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Localization of Sound Sources in Normal Hearing and in Hearing Impaired People

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This article presents results of investigations of the angle of directional hearing acuity (ADHA) as a measure of the spatial hearing ability with a special emphasis on people with hearing impairments. A modified method proposed by Zakrzewski has been used – ADHA values have been determined for 8 azimuths in the horizontal plane at the height of the listeners' head. The two-alternative-forced-choice method (2AFC), based on a new system of listeners' responses (left – right instead of no difference – difference in location of sound sources) was the procedure used in the experiment. Investigations were carried out for two groups of subjects: normal hearing people (9 persons) and hearing impaired people (sensorineural hearing loss and tinnitus – 9 persons). In the experiment different acoustic signals were used: sinusoidal signals (pure tones), 1/3 octave noise, amplitude modulated 1/3 octave noise, CCITT speech and traffic noises and signals corresponding to personal character of tinnitus for individual subjects. The results obtained in the investigations showed, in general, a better localization of the sound source for noise type signals than those for tonal signals. Inessential differences exist in ADHA values for particular signals between the two groups of subjects. On the other hand, significant differences for tinnitus signals and traffic noise signals were stated. A new system of listeners' responses was used and appeared efficient (less dispersion of results compared to the standard system).

Keywords: localization of sound source, ADHA, tinnitus, left-right answer system.

1. Introduction

Localization of sound is a basic function of the auditory system, contributing directly to survival by indicating the positions of mates, prey or enemies. In the day-to-day life directional hearing is used almost all the time in monitoring the environment. Every person is affected by propagating sounds present in the environment. Unlike the eyes, the ears are always *open* and irrespective of our state of consciousness we can always hear the sounds of the environment in its entire spatiality. We can hear sounds even when it is dark or foggy – this ability of locating sound sources in space combined with our sense of hearing can help us to find or to avoid objects. It is the hearing analyzer that plays a significant role in spatial orientation while other senses make an important contribution to the perception (Wightman, Kistler, 1997).

Directional hearing has for years been the focus of attention of neurologists, physiologists and otologists. Despite many very diversified experimental studies, the phenomenon of localization has not been fully explained. The localization ability is one of the higher activities of the hearing organ in the ganglion cells of the brain stem (Pruszewicz, 1994). The results of many studies suggested that there is a possibility of a suppressing action from the auditory path of the ear that was stimulated earlier to the auditory path of the ear that is stimulated later.

Although the physiological mechanisms that operate in the process of sound localization are likely to be extremely complicated, a simplified conceptual structure as representation of the major phenomena can be adopted. Accordingly, one can imagine that the auditory systems measures certain physical parameters of the signals at the two ears and that the brain interprets these measured parameters in terms of possible locations of sound source. When this simplifying conception is adopted and one assume that inputs to the brain are restricted to just two pressure-versus-time waveforms, the three basic cues are: the interaural time difference (ITD), interaural intensity difference (IID) and the monaural frequency spectrum of the signal received at each ear. It should be noted that some other factors influence the localization of sound sources. One set of factors that may influence the judgements of the listeners is the knowledge about the sound source and the acoustic characteristics of the surroundings. In addition, there are nonacoustic cues such as motion or position of the head and visual information that must be considered. All these interacting factors make it difficult to obtain precise measurements of sound localization in a natural environment. Most studies are therefore conducted in more controlled situations (Hausler *et al.*, 1983).

Mills was the first who attempted the solution of the quantitative problem connected with the determination of the spatial segregation of information perceived by the auditory system (Mills, 1958). He defined a quantity, which helps to evaluate the perception of small changes of the direction, from which the sound propagates. It is the audible angle, defined by the subject as the just noticeable change of the angle from which the sound propagates with respect to the location of the reference sound source (MAA – minimum audible angle).

At about the same time Zakrzewski developed a method, which also permits the determination of angular values for the position of the sound source (Zakrzewski, 1960). In his study the subject received two consecutive signals from different places within a circle around which the loudspeaker was moving (the subject was located in the centre). The smallest angle between two loudspeaker positions when the subject recognizes that both signals come from two different places in the space was called the angle of directional hearing acuity (ADHA).

Many of the main features of sound localization in normal hearing subjects have been clarified in recent years although the phenomenon is still not fully understood (Blauert, 1997; Hartmann, 2000). On the other hand, sound localization with impaired hearing is still not well characterized and has not been studied systematically. The difficulty in characterizing sound localization in listeners with various impairments appears to be a consequence of multiple factors. In the nonhomogeneous group of impaired listeners it is often very difficult to classify properly a given hearing impairment and to know the nature of the underlying pathology. This means that generalizations over groups of patients are problematic and, in comparisons between studies, subjects placed in categories with a common name often have very different kinds of impairment (Hausler *et al.*, 1983). This especially refers to patients suffering from tinnitus. Tinnitus, from the Latin word *tinnitus* meaning "ringing", is the perception of a sound within the human ear in the absence of a corresponding external sound. About 17% of people, including children, report tinnitus symptoms in epidemiological studies. Tinnitus sensations range from mild unilateral ringing, rushing, whistling to severe force such as noise of waterfalls or roaring of engines. In extreme cases tinnitus can lead to suicidal attempts. Generally, the appearance of tinnitus in the ears produces fear of one's health and sometimes of one's life. Many patients suffering from tinnitus are relieved when subjected to an external acoustic stimulation. Sounds of the external world, particularly the sounds of nature as well as music, can reduce the problem (Jastreboff, Hazel, 1993).

There is a strong association between the pitch of tinnitus and the frequency range of abnormal hearing. Patients with low-pitched tinnitus usually have the greatest amount of hearing loss, whereas those with high-pitch tinnitus often have the least amount of hearing loss (Snow, 1997).

The study under investigation had two main aims. The first one was to evaluate the differences between the normal hearing and hearing impaired subject, in new measuring conditions (left – right answers), for standard signals. Much more intrinsic was the second one that consist in finding the manner in which the "tinnitus signal" influences localization ability. This task is rather difficult because the character of tinnitus is remarkably subjective and the objective methods of its precise description do not exist.

2. Experimental investigations

2.1. Methodics

The study was conducted using a setup with a mobile loudspeaker. The loudspeaker was fixed to a 1.5 m radius arm and moved around a circle. The subject's head was in the middle of the circle. ADHA measurements were conducted for 8 azimuths in the horizontal plane at the height of the listener's head in the range of 0–360°, every 45°. The listener sat on a special chair with a head support to prevent head movements.

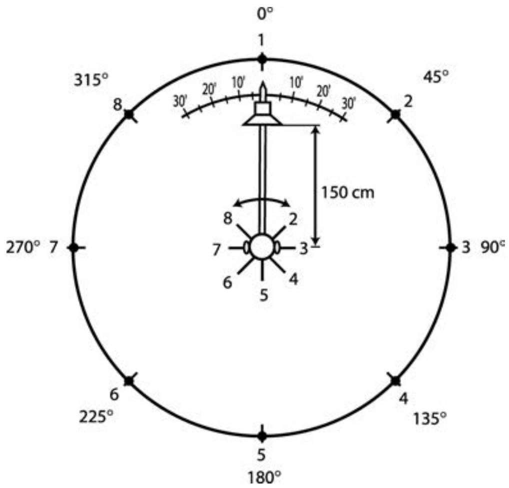


Fig. 1. The listener's position with respect to the loudspeaker.

The intrinsic difference of the ADHA method in comparison with the method proposed by Mills consists in the manner in which the loudspeaker is moved: in the ADHA method only to the right or to the left, while in the Mills' method to the right and to the left, alternately, from the 0° position. In these experiments the movement of the loudspeaker was only to the right. The measurement was repeated with the listener's position changing clockwise. At azimuths of 45°, 90° and 135° the loudspeaker was positioned opposite to the listener's left ear, at azimuths 225°, 270° and 315°, opposite to the listener's right ear. At angle of 0° the listener sat exactly in front of the loudspeaker and at the angle of 180° he sat with his back to the loudspeaker (Niewiarowicz *et al.*, 2005). The arm with the loudspeaker was positioned using a stepping motor. The motor was controlled by means of a controller programmed via a PC and Matlab.

The 2AFC method was used to determine the ADHA values. The subjects listened to the signals in an anechoic chamber at the Institute of Acoustics of the Adam Mickiewicz University. The chamber meets the requirements of ISO 3745-1977.

The experiment controlling software, which executed the 2AFC procedure and controlled the motor, generated test signals and collected the subject's responses, was implemented in the Matlab environment. Test signals were generated using the MARIAN UCON CX external audio interface, which was connected to the PC via the USB port. The signals were generated with the sampling frequency of 44100 Hz and resolution of 16 bits. The loudspeaker generated 2 signals from 2 positions. The angle between the successive positions of the loudspeaker in one attempt was determined on the basis of the subject's response and the rules of the adaptation procedure. After each pair of stimuli was generated the subject was asked to say whether the second signal in the pair was **to the right** or **to the left** compared to the first signal. This is a new feature in experiments of this type, where normally subjects are asked to respond **yes** or **no**, depending on whether they could distinguish the directions from which they heard the sound.

The method 2AFC is often used in psychological tests and sociological surveys and its merits and limitations are extremely discussed in the psychological, sociological and methodological literature (Cronbach, 1990). Its standard form requires the **yes** or **no** answer. One can assume that the **left – right** method used in this study is more demanding for the subjects. The method faces subjects to verbally report their subjective impressions and it forces them to demonstrate stronger attention, concentration and effort. One can therefore assume that the subjects' answers will be more precise and will have more differentiating power. This method is also less susceptible to induce subjects to provide accidental answers, given mostly to get rid of a problem.

The experiment employed the 2AFC procedure with 6 turning points and an additive step. A single threshold was determined as an arithmetic mean of the last 4 turning points.

2.2. Signals

The following signals have been used in the investigations:

- sinusoidal, 1/3 octave band noise, 1/3 octave band noise with amplitude modulation:
  - *modulation frequency 4 Hz*;
  - *modulation depth 100%.*
- frequencies of 500, 1000 and 4000 Hz (for sinusoidal signals and as mid-frequencies of the noise bands),
- traffic noise (Makarewicz, 1994), CCITT speech noise.

The signal frequencies were chosen basing on the localization abilities of our auditory system. For the subrange of low frequencies, effective physical factors that permit precise localization of the source include interaural phase differences for tones, interaural time differences for complex signals and the correlation between the signals reaching the right and left ears in the case of noises. In the case of high frequencies for a tone signal of a frequency of 4000 Hz, there is a considerably interaural difference in intensity and, additionally, a difference in the spectrum in the case of complex signals. The frequency of 1000 Hz is the accepted limit for the two basic factors mentioned above that affect the spatial hearing ability, i.e. the interaural time difference, which to a certain degree continues to help to localize the sound and the interaural intensity difference that becomes significant for this frequency (Middlebrooks, 1992). The selection of noise signals, i.e. 1/3 octave band noise and 1/3 octave band noise with amplitude modulation, was motivated by the fact that noise sounds are close to natural sounds, characteristic for the surrounding environment. The same 1/3 octave band noise signals were amplitude modulated with a frequency of 4 Hz (this value is significant in the speech perception process by different set-ups, e.g. hearing aids).

The duration of the signal was 1.5 s and the interval between the signals was approximately 5 s. Furthermore, the attack and decay times of 50 ms were used in the signals. These values were selected on the basis of the results of the investigations conducted on the effect of the sound attack time on the accuracy of the localization (Florkowski, 1980).

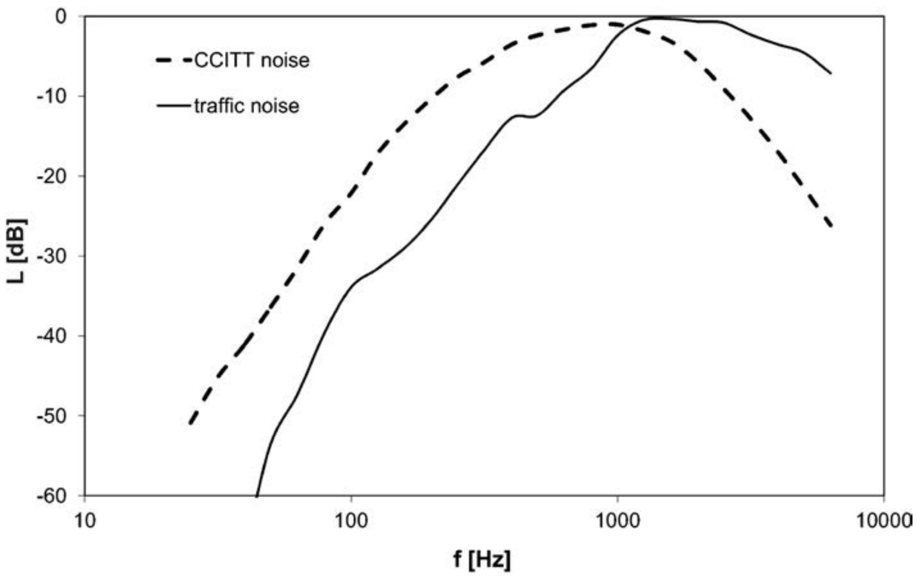


Fig. 2. The relative spectrum of the traffic noise and the CCITT speech noise.

The essential signals in these investigations were "tinnitus signals" used in the case of hearing impaired subjects. As tinnitus is a subjective phenomenon, it is difficult to evaluate physical parameters and create signals that would correspond in their form to the character of the individual tinnitus sensations of subjects. To this end, each subject performed the test, which consisted in listening to the signals of different spectral structure. This structure was created by two parameters:

- f – centre frequency of noise band,
- Q – quality factor, which decides of the shape of the spectrum.

The subject's task was to point out the signal, which would sound as closely as his own tinnitus. Exemplary shapes of the spectra of "tinnitus signals" are presented in Fig. 3.

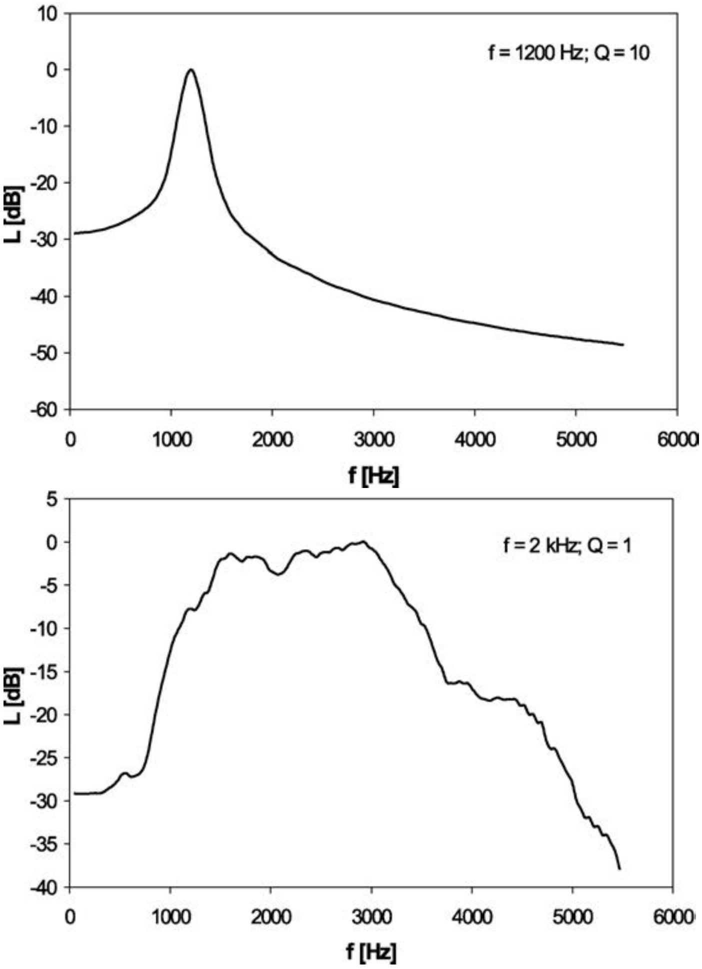


Fig. 3. Exemplary spectra of "tinnitus signals".

2.3. Subjects

The investigations were carried out for two groups of subjects:

- normal hearing subjects – 9 (4 male, 5 female) – normal hearing confirmed by audiometric and acumetric measurements,

- hearing impaired subjects – 9 (7 male, 2 female) in the range of age 45–71 with monaural or binaural sensorineural hearing loss not exceeded 50 dB in the range of investigations – all subjects were suffering also from tinnitus,
- tinnitus centre frequency range for particular subjects – 300–6000 Hz,
- quality factor Q – 0.5–45.

The data of subjects are presented in Table 1.

Table 1. Data of subjects.

Subject	Age	Gender	Deafness	Tinnitus	
				Frequency	Q
ab	51	Male	Binaural	4500	7
lk	45	Male	Binaural	3500	6
jl	67	Male	Monaural	3500	5
gs	57	Female	Monaural	300	2
bw	73	Male	Binaural	1450	35
rb	53	Male	Monaural	1400	0.5
zk	74	Male	Monaural	4000	45
jl	56	Female	Binaural	1200	10
ek	60	Male	Monaural	2000	1

3. Measurement results

At the first stage an analysis of the distribution of ADHA values was made. It was found that the distribution of ADHA values for different azimuths is asymmetric. For this reason, in the analysis of ADHA values a positional measure in the form of the median was adopted. The median for an n-element sample was determined as follows: from x_i elements of the sample a non-decreasing sequence was made and in case when the number of n-elements in the sequence was odd, the central element was assumed to be the median. It was calculated from the formula:

$$Q_2 = X_{n+1/2},$$

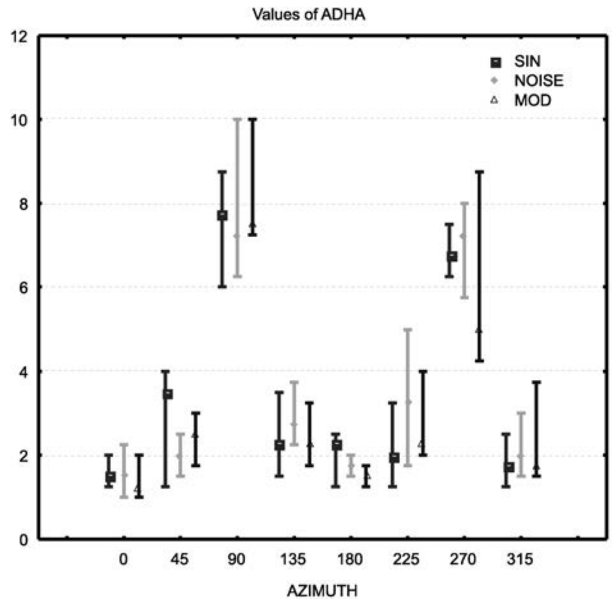
whereas an even number of n-elements of the sequence was calculated from the formula:

$$Q_2 = (X_{n/2} + X_{n/2+1})/2.$$

The lower quartile (first) – Q_1 and the upper quartile (third) – Q_3 were also determined.

The results obtained for normal hearing subjects confirmed earlier author's observations that for all types of signals the best localization ability was recorded for the sources located directly in front of the listener's head and the worst for a lateral azimuth. Lower ADHA values (better localization ability) were obtained for noises. More interesting was the statement that differences in the ADHA values between normal hearing and hearing impaired subjects were not very significant excluding azimuths 90° and 270°. This is demonstrated in Fig. 4.

a)



b)

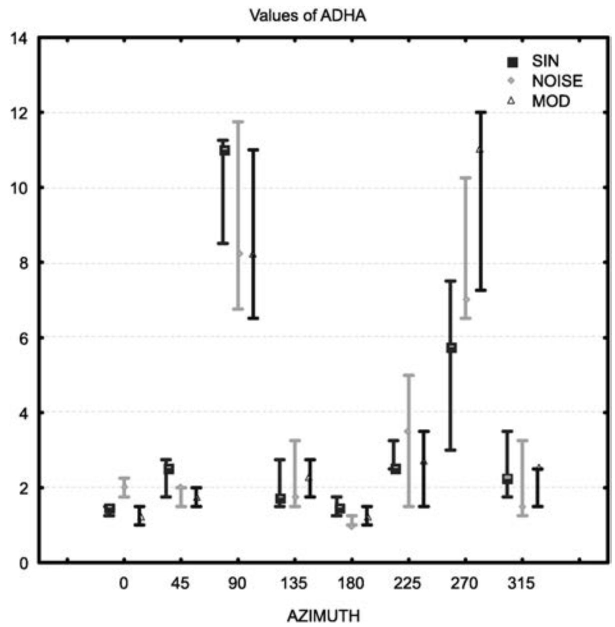


Fig. 4. Values of median, upper and lower quartiles for sinus, noise and modulated signals: a) normal hearing, b) hearing impaired.

The preliminary measurements for hearing impaired subjects were performed using all types of signals mentioned above. The statistical analysis of results (analysis of variance – ANOVA\MANOVA) for individual types of signals showed a high homogeneity of variance which allowed averaging over the signals [$F(3,576) = 1.09$; $p = 0.35$]. That was the reason that in further investigations traffic noise was representative as a reference signal.

On the other hand it was found that there are important differences between subjects [$F(8,576) = 8.98$; $p < 0.001$] and therefore a post-hoc test was conducted. Tukey's T test enabled to identify the homogenous group consisting of 6 subjects. The variance analysis conducted for this group confirmed the absence of statistically significant differences between these six hearing impaired subjects [$F(5,384) = 1.90$; $p = 0.09$].

In the picture below the results of comparison of ADHA values for traffic noise and tinnitus signals are presented.

As seen in Fig. 5, important differences exist between ADHA values for traffic noise and "tinnitus signals", especially for the azimuths of 90° and 270°.

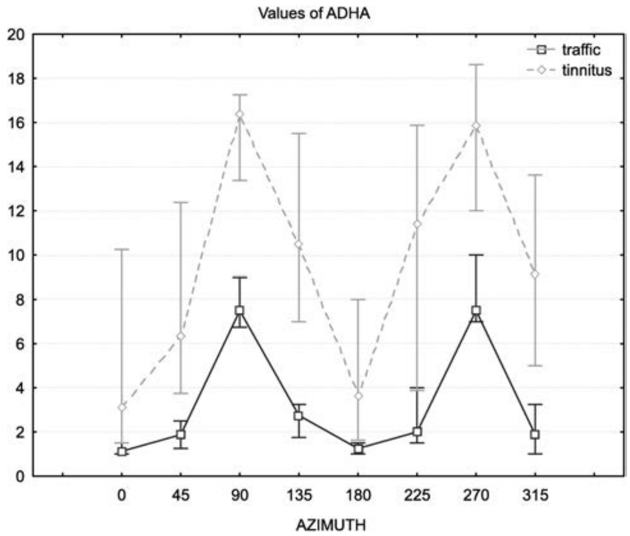


Fig. 5. Values of median, upper and lower quartiles for traffic noise and "tinnitus signal".

4. Discussion

As mentioned in the Subsec. 2.1, the new method of left-right answers is more demanding and thus more precise than the standard method yes-no. The results obtained in these studies show a smaller dispersion of the values (evaluated on the basis of the difference between the lower and upper quartiles) compared with the results obtained by the standard method presented in (Niewiarowicz *et al.*, 2005). This fact confirms the superiority of the method used in the investigations.

It is apparent from the data presented in Fig. 4 a,b that ADHA changes show a similar tendency both in normal hearing and in hearing impaired people. If comparisons are made between the two groups of listeners, it can be stated that the greatest differences are observed for the azimuth of 90° (for sinus signals) and that of 270° (for modulated noise signals). For other azimuths, these differences are not significant and do not exceed approximately 1°. Thus, it can be concluded that the hearing impairment (not deep sensorineural hearing loss and the presence of tinnitus) did not deteriorate significantly the ability to localize sound sources for standard acoustic signals.

The results shown in Fig. 5 indicate that there are significant differences in the values of ADHA for traffic noise signals and tinnitus signals. For all azimuths (except that of 45°) they are not smaller than 2° and for 90° and 270° reaches 6°. Perhaps the explanation of this phenomenon can be found in the fact that the tinnitus signal is similar in nature to the own tinnitus of a subject. Therefore, the external signal reaching the ear may be "mixed" with the own tinnitus. In this way the cues, which decide about the localization abilities could be weakened. Some influence on the deterioration in the ability of localization may be related to the psychological aspects. Most of the subjects reported a growth of annoyance and mental tiredness. This had undoubtedly an impact on the reduction of concentration and consequently a deterioration of the quality of answers.

5. Conclusion

The investigations carried out lead to three main conclusions:

- there is no significant difference between normal hearing and hearing impaired subjects for standard signals,
- significant differences exist in hearing impaired subjects for reference signals and "tinnitus signals",
- the new method based on the "left-right" answers is much more efficient and accurate.

Acknowledgments

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