


# The use of the vibroacoustic system for determining the range of a ski jump for training athletes

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## ABSTRACT

The principle of vibroacoustic systems operation for determining the distance of a ski jump from a springboard, the possible location of sensors on the springboard and sensor signals that occur when athlete lands are considered. The problems of calculating the jump distance and methods for solving these problems are described. The interrelation of the technique of performing a jump (the spatial position of the skis at the time of landing and the normal component of the landing speed relative to the surface of the springboard) with the form of sensor signals is considered. Real waveforms of signals obtained both during the summer artificial covering of the springboard and in winter, as well as generalized results of experimental operation of the system on springboards with different heights of the acceleration mountain are presented. It is shown that the use of vibroacoustic systems allows achieving the required accuracy of determining the ski jump distance – 0.5 m, and the integration of the system with the general jump monitoring system opens up new opportunities for independent training of athletes and training of a group of athletes under the guidance of a coach.

**Keywords:** Performance analysis of sport, Physical conditioning, Ski jumping, Jump technique, Jump parameters, Sensor location, Digital signal processing.

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## INTRODUCTION

The first attempts to create an automated system for determining the distance of a ski jump from a ski jump were made long before the advent of video recording and video image processing systems. Such systems usually consisted of several sensors located on the landing mount and a signal processing device, in particular, either magnetic or acoustic sensors were used, as, for example, in (Bychkov and Aronov, 1993). When using acoustic sensors, the principle of operation was based on measuring the delay time of the signal that occurs when a skier lands in various acoustic sensors and calculating the distance to the landing point based on their obtained delay time values by analogy with the geodetic triangulation method.

However, in many cases it was not possible to achieve the accuracy required by the International Ski Federation (FIS) (International ski federation, 2018) to determine the jump distance due to the reasons described below.

1. The speed of sound in different materials used in the surface structure of springboard is different. Velocity of acoustic wave propagation depends on the density and humidity of snow and the geometrical form of snowflakes.
2. A skier of an athlete is not a point source of acoustic wave.
3. The strongest acoustic signal is not always corresponding to the position of the foot of a skier.
4. A long and powerful acoustic signal can occur when the end of the ski touches the surface of the springboard before the skier lands.

These reasons are discussed in more detail in (Kiesewetter, Korotkov, Malyugin, 2015 – Kiesewetter et al, 2016).

The problem of determining the speed of sound propagation in the surface of the springboard is partially solved by using a calibration source of an acoustic signal placed under the surface of the springboard (Slavskii, 2011). However, the use of such devices does not eliminate the remaining problems of determining the jump range mentioned above. Therefore, systems with the determination of the skier's landing point by the signal delay in various sensors are first-generation systems. Other technical solutions are also known, for example, the US patent (US Patent 4089057, 1978), in which impact sensors are supplemented with a laser system.

It is possible to achieve the required accuracy of determining the jump distance (0.5 m) by using a large number of sensors located in one line or in the form of several parallel lines from the top of the landing mountain to its bottom. The specified accuracy can be achieved at the distance between the  $L_d$  sensors of 1 m or less. The measurement accuracy increases, and the probability of error decreases at the distance  $L_d$  equal to 0.5 m. The technical problems of organizing the data collection from sensors and the integration of the vibroacoustic system into the general monitoring system for ski jumping are considered in (Kiesewetter, Korotkov, Malyugin, 2015 –Kiesewetter et al, 2016). There are various technical solutions for the design of such a system, which depend on the type of sensors used. Studies carried out on several trampolines have shown that a good result can be obtained either using accelerometers or fibre-optic sensors installed perpendicular to the direction of movement of athletes when landing with an interval of 0.5 ... 1 m.

## METHODS

The method of signal processing in such systems differs significantly from the method used in first-generation systems. The presence of a large number of sensors allows us to base the calculations of the jump range on

the sequence and waveforms that occur in the sensors, and then, if necessary, refine or verify the obtained value using the measured signal delay times.

Typical signals from sensors when skier lands are given, in particular, in (Kiesewetter, Korotkov, Malyugin, 2015). It is obvious that the waveforms of the signals (signal shape, amplitude, etc. parameters) depend on the technique of performing the jump and landing of the athlete. Currently, there is no information in scientific papers about the influence of the technique of performing a ski jump on the signal parameters. Understanding the main trends will improve the quality of signal processing to determine the jump distance, and vice versa – use the calculated parameters of the signals to obtain objective quantitative parameters of the jump technique.

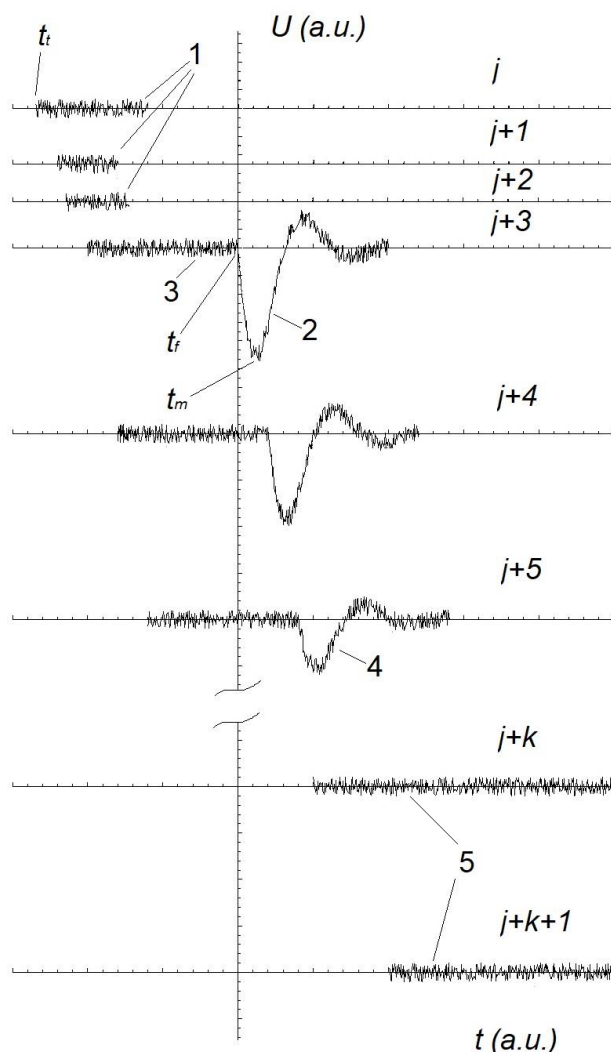


Figure 1. Schematic representation of waveforms, along the abscissa axis-time in relative units, along the ordinate axis-the voltage at the output of the sensors in relative units; types of signals: 1 – noise caused by touching the end of the ski before landing, 2 – signal by elastic deformation of the springboard cover under the action of the athlete's foot, 3 – noise caused by the impact of the ski at the time of landing, 4 – the signal 2 modified during the propagation of an acoustic wave, 5 – noise caused by sliding skis on the springboard cover.

Let us consider the waveforms of sensor signals in more detail, taking into account the main phases of the skier's landing, noted in (Kiesewetter, Korotkov, Malugin, 2015; Kiesewetter et al, 2016). It is convenient to consider the waveforms in the following form: on one graph there are several waveforms from different sensors, the waveforms on the graph are shifted along the ordinate axis in such a way that the waveform corresponding to the sensor located above all on the landing mountain is also displayed on the graph above all, and the waveforms of signals from sensors located below are shifted down on the graph; along the abscissa – time axis, the beginning of all waveforms corresponds to the same moment in time (i.e. the signals are synchronized).

To explain the main patterns, it is convenient to use schematic, rather than real waveforms of signals that display only the considered patterns and do not take into account secondary effects. An example of schematically depicted waveforms for the case when a skier touches the surface of the springboard with the end of the ski before landing is shown in Figure 1.

In general, we will assume that the first touch was recorded by the sensor with the number  $j$ , and we will denote the moment of touch time as  $t_j$ . In Figure 1, the areas of the waveforms 1 correspond to the noise that occurs when the end of the ski (or both skis) moves along the surface of the ski jump coating. The standard square amplitude of noise when touching the summer surface of the springboard is significantly greater than when touching the winter surface – i.e. snow, which must be taken into account when implementing the system hardware and in the signal processing software used. The signal corresponding to the moment of landing of the skier, that is, the touch of the athlete's foot on the springboard surface, is indicated in Figure 1 as number 2. The signal appears in the sensor with the number  $j+3$ ; the corresponding moment of time is indicated as  $t_k$ . At this point in time, the skier's foot begins to create compression of the ski jump cover, which leads to acceleration of the accelerometer module. Since the springboard coating is springy, i.e. it has the property of elastic deformation, relaxation begins at the time  $t_m$  (Figure 1) and vibrations of the springboard coating occur. In some cases, there are also fluctuations in the entire design of the springboard near the landing site of the athlete.

The duration of the athlete's flight  $\Delta t_k$  from the moment the end of the ski touches the landing is equal to the value  $t_j - t_k$ . The area of overlap of signals 1 in neighbouring sensors, as well as the shape of the envelope of signal 1, depends on the design of the springboard cover. Touching the surface of the springboard with the end of the ski leads to decrease in the longitudinal component of the athlete's flight speed, respectively, to a decrease in the jump range, i.e. to a deterioration in the sports result. The value of  $\Delta t_k$  is an objective quantitative assessment of one of the parameters of the quality of the jump, which can be measured using vibration-acoustic sensors more accurately than using a video fixation system, since at a small distance from the end of the ski to the surface of the springboard (a few centimetres or less), the video fixation system may not be effective. In the case of intermittent touch, an updated value of  $\Delta t_k$  can be used for an objective assessment of the jump quality, taking into account the total touch time, which is difficult to obtain by processing the video image, especially since the existing software does not allow determining this value.

If the athlete's feet touch the surface of the springboard exactly above the sensor (in this example, above the sensor with the number  $j+3$ ), then the jump distance is determined by the position of the corresponding sensor on the landing mountain; no additional adjustment of this value is required. A signal similar to the signal that occurs when a skier lands occurs in the next sensor located below (in this example, in the sensor with the number  $j+4$ ), but the signal amplitude is less than in the sensor  $j+3$ . This signal is caused by fluctuations in the surface and structures of the springboard, as well as the impact of skis on the surface of the springboard immediately after landing and during the initial phase of sliding. A signal similar to signal 2, but with a

significantly lower amplitude, is also observed in other sensors. The signal is caused by the propagation of an acoustic wave caused by the skier landing. The further away a sensor is located from the sensor over which the skier's foot landed, the greater the signal delay value. Figure 1 shows only the waveform of the sensor signal with the number  $j+5$  as an example. Signals similar to signal 2 also occur in sensors located on the landing mountain above the athlete's landing site. In Figure 1, these are sensors with the numbers  $j$ ,  $j+1$  and  $j+2$ . However, the signals of these sensors are usually significantly weaker than the signals of sensors located below the landing site, since the acoustic compression wave has the direction towards the bottom of the landing mountain along the surface of the springboard. Therefore, these signals are not shown in Figure 1.

If the place of landing of the skier's foot is located between two sensors, then the specified value of the jump distance can be obtained by interpolation-extrapolation of the dependence of the characteristic points of signal 2 (the beginning, maximum and transition through zero of signal 2) on the distance (in fact, the location of the sensors). This approach allows you to determine the distance of an athlete's jump with an accuracy exceeding the distance between the sensors. Theoretically, if the distance between the sensors is 1 m, the estimated jump distance can be determined with an accuracy of better than 0.1 m, which is less than the length of the athlete's shoe. In this case, the obtained value is not related to any area of the athlete's shoe sole but is the result of numerical processing of signals arising from the conditionally integral impact of the athlete's foot.

Signal 2 in the sensor  $j+3$ , as well as  $j+4$ , can be preceded by signal 3, similar to signal 1, but more powerful, due to the impact of the entire surface of the athlete's skis when landing. Signal 3 can continue after the termination of signal 2, which is due to a later touch of the front ends of the skis on the springboard surface and their oscillation. The noise signal and some deformation of the springboard surface caused by this reason occur for the sensor located above the sensor  $j+3$ , i.e.  $j+2$ . However, such signal does not carry useful information and is not shown in Figure 1.

The maximum signal amplitude 2 ( $U_{2max}$ ) reached at time  $t_m$  (Figure 1), which is the maximum acceleration value of the sensor, depends on the speed of approach of the athlete's foot to the surface of the springboard, the athlete's mass and the duration of the impact associated with the longitudinal speed of the athlete's movement, as well as with the terrain of the landing mountain. The value of  $U_{2max}$  is associated with the technique of performing a jump, but what value is optimal for achieving the best sports result is currently unknown. It can also be assumed that information about the average value of  $U_{2max}$  will help coaches (or referees) make the right choice of the starting point on the acceleration mountain. It should be noted that it is impossible to determine the maximum acceleration of the sensor or the parameters of the deformation of the springboard surface at the moment of landing of the athlete using the video fixation system.

When an athlete's skis slide on the surface of the springboard, a noise signal also occurs, indicated in Figure 1 by the number 5. The sensor signal with the number  $j+k+1$  is partially depicted. Using these signals, it is possible to estimate the longitudinal sliding speed of an athlete on a springboard, determine the place of the athlete's fall, if such an event occurs, etc. However, this signal does not carry any useful information about the technique of performing a ski jump, so it is not considered further.

The algorithm for determining the jump distance for the case of different distances of the athlete's legs at the time of landing, including with a certain time delay, is somewhat more complicated. The signal form 2 may differ from the typical signal form shown in Figure 1, and in this case the signals themselves occur in two sensors at once, and these may not be neighbouring sensors. The most difficult case for determining the

jump distance is the case of an athlete landing first on one leg, and then, with a significant delay, on the other leg. Then it is necessary to pre-divide the signals into two time intervals, in each of which the above-mentioned digital signal processing algorithm should be used. Currently, the method of processing such signals is being improved.

The use of sensors located in a line in the middle of the landing mountain may not be enough to achieve the accuracy of determining the jump distance of 0.5 m on trampolines with a wide landing mountain and a high acceleration mountain. In this case, it is advisable to use several sensor lines simultaneously (as, for example, in (Kiesewetter, Korotkov, Malyugin, 2015)) or fibre-optic sensors installed perpendicular to the landing mountain (Kiesewetter et al, 2016). Since the principle of operation of fibre-optic sensors is based on registering the deformation of the fibre, and not measuring acceleration, the signal processing algorithm for determining the jump distance in such system becomes more complicated, but the essence of the method is preserved.

## RESULTS

A vibroacoustic system for determining the distance of a ski jump, integrated into the general monitoring system, was installed on the K-40 and K-75 springboards in the village of Toksovo, Leningrad region, Russia. These jumps were not equipped with a permanent video recording system with the ability to determine the distance of the athlete's jump. On each springboard, the monitoring system contained the vibroacoustic system for determining the jump distance, the wind speed and direction sensor, the device for measuring the velocity of an athlete on the acceleration mountain before performing a jump, the synchronization system, the server, the remote start control system, the data collection system from judges' consoles (or computers) and information display devices – a start and information scoreboard. Analog accelerometers with the multi-channel analog-to-digital converter and the data transmission system to the server were used as sensors. The sensors were arranged in the line in the middle of the landing mountain with the interval of 1 m. The interaction of these parts of the system is described in detail in (Kiesewetter, Korotkov, Malyugin, 2015).

As an example, Figure 2 shows real waveforms of signals when an athlete lands on the summer surface of the springboard. The second waveform from above (blue) corresponds to the place of landing of the athlete: it has a typical shape (indicated in Figure 1 as 2) with superimposed noise. The waveform 1 in Figure 2 (red) contains only noise and a signal caused by the waveform of the springboard structure. The waveform 3 (green) has a shape similar to the shape of the waveform 2. The subsequent waveforms 4 and further have a shape different from the typical waveform caused by the skier's foot touching the surface of the springboard. Waveforms 5 and further have a significant delay of the specified signal, as well as a change in its shape due to the high attenuation coefficient of the high-frequency part of the acoustic wave spectrum. The noises caused by the athlete's skis sliding on the surface of the ski jump cover (duration of approximately 0.2 seconds) have a time offset increasing with the sensor number. In the given example, the first waveform was not preceded by signals from sensors located higher on the landing mountain. That is, the given waveforms correspond to the technique of performing a jump, in which the athlete in flight and before landing does not touch the surface of the springboard with the end of the skis. The spread of the  $U_{2max}$  value indicated above for various jumps was almost one order of magnitude.

Typical waveforms of sensor signals obtained in winter with snow covering the springboard are shown in the Figure 3. The waveforms presented in Figure 3 are shown on the same scale as in Figure 2 in order to facilitate their comparison. It follows from the data obtained that the signals are significantly weaker. The amplitude of the signals can be increased by increasing the gain of the analog-to-digital converter, performed



using existing software. It can be expected that the amplitude of the signals will depend on the thickness of the snow cover, the density and humidity of the snow, and other factors. However, the general patterns discussed earlier are preserved, which allows using the same algorithm for digital signal processing.

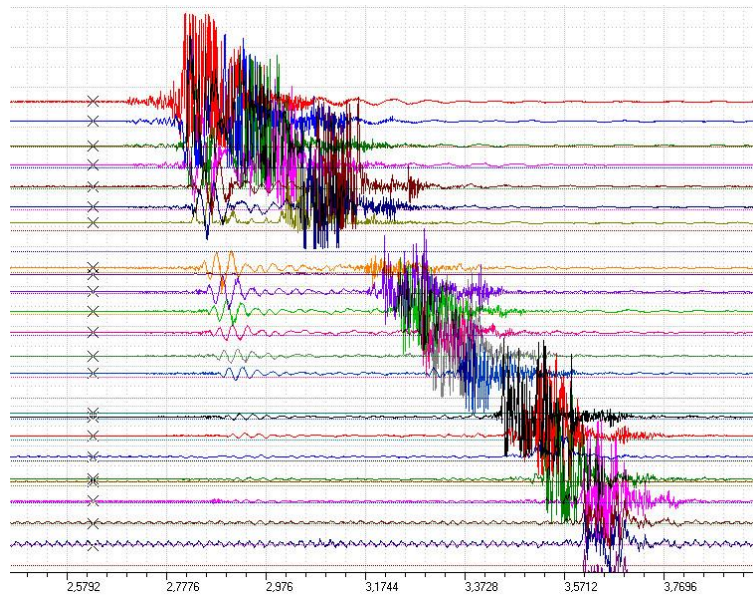


Figure 2. Typical waveforms of sensor signals when a skier lands on the summer artificial surface of the springboard: on the abscissa axis – the time in seconds from the start of the synchronization pulse, on the ordinate axis – the voltage at the output of the accelerometers; the lower the waveform is shifted in the figure, the lower the sensor is located on the landing mountain.

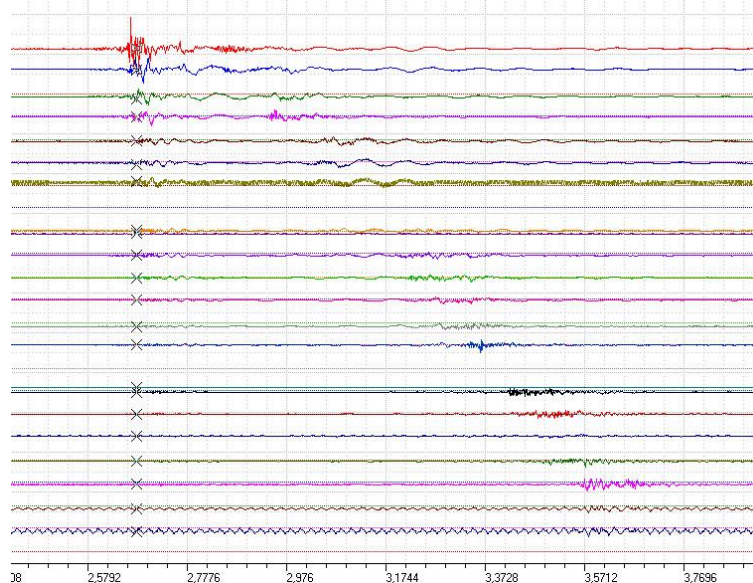


Figure 3. Typical waveforms of sensor signals when a skier lands on the snow surface of one springboard in winter: on the abscissa axis – the time in seconds from the start of the synchronization pulse, on the ordinate axis – the voltage at the output of the accelerometers; the lower the waveform is shifted in the figure, the lower the sensor is located on the landing mountain.

## DISCUSSION

The system was tested both during the training of athletes and during competitions. The integration of the vibroacoustic system with the general ski jumping monitoring system allowed athletes to independently obtain data on the jump distance and some other parameters during training, in particular, to assess the quality of skis sliding on the surface of the coating on the acceleration mountain and, if necessary, take appropriate measures (clean the ski jumping coating, choose a suitable lubricant for skis, etc.). The presence of a wind direction and speed sensor in the system made it possible to take into account these parameters for the correct self-assessment of the technique of performing a jump by an athlete. The use of a remote start control device allowed the coach to organize training jumps from a springboard, being in the place most convenient for observing the training process and performing jumps.

## CONCLUSION

The use of the vibroacoustic system for determining the distance of a ski jump, integrated into the general jump monitoring system, simplifies the assessment of sports results during the training of athletes both independently and under the guidance of a coach, which allows achieving the best sports results.

## AUTHOR CONTRIBUTIONS

D. Kiesewetter has developed the signal processing technique, manufactured the software and hardware of the device. V. Malyugin has performed the experimental study and equipment testing. K. Korotkov has performed the experimental study and processed experimental data. S. Zyryanov has developed the concept of the hardware implementation of the measurement method and performed the installation of sensors.

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## DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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