance of survival tends to be zero as well.

The principles on how to determine the search strip width based on measurement statistics were described shortly after the first transceivers came on the market (e.g. Good, 1987). Before the advent of digital transceivers towards the end of the 1990s it was common to use either 20 m or 40 m for the search strip width depending – one is tempted to say – on national tradition. The results of a comparative study on the performance of transceivers initiated by the International Commission of Alpine Rescue (ICAR) showed that the search strip width to be applied very much depended on the transceiver characteristics (Krüsi et al., 1998; Schweizer, 2000). Meier (2001) suggested a relatively simple method to approximate the search strip

* Corresponding author. Tel.: +41 79 236 36 76.
E-mail address: manuel@genswein.com (M. Genswein).

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width. A further test, particularly focusing on the search strip width, showed that the times when the search strip width was considered a universal constant in avalanche rescue were gone (Schweizer and Krüsi, 2003). Clearly, the search strip width has to be considered as a transceiver specific property which obviously complicates avalanche rescue training. However, this fact was often oversimplified by suggesting a search strip width of 40 m for analog transceivers and of 20 m for digital ones (e.g. Winkler et al., 2006; Tremper, 2001). Though, results obtained with a method proposed by Meier (2001) had clearly shown that the search strip width is not very much lower than the maximal range that can be obtained in co-axial antenna position. As the further generations of digital transceivers had improved range, a search strip width of 20 m was clearly too narrow — in other words not at all optimized on the survival chance.

The aim of this study is to present a novel simulation approach to obtain a survival optimized search strip width that takes into account the relevant factors that affect the search time based on realistic – rather than worst case – assumptions for these factors.

2. Methods

2.1. Previous approach

In the past, four different methods had been proposed to determine the search strip width based on range measurements. The methods were related to the fact that the electromagnetic field of a transmitting beacon at 457 kHz resembles the characteristics of a dipole in the near field (about ≤100 m), and that there are three typical antenna configurations between transmitting and receiving beacon (considering just one, the main and longest antenna which is most decisive for signal search): a) co-axial, b) parallel and c) perpendicular (for details see Meier, 2001). The range in the three positions decreases from a) to b) to c). In configuration c) the voltage induced in the antenna coil by the magnetic field of the transmitting beacon is theoretically zero due to the fact that all the field lines are perpendicular to the plane of the receiver antenna, i.e. the minimal range is by definition 0 m. In practice, even with only one antenna receiving, a few meters will always be measured due to 1) slight deviations from the exact perpendicular orientation causing very large changes of the received signal since it is proportional to the sine of the deviation and 2) spurious emissions by parts of the transmitter circuits other than the antenna itself. For theoretical reasons as well as for practical ones (inconsistent measurements with large dispersions), it hence does not make sense to determine the range of a transceiver in the perpendicular position.

Three of the four methods were described in Schweizer and Krüsi (2003). In the following we only shortly summarize the methods. (1) The first method requires a large number of range measurements with random antenna configuration (also called effective or usable range). In that case, the search strip width has been defined as twice the “98%”-effective range with the “98%”-range defined as $r_{98} = \bar{r} - 2\sigma$. (2) The second method is known as the “40%-rule” and will not be discussed here any further as it is completely outdated. (3) The third method was proposed by Meier (2001). The search strip width is based on measurements of the maximum range in co-axial antenna position and is equal to the “98%”-maximum range. The method takes into account adjustments for reduced performance due to factors such as a non-optimally aligned search beacon, low battery power or temperature effects. These assumptions yielded a ratio of effective range to maximum range of 0.5. (4) Occasionally in the past, and again more recently (e.g. Semmel and Stopper, 2007), it was tried to determine the search strip width by measuring the minimal range. Consequently, twice the minimal range would then be the search strip width. As shown above, this fourth method does not make sense – for theoretical and practical reasons – and will not be further discussed.

2.2. Simulation approach

It is obvious that very many factors affect the search time and hence the optimal choice of the search strip width. This has been exemplified by the method proposed by Meier (2001) — which was a considerable milestone and already led to higher search strip widths than presently used. However, all previous methods rely partly on worst case scenarios. Given the large number of factors and that the search strip width has to be survival chance optimized, a simulation approach seems most appropriate. This allows incorporating a vast amount of variables from different fields of influence with various dependencies between the input variables.

Table 1 summarizes the various variables that were considered for the simulation. In the following additional details and justifications for the choice of the distributions are given.

2.3. Rescuer dependent input variables

Rescuer dependent input variables show the performance of a rescuer. Performance may vary in many aspects: physical fitness (i.e. search velocity), level of training (i.e. awareness of the rescuer to rotate the receiver in 3d during signal search) and discipline (compliance of the rescuer with the rules during the rescue, for example, does the rotation of the receiver in signal search really include all three dimensions).

The search velocity is assumed to be 1 m/s during signal search and 0.5 m/s in coarse search.

Not all rescuers are aware of the necessity of the 3d-rotation of the receiver during signal search and out of those who are aware, not all comply in the full extent to the rules. However, some movement of the receiver always exists (±45°) while moving on the uneven surface of debris. The majority comes within 10–25° of the optimal rotation. Corresponding assumptions and consequences on the loss of range are shown in Fig. 1.

The systematic application of a given search strip width in the terrain requires the rescuer to be able to estimate absolute distances in an environment with low visual reference of any kind. The simulation does not take into account that rescuers may under or overestimate distances. However, extensive practical experience shows that overestimating distances is in this application environment by far more common than underestimating distances. In practice, this means that rescuers will in most cases apply search strip width narrower than they assume.

2.4. Receiver based input variables

Receiver based input variables show the technical performance of the receiver. Receiver sensitivity at 457 kHz, measured in the field based on the definition of realistic maximum range as well as tolerance towards frequency offset are examples for variables taken

Table 1
Variables entering the simulation.

Group of factor	Variables
Rescuer	Search velocity
	Suboptimal rotation of the receiving device in signal search
Receiving device	“Realistic” maximum mange
Transmitting device	Transmitted field strength
	Temperature of the transmitter
	Transmit frequency deviation
	Remaining battery capacity
Avalanche scenario	Deposit size
	Location of the buried subject
	Best possible transmitter orientation relative to center line of the search strip
	Fine search, probing and excavation time

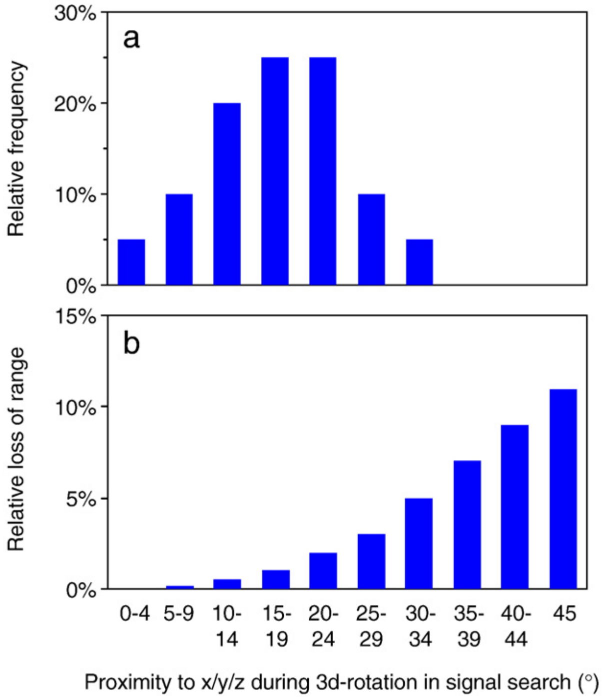

Fig. 1. (a) Frequency distribution for suboptimal 3d-rotation of the receiving device in signal search. (b) Corresponding loss of range due to suboptimal 3d-rotation of the receiving device.

into account. The key input variable is certainly the range of the receiving beacon. In the past, range was based on measurement statistics. We propose a new approach (Zurkirch, personal communication) and define the so-called "realistic maximum range" which fully characterizes the range of the receiving beacon. The realistic maximum range is technically measured and therefore free of human-specific influences such as quality of human hearing or concentration of the test person during measurements. Due to the very low acceptable interference level, measurements need to be done outside of a building, but with some battery driven measurement devices. The "realistic maximum range" is defined as follows:

(1) Test setting and transmitter: Transmitter at 457 kHz ($\pm$10 Hz) and 2.1 μA/m in 10 m distance, co-axial antenna orientation, interference free environment, no conducting parts nearby.
(2) Receiver setup: The measurement must be repeated with 10 receivers of the same brand and type. The mean value of the 10 results counts as the final result.
   (a) Analog receiver setup: Receiver in co-axial antenna orientation. Approach the transmitter to the point where technically measured signal-to-noise ratio is at least 6 dB. In practice, this means that there is a clearly audible, distinct search tone.
   (b) (i) Digital receiver setup for distance criterion: Receiver in co-axial antenna orientation (main antenna). Approach the transmitter to the point where during 5 subsequent minutes, 80% of the pulses are recognized and indicated in each one of the five 60 s windows. The variance of the indicated distance must not exceed $\pm$10% of the mean indicated distance.
   (ii) Digital receiver setup for direction criterion: Start at the distance evaluated as described above. Turn receiver 45° clockwise from co-axial position and turn it on. Then, turn on transmitter: Direction indications must be within $\pm$30° within 60 s. Turn receiver off. Repeat procedure by turning receiver 45° counter clockwise to co-axial orientation and turn on transmitter: Direction indications must be within $\pm$30° within 60 s.

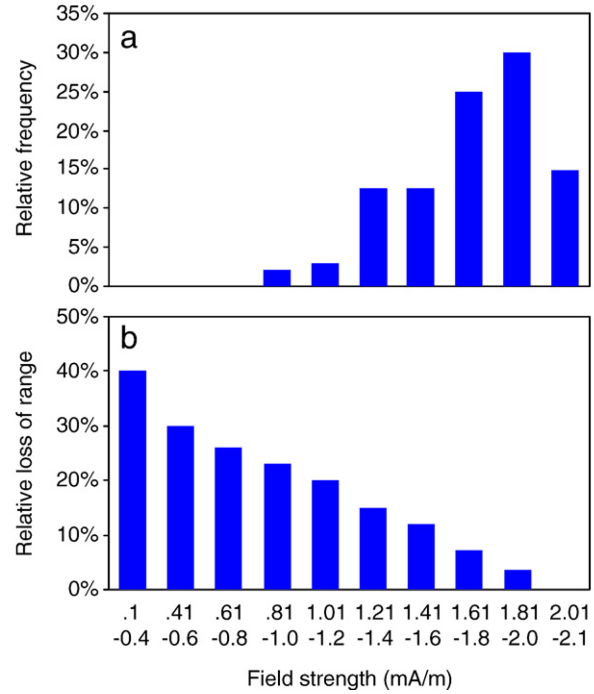

Fig. 2. (a) Frequency distribution of transmitted field strength. (b) Corresponding loss of range due to reduced transmitted field strength.

Values for the realistic maximum range tend to be lower than the maximum range values as measured with the method proposed by Meier (2001) as the signal-to-noise ratio of 6 dB used in the realistic maximum range definition is well above what human hearing of average test personnel requires to recognize the first signal.

2.5. Transmitter based input variables

Transmitter based input variables included the transmitted field strength (Fig. 2), the temperature of the transmitter (Fig. 3), the

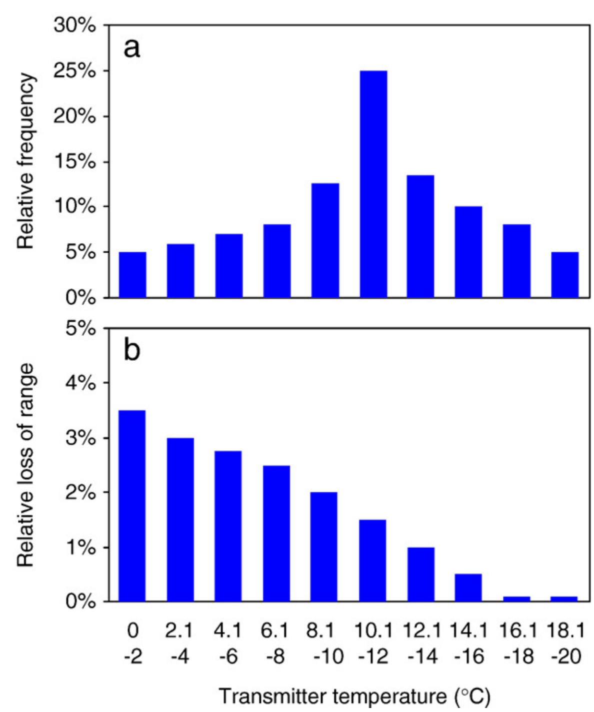

Fig. 3. (a) Frequency distribution of temperature of the transmitter. (b) Corresponding loss of range due to transmitter temperature.

frequency deviation of the transmitter (Fig. 4) (within the shown frequency range, receivers with digital signal processing (DSP) do not suffer from this effect) as well as the remaining battery capacity (Fig. 5) (valid for transmitters without constant output).

The distribution for transmitted field strength (Fig. 2) is based on measurements of devices in use and field strength of devices sold today. As the transmitted field strengths influences battery life, many manufacturers transmit a signal that is weaker than the maximal level of 2.1 mA/m defined by ETS 300718. Furthermore, the transmitted field strength may decrease over time due to deterioration of performance and precision of the electronic components.

The distribution for temperature of the transmitter (Fig. 3) is based on assumptions on carrying methods, clothing (insulation) and outside temperature profile. The temperature of the transmit frequency determining quartz crystal leads to a temperature depending offset from the nominal transmit frequency of 457 kHz resulting in loss of range for non-DSP devices with hardware preset receive filter characteristics.

The distribution for transmit frequency deviation (Fig. 4) is based on measurements of devices in use (service center statistics) and sold today. Transmit frequency deviation leads to loss of range for non-DSP devices with hardware preset receive filter characteristics.

The distribution of remaining battery capacity (Fig. 5) reflects experience of service centers. Loss of range reflects that the vast majority of avalanche rescue transceivers run the transmitter with the voltage supplied by the batteries without additional voltage stabilization. Dropping battery capacity of alkaline cells leads to dropping supply voltage for the transmitter and therefore to dropping transmitted field strength and shorter range. The internal resistance of alkaline cells greatly varies between products and even within production lots. Furthermore, internal resistance is temperature dependent. The fact that the devices are powered by consumer quality alkaline cells adds a considerable amount of uncertainty to some input variables.

2.6. Avalanche scenario dependent input variables

Avalanche scenario dependent input variables included size of the debris, position of the buried subjects within the debris and within the

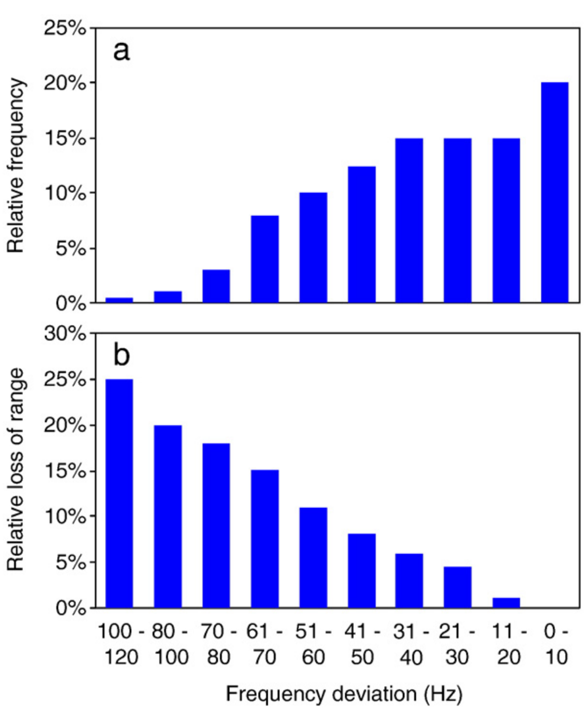

Fig. 4. (a) Frequency distribution of transmit frequency deviation. (b) Corresponding loss of range due to transmit frequency deviation (for non-DPS receivers only).

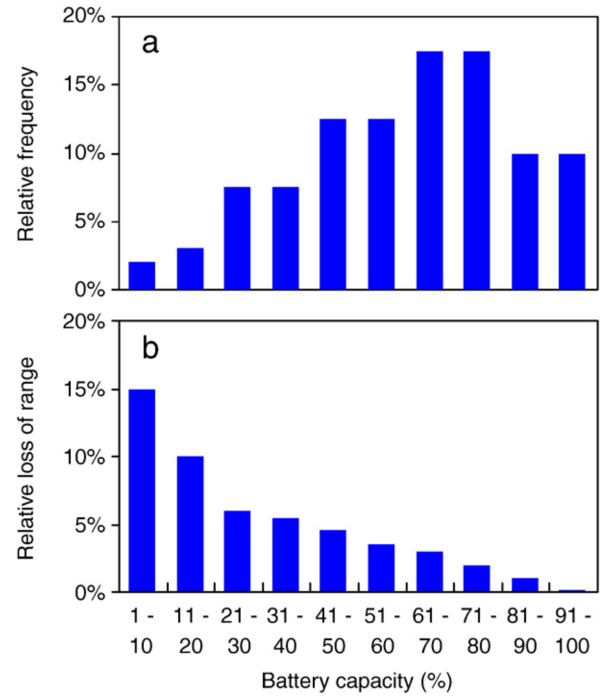

Fig. 5. (a) Frequency distribution of remaining battery capacity (transmitter). (b) Corresponding loss of range due to reduced battery capacity.

search strip as well as the orientation of the transmitting antenna on the deposit.

The size of the deposit is based on avalanche accident statistics from Switzerland (1970–1971 to 2005–2006) (Fig. 6). The deposit size from all recreational avalanche accidents in the SLF database was extracted where at least one person was fully buried (no visible parts). The median avalanche deposit size A in the sample ($N=267$) was 8400 m^2, with a range from 80 m^2 to 275,000 m^2. Three quarters of the avalanches had a size of less than 22,500 m^2, the lowest 25% were smaller than 2500 m^2. Hence, the sample contains very many small and a few very large avalanches — though it is representative.

The simulation randomly picked a deposit size and divided the area by the width of the search strip (A/a). Only deposits with $A \geq a^2/2$ were considered for the simulation. This assumption ensured that the combination of small debris size and large search strip width did not lead to unrealistically wide, but short search strips.

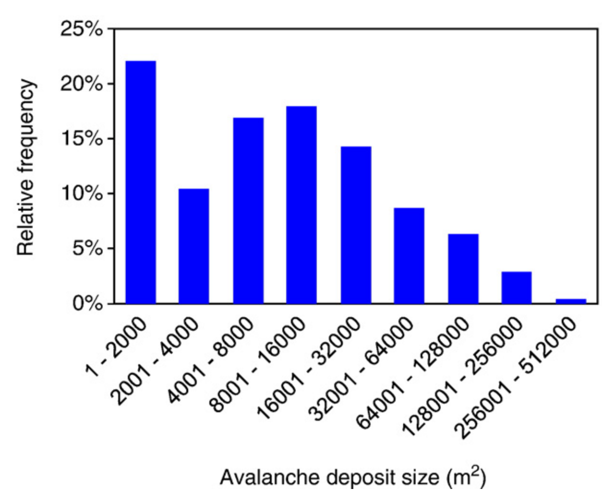

Fig. 6. Avalanche deposit size based on Swiss avalanche accident statistics ($N=267$).

As avalanche accidents statistics usually do not provide information on location of the buried subjects and as we do not want to make any assumption on the last seen point etc., we have assumed that the buried subjects can be buried anywhere in the deposit (uniform distribution).

For the best possible transmitter orientation relative to the center line of the search strip we assume that in two thirds of the cases at least parallel coupling can be reached (Fig. 7). For DSP devices with two receiving antennas active during signal search, in one third of the cases at least parallel coupling can be reached.

Times for fine search, probing and excavation were considered in the simulation. Whereas signal search and coarse search were implemented as part of the simulated transceiver related search times, the fine search, probing and the excavation process was taken into account by a fixed 15 min addition to the transceiver search times. This is a realistic value taking into account that the median burial depth for completely buried avalanche victims is about 100 cm (Harvey and Zweifel, 2008).

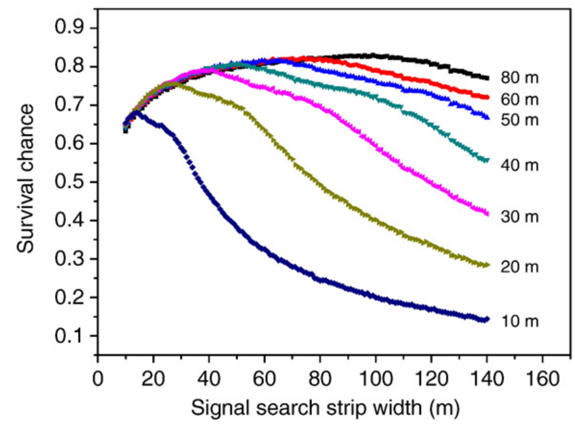

Fig. 8. Results of simulation showing survival chance as a function of the search strip width for different values of the realistic maximum range for a transceiver without DSP.

2.7. Survival chance as a function of burial time

Based on the survival chance for buried subjects in the backcountry as a function of burial time (Brugger et al., 2001), it was decided whether the subject was alive or deceased at the end of the simulated rescue time.

2.8. Multiple searches

If the search of the debris with the initially applied signal search strip width did not lead to success, the debris needed to be searched again by cutting the value for the search strip width in half. This approach of applying a finer search pattern in case of an unsuccessful initial search is widely accepted in avalanche rescue and applied for decades in probe line search strategies.

In case multiple searches became necessary, the simulation included a strong decrease of the rescuer's performance reflecting the decrease of physical performance and motivation usually associated with this occurrence. This was implemented by reducing the search velocity by 0.6 during the second search and by limiting the number of searches to 2. Therefore, the proposed values for a survival chance optimized signal search strip width make it very unlikely that the rescuer ever needs to search the debris more than once.

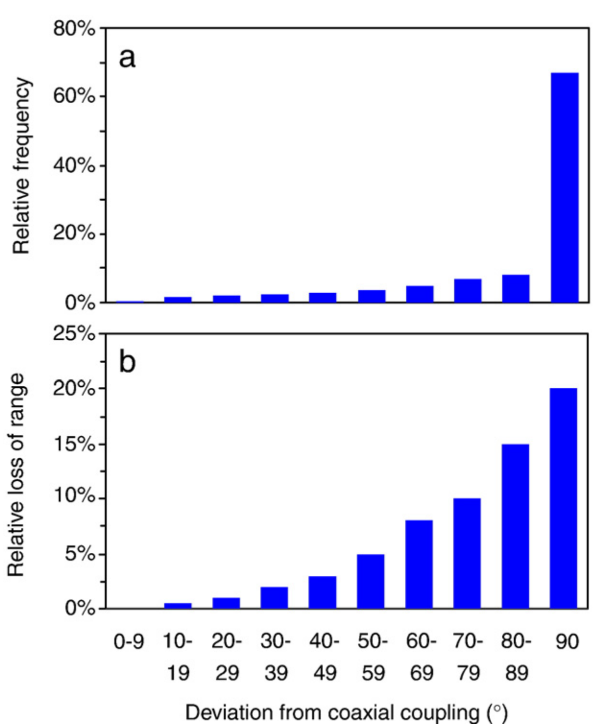

Fig. 7. (a) Frequency distribution of best possible transmitter orientation relative to center line of the search strip. (b) Corresponding loss of range due to transmitter orientation.

2.9. Simulation procedure

Based on a given realistic maximum range (which can be varied) and assuming a certain initial search strip width (e.g. 10 m) the rescue time was simulated, and evaluated whether the subject was still alive or deceased (according to the survival curve). This procedure was then repeated 80,000 times, with different values for the various variables randomly chosen according to the distributions shown above. Within this sample then all possible combinations (also worst cases) existed according to their frequency. Finally, we obtained for a given realistic maximum range and a given search strip width the average survival chance.

The search strip width was then increased continuously (still for the same realistic maximum range) and the above procedure was repeated. At the end, we obtained the survival chance for a given maximum range as a function of the search strip width. The curve will show a maximum which will indicate the optimal search strip width for a device with a given realistic maximum range. The whole procedure was then repeated for different values of the realistic maximum range.

We simulated three different receivers: (a) a device without digital signal processing (non-DSP), (b) a device with digital signal processing and one antenna on receive during signal search (DSP1), and (c) a device with digital signal processing and two antennas on receive during signal search (DSP2). The DSP devices do not suffer from a loss of range due to a frequency deviation of the transmitter, whereas the non-DSP device does. With a DSP2 device a more optimal coupling position can be achieved than with a DSP1 device (Table 1, Fig. 7). Accordingly, the corresponding loss of range is reduced with a DSP2 device.

3. Results

The simulation allows calculating the survival chance optimized signal search strip width for any avalanche rescue transceiver with a given realistic maximum range (as determined above).

Fig. 8 shows the survival chances of the buried subject as a function of the search strip width for various values of the realistic maximum range for a non-DSP device. For each curve (corresponding to a given realistic maximum range) a maximum exists. The maximum indicates the width of the signal search strip for which the survival chance is

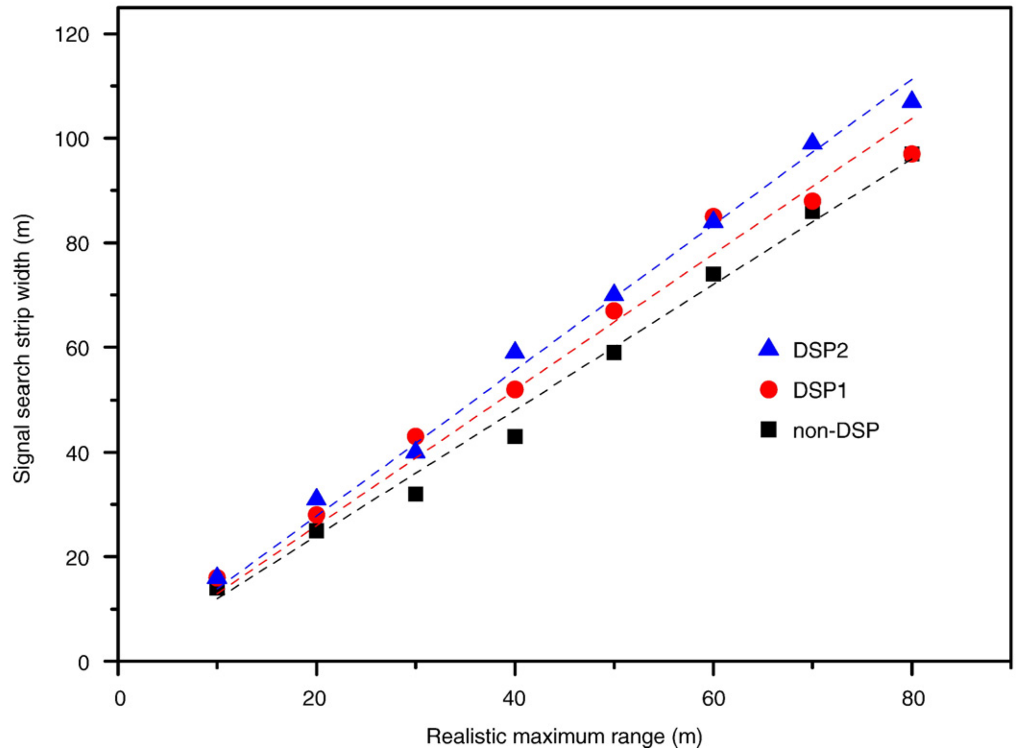

Fig. 9. Optimal signal search strip vs. realistic maximum range for a transceiver without DSP (non-DSP), a transceiver with one receiving antenna (DSP1) and with two receiving antennas (DSP2) during signal search. Dashed lines indicate linear fit.

greatest (or the mortality lowest). As can be seen, for example for a realistic maximum range of 50 m, the optimal search strip width was about 60 m.

The maximum values are compiled in Fig. 9 for all three types of receiving devices simulated (non-DSP, DSP1 and DSP2). The optimal search strip width increased with increasing realistic maximum range. The slope (± standard error) was about 1.20 ± 0.020, 1.30 ± 0.031 and 1.39 ± 0.019, for non-DSP, DSP1 and DSP2 devices, respectively.

In Fig. 10 the effect of the realistic maximum range on the survival chance is shown for all three devices simulated. The survival chance

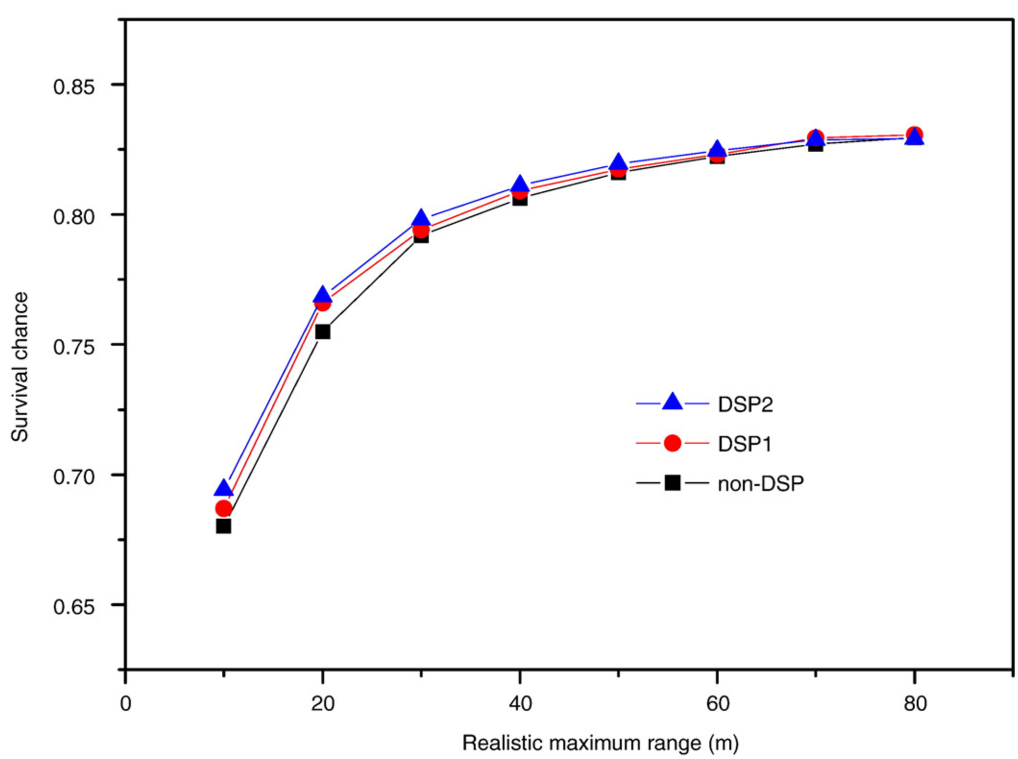

Fig. 10. Effect of realistic maximum range on survival chance for the three different transceivers simulated (see Fig. 9).

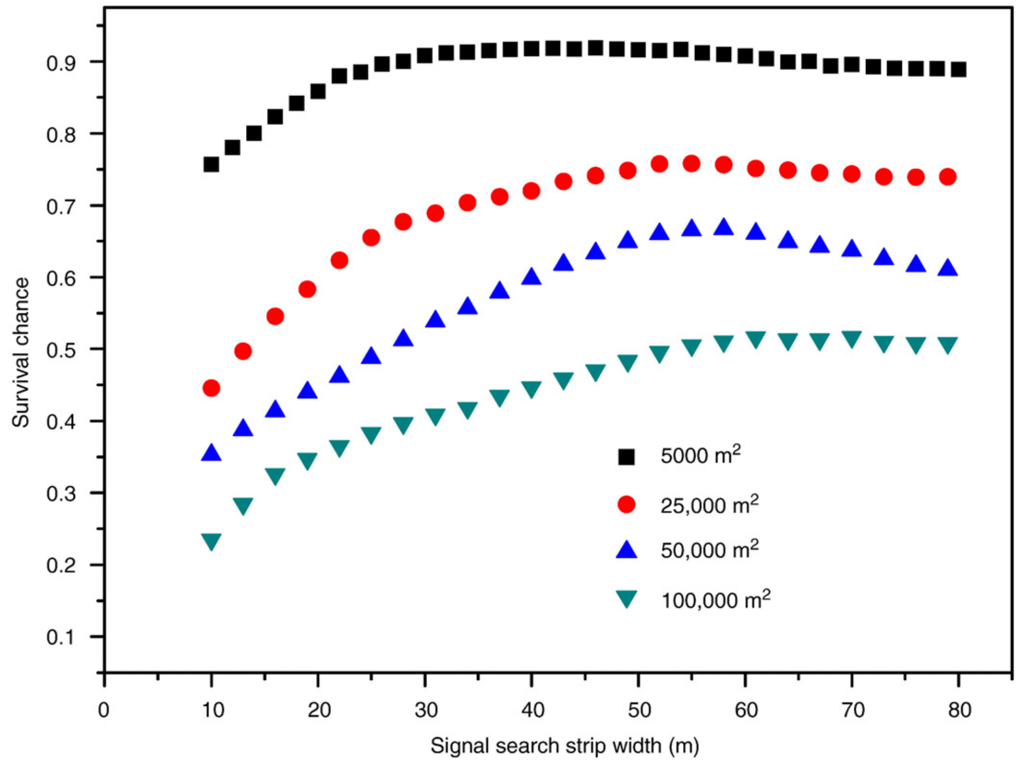

Fig. 11. Effect of avalanche deposit size on optimal search strip width for four different avalanche deposit sizes. Simulated transceiver is a DSP device with a realistic maximum range of 40 m.

increased with increasing range of the device indicating that a beacon with a large range allowed short search times due to a large search strip width. For example, for a non-DSP receiver with a realistic maximum range of 20 m the mortality was about one third higher than for a receiver with 50 m realistic maximum range.

4. Discussion

The avalanche deposit size distribution contains many small avalanches. On very large avalanche deposits the optimal search strip width is therefore slightly larger. However, it seems not practical to make the search strip width dependent on avalanche size. Fig. 11 shows the optimal search strip width for increasing avalanche size.

In most cases with a median deposit size of 8400 m^2 corresponding to a square of about 92 m×92 m the search strip width is not a big issue if the rescuers have some hints where the subject might be buried (e.g. if the last seen point is known).

For a receiver with digital signal processing the optimized signal search strip width was about 8% larger than for a non-DSP device. The wider tolerance of receivers with digital signal processing towards transmitters with a frequency offset seems to be important.

The 3d-rotation of the receiving device is important for all devices with antennas of considerably different lengths. If all rescuers would perfectly rotate the device in all three dimensions, the signal search strip width would be approx. 10% higher. On the contrary, if everybody would stop at all with actively rotating the device in all three dimensions so that only the unintended movement of the device due to the progress of the rescuer on the uneven avalanche debris would be left, the signal search strip width would have to be approx. 10–15% smaller.

The more antennas a receiver has (up to three) and the more simultaneously all antennas are (technically) receiving in the signal search phase, the more error tolerant is the receiver towards rescuers who do not optimally rotate the device in all three dimensions. Only a receiver with three antennas of the same sensitivity simultaneously on receive at all times completely eliminates the necessity of the 3d-rotation. Such devices are today only applied in 3d external antennas for helicopter based transceiver search.

The shorter the realistic maximum range, the greater is the gradient of decline of survival chances (Fig. 10) and therefore error tolerance for underestimating distances (i.e. the search strip width) in the field rapidly decreases. On the other hand, if a rescuer using a transceiver with a realistic maximum range larger than about 50 m, under- or overestimates the search strip width, the effect on the survival chance is minimal.

Compared with the methods proposed by Meier (2001) or Good (1987), the simulation based approach takes a by far wider range of influencing variables into account. However, whereas the previous methods applied constant penalty factors for the range reducing factors, the simulation tries to reflect for each parameter as closely as possible the real situation in the field, where accumulations of negative only factors have a very low probability.

With the simulation approach, the search strip widths were somewhat larger than the ones that can be determined with the method by Meier (2001). Whereas the values for maximum range as determined by Meier (2001) are some greater than our “realistic maximum range”, his rather conservative assumptions for the remaining parameters led to a multiplier of 1 compared to the 1.2 (non-DSP), 1.3 (DSP1) or about 1.4 (DSP2) multipliers. Consequently, our survival change optimized assumptions yielded an overall somewhat larger search strip width. So the results of the two methods are comparable, but the simulation approach is more comprehensive and does not require time-consuming and partly subjective field tests. In addition, our approach optimizes the signal search strip width based on highest possible chances of survival.

To further validate the simulation we did a sensitivity study for a number of variables that enter the simulation: the maximum number of multiple searches, the signal search velocity, the penalty factor for multiple searches and the time for fine search, probing and excavation.

A lower/higher number of searches led to a significant decrease/increase of the survival chance for small ranges and large search strip widths. However, in the relevant range of the search strip width, i.e. around the maximum survival chance, the survival chance hardly changed, and moreover the position of the maximum did not change. Consequently, the optimal search strip width for a given realistic maximum range did not depend on the number of searches.

Decreasing the signal search velocity from 2 m/s to 0.5 m/s reduced the average maximum survival chance from 0.86 to 0.7 (averaged over all ranges). Yet the position of the maximum, i.e. the optimal search strip width for a given realistic maximum range, stayed the same.

As for the number of searches, the penalty factor for multiple searches affected the survival chance for small ranges and large search strip widths, but not in the relevant region. Note that the maximal survival chance was reached if the rescuer found the buried subject during his first signal search; this result is independent of the penalty factor.

Finally, the survival chance decreased considerably, that is from 0.85 to 0.6 (averaged over all ranges) if the time for fine search, probing and digging out the buried subject increased from 10 min to 20 min. Again, the position of the maximum survival chance for different realistic maximum ranges was not influenced by the time for fine search, probing and digging.

5. Conclusions

We have presented a novel approach to determine a survival optimized signal search strip width. The simulation showed that survival chance optimized values for the signal search strip are about 20–40% larger than the realistic maximum range — depending on technical characteristics of the receiver. The location of the maximum survival chance for a given realistic maximum range was not sensitive to some of the key input variables, whereas the survival chance itself did depend on those variables.

The values for the survival chance optimized search strip width were considerably larger than the standard recommendations within many countries and organizations. Narrowing the signal search strip width below the proposed values leads to an increase of the average signal search time and therefore directly reduces the survival chances of the buried subjects. We therefore recommend re-assessing the present usage of the signal search strip width.

Currently, the simulation is focused on optimizing the survival chance optimized signal search strip width. However, in future applications, the simulation may be used to optimize a broad variety of search parameters or even entire search systems.

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