AUDIMIR
Directional Hearing at Microgravity*

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In October 1991 the first Austrian cosmonaut spent one week on board the Soviet space station MIR. One of the 14 experiments carried out there was AKG's AUDIMIR, a psychoacoustics technological experiment. AUDIMIR was designed to investigate the accuracy of directional hearing and its role as part of the human orientation system at microgravity.

0 INTRODUCTION

It was on October 2, 1991, at 6:59 a.m. central European time, that Franz Viehböck, Austria's first cosmonaut, set off from the Soviet Cosmodrome at Baikonur for a 6-day space flight in the MIR space station, a joint Austrian–Soviet project called AUSTROMIR. Viehböck and his Soviet colleagues A. A. Volkov and T. Aubakirov reached the space station aboard the Soviet Soyuz class spaceship TM-13 on October 4. Having successfully completed a long list of experiments, the first Austrian cosmonaut returned to earth safely on October 10.

The AUSTROMIR project was included in a treaty on a joint Austrian–Soviet space flight, signed by the Republic of Austria and the Union of Socialist Soviet Republics in October 1988. The treaty goes back to an invitation made by prime minister Ryshkov in 1987.

The AUDIMIR experiment investigating directional hearing at microgravity was performed on the second and fifth days on board the space station. AUDIMIR and 13 other experiments had been selected in May 1989 from 34 submitted projects.

AUDIMIR was the first basic study of auditory orientation in space at microgravity. The project started from the assumption that in the absence of gravity, orientation by auditory cues would have to play a much more important role. The experiment was based on recent psychoacoustic discoveries about spatial perception as well as on technological advances in audio signal processing which enable these discoveries to be utilized in engineering.

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1 DIRECTIONAL HEARING AND MICROGRAVITY

Persons with normal hearing are capable of localizing sound sources in space. This faculty depends on binaural hearing. Directional hearing can also be utilized for orientation in space. Imagine the following experiment.

You are sitting on a revolving chair in a completely dark room. The chair is made to spin and gradually stops again. Now you no longer know your position relative to the room—you have lost your bearings. If, however, another person stands at a specific location in the room and keeps talking while you are spinning around, you always know which way you are facing because you are able to take "acoustic bearings."

Under normal conditions, humans use the vestibular apparatus, the senses of touch and sight, as well as the ears, to determine their position in space. Auditory orientation is only of marginal significance. In the absence of gravity, the vestibular apparatus and the sense of touch provide no cues, which makes it seem likely that astronauts rely heavily on visual and auditory cues for orientation in space. This theory has been corroborated by statements of cosmonauts to the effect that in the space station they use the noises made by certain devices for orientation.

During a space walk cosmonauts may not see the space ship or the earth, which leaves them without any visual cues for orientation. When communicating with other persons by radio and headphones, which is mandatory during a space walk in any case, the intracranial (middle-of-the-head) localization associated with conventional headphones makes auditory orientation impossible as well.

At this point the possibly related problem of space sickness should be mentioned. Space sickness, which is characterized by disorders of the autonomic nervous system (nausea, vertigo), is probably brought on by the "confusion" of the human orientation system caused by the absence of gravity. The confusion is due to some of the cues received by the vestibular apparatus, touch sense, eyes, and ears being contradictory, so the brain cannot derive a consistent picture from them. In this context, the intracranial localization associated with the use of headphones adds another sensory mismatch. Eliminating this mismatch may help humans feel more at ease at microgravity.

2 THE AUDIMIR EXPERIMENT

The AUSTROMIR project provided the first opportunity for AKG and its Austrian and Soviet partners to conduct basic research into the aforementioned subjects. Also, AUDIMIR was intended to show how space communications systems could be improved. The experiment comprised two phases. The first phase was to show whether microgravity affects the faculty of directional hearing as such, that is, whether it becomes more or less accurate. The purpose of this was to verify observations of temporary changes reported by Soviet scientists in earlier experiments under simulated microgravity conditions.

In these experiments microgravity is simulated by prolonged periods of rest in bed with the bed being tilted at various angles (orthostatic position—the head is higher than the body; antiorthostatic position—the head is lower than the body). This kind of low muscular movement (hypokinesia) causes similar reactions as microgravity causes in certain regions of the human body. Prolonged hypokinesia, lasting for 12 to 182 days, had been found to cause a temporary deterioration of localization accuracy by 30%. During short-term antiorthostatic rests (for up to 8 hours) both a deterioration of the localization accuracy and a lateral displacement of the sound source locations had been observed.

The AUDIMIR experiment specifically examined front localization. The cosmonaut was presented with noise bursts from either center front, left front, or right front for examining horizontal localization, or from above or below for examining median-plane localization.

The second phase of AUDIMIR was the first investigation ever of the hearing system as part of the human orientation system. Earlier neurophysiological research had only looked at the vestibular, visual, and somatic sensory systems. The objective was to demonstrate the increased importance of spatial hearing for the human orientation system at microgravity. However, this cannot be proven directly, as, for instance, by measuring a specific parameter on the body of the subject. The only viable approach is to draw appropriate conclusions from specific reactions of the subject.

Humans determine their position in and movement through space from cues they receive from the vestibular apparatus; somatic sensory cells in the skin, muscles, and joints; as well as eyes and ears. The orientation system can be tricked, however. If you stand on a bridge and stare into the water for a long time, you will feel as if the bridge were moving upstream through the water. Similarly, if you look out of the window of a standing train, watching the train on an adjacent track depart, you believe your own train starts moving. In both cases excessive reliance on visual cues creates an illusion of movement [1].

By way of analogy, AUDIMIR was designed to trigger an illusion of movement by auditory cues. In terms of the aforementioned examples, this would mean that the sound of water flowing by or of a departing train would be used to create an audiokinetically induced illusion. Under normal terrestrial conditions, this is nearly if not totally impossible. But if it is true that in a weightless environment auditory orientation is more important, then there should be a better chance of creating an illusion of movement by sound signals. The "intensity" of the illusion can thus be considered an indirect measure of the importance of auditory orientation.

The test stimuli used for AUDIMIR included white noise and a few bars of a Viennese waltz, and it simulated a sound source moving around the subject's head. If audiokinetic stimulation were successful, then the subject would perceive the sound source (such as the waltz orchestra) as being at rest and him- or herself as rotating.

Kinetic illusions are characterized by specific eye movements of the subject. An objective value can thus be obtained by measuring the eye movements by electrooculography (EOG). Perceived orientation can be determined by questioning the subject.

3 REALIZATION

The realization of psychoacoustic experiments requires precisely controlled acoustic environments. In experiments on directional hearing it is particularly important to watch out for unwanted ambient noise, which could corrupt the results.

Apart from the fundamental problem of setting up moving sound sources, a space station does not provide the desired acoustic conditions. There is no anechoic chamber and constantly running machinery creates a high noise floor. The only solution to this problem is the presentation of test stimuli over headphones in order to eliminate ambient noise.

However, since with conventional headphones the sounds are heard inside the head, meaningful localization of sounds would be impossible. The test stimuli therefore had to be subjected to binaural processing in order to ensure localization outside the head like in natural hearing. The realization of AUDIMIR was based on the experience gained by AKG over the last few years in developing binaural systems for music recording and headphone reproduction [2]–[4]. Figs. 1–4 show the principle of binaural processing.

Fig. 1 shows a "natural" hearing situation. The sound source is a loudspeaker (LS) radiating a sound burst. The burst arrives at the subject's head from the left. Measurements of the burst taken right in front of the two tympani (Tfl, Tfr) show that the burst has been severely "distorted." On its way from the loudspeaker to the two tympani it has been modified by various physical influences (shadowing, diffraction, reflections, resonances). These influences depend on the physiological properties of the body (such as shape of head, shape of ears) so that the measured results vary from person to person. This spectral modification can be described by the head-related transfer function (HRTF).

Fig. 2 shows the results of one measurement each of the ears of the two Austrian prospective cosmonauts C. Lothaller and F. Viehböck in a situation as depicted in Fig. 1. The HRTF depends on the angle of sound incidence. In the course of its development, the human brain has learned to identify the location of a sound source from the spectral modification of the sound (that is, from the HRTF).

In contrast to a natural situation, Fig. 3 shows the situation in conventional headphone listening. The burst is picked up by the microphone (MK) next to the sound source (LS) and fed to the headphones (KH). The strictly electrical signal transfer eliminates the spectral modification of the burst by the body. Thus it arrives at the tympani unmodified and is identical on the left and right. Therefore the brain does not receive the cues from which it is normally able to "compute" the source location—the sound burst is perceived as originating inside the head.

In order to provide a natural listening experience which enables the listener to localize sound sources, the burst needs to be modified exactly as it would be in natural hearing. To this end, the microphone output signal is passed through a pair of filters that simulate the HRTFs, as shown in Fig. 4. Tympanum measurements yield the same results as for natural hearing and the brain receives the familiar cues from which it can identify the sound-source location. The practical implementation of this principle has become possible only recently, mainly due to the fast progress of digital signal processing.

To perform the experiment in the space station MIR, a signal source, a filter pair for binaural processing, and suitable headphones were needed (Fig. 4). This setup generated the test stimuli and processed them according to the various target azimuths and elevations. For the second phase of AUDIMIR, the simulation of moving sound sources was also needed. The hardware for the experiment had to meet the following requirements:

- Low weight.
- Low power consumption.
- High reliability under space flight conditions.
- There being only limited time for the experiment, the test sequence had to be as time efficient as possible.
- During the experiment the Austrian cosmonaut was the subject, assisted by a Soviet colleague. Although the test sequences had been practiced prior to the flight, the difficult conditions during a space flight had to be taken into account. Therefore the equipment had to be extremely easy to operate.
- Signal generation, processing, and reproduction needed to conform to high-quality acoustic standards.
- Ambient noise had to be sufficiently attenuated.
- The AUDIMIR hardware was to be used for sound-signal generation in another Austrian experiment (MONIMIR, University of Innsbruck) as well.

These requirements were fulfilled through consistent

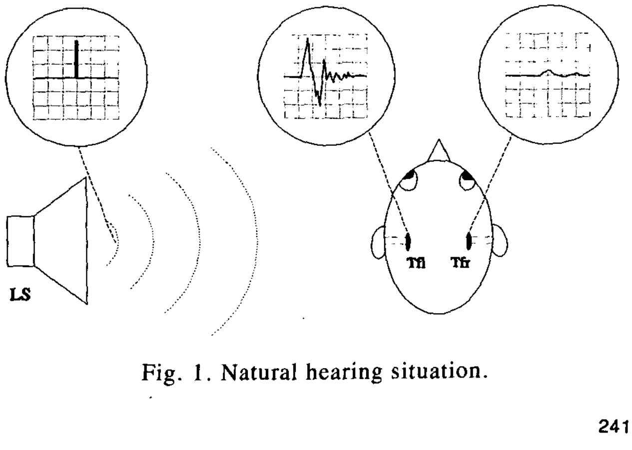

Fig. 1. Natural hearing situation.

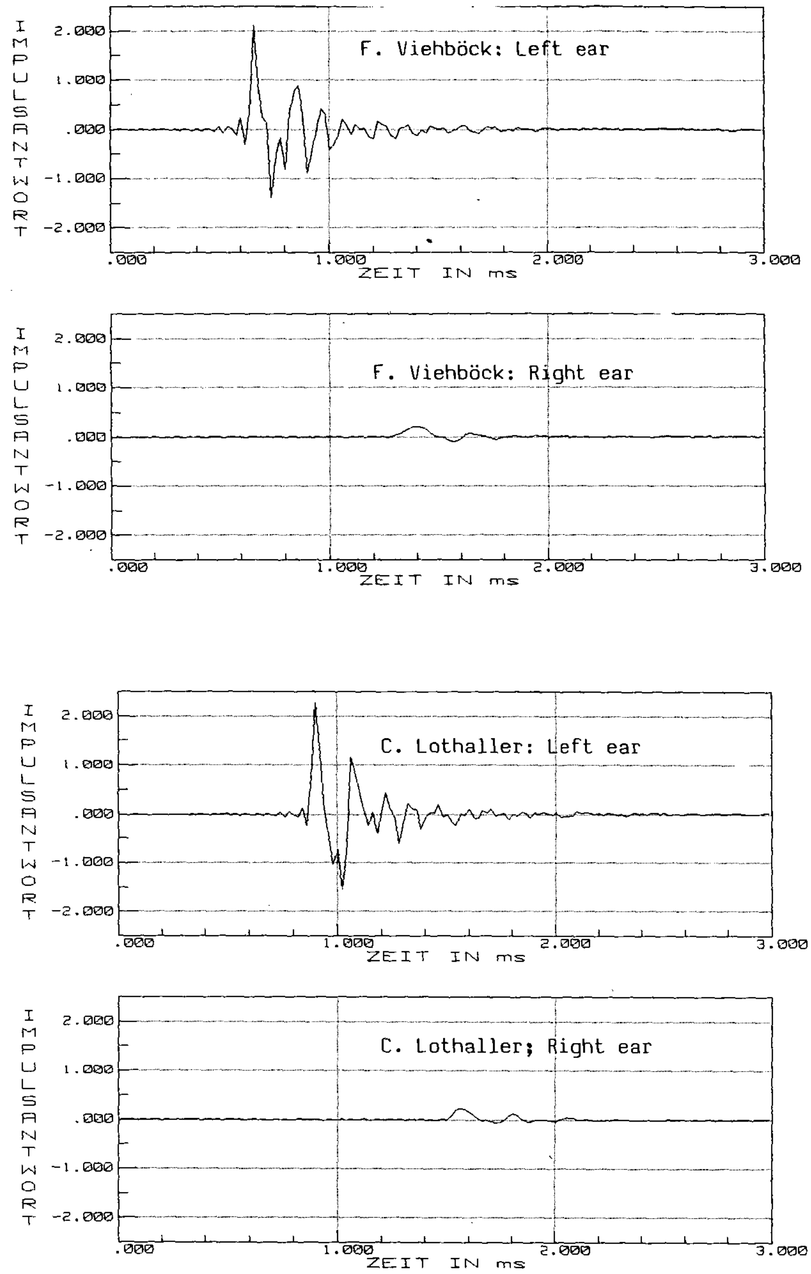

Fig. 2. Impulse responses for sounds from left.

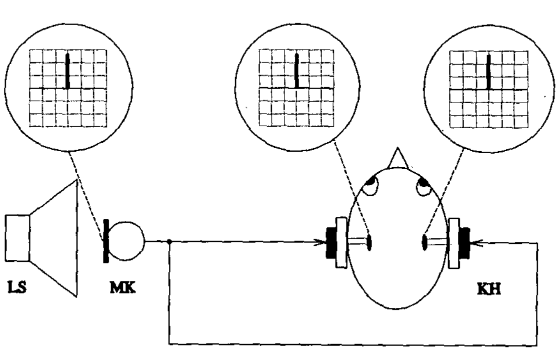

Fig. 3. Conventional headphone reproduction.

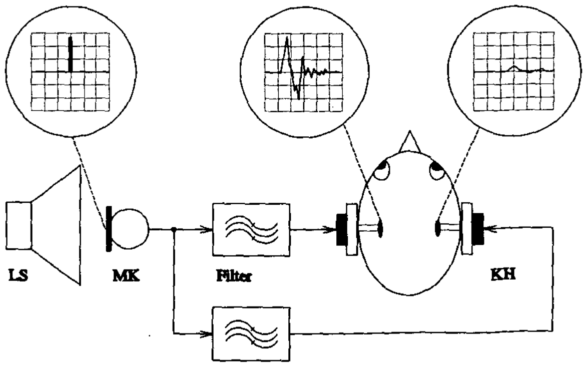

Fig. 4. Headphone simulation of natural hearing.

use of digital circuitry.

The test stimuli are stored in semiconductor memory (PROMs). One reason for this is that only short-duration "rough" signals are stored for later processing during the experiment. This storage medium is much lighter and consumes much less power than other media (such as tapes or audio cassettes) and greatly simplifies signal selection control.

The binaural processing, that is, the simulation of HRTFs, is performed by digital FIR filters. This function has been implemented in a 24-bit signal processor (Motorola DSP 56001). Thus the test stimuli were only processed live, that is, during the actual experiment. The entire electronic circuitry (power supply, signal memory, signal processor, headphone amplifier) is contained in a box weighing only 1.3 kg (Fig. 5).

The experiment was controlled by the software running on the DATAMIR system via a serial interface. DATAMIR is an AT-compatible PC designed for the control of 10 experiments of the AUSTROMIR project and recording the measured data.

During the first phase of the experiment, the azimuths of the acoustic stimuli as a function of the subject's answers were calculated and entered into the AUDIMIR electronic system. The assistant entered the subject's answers on the keyboard. In the second phase the movement of the sound source was controlled by DATAMIR. Simultaneously an EOG was recorded.

The headphones had to provide a high sound quality in order to reproduce the binaural cues properly. High noise attenuation was needed to prevent ambient noise interference. For this reason sealed-back headphones (AKG K 270) were used. Since the AUDIMIR hardware was also to be used in the MONIMIR experiment, the earphones used no standard headband but instead could be fitted inside the MONIMIR "helmet," which was used for head-position measurements (Fig. 6). The headphones acoustically sealed the cosmonaut off from his environment. His assistant therefore had to use a microphone whose signal was fed to the headphones.

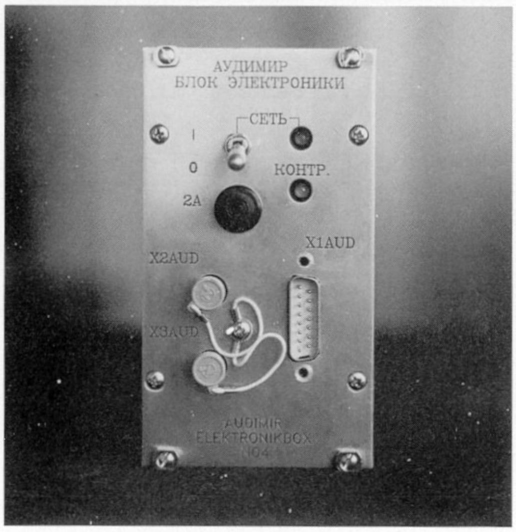

Fig. 5. AUDIMIR electronic box.

The cosmonaut used a dictaphone to record his subjective observations.

In order to simulate sounds from a variety of directions, the HRTFs for all required angles had to be measured. This was done by placing a miniature microphone in each ear canal of the subject and presenting sounds from various angles. The data obtained were then digitally processed for simulation by FIR filters.

The measurement technique we used is similar to the one described in [5]. A "filter language" (FIM Filter Manager) specifically designed by AKG for these purposes was used for the processing of the rough data obtained (windowing; sample-rate conversion; corrections for microphone, loudspeaker, and amplifier; headphone equalization).

Since individual differences are too significant to be ignored, both prospective cosmonauts were measured (see Fig. 2). The decision as to who would actually fly was made shortly before the launch, so the parameter sets for both cosmonauts had to be kept ready. In fact, the equipment was not programmed for the cosmonaut until shortly before the experiment, during the flight.

4 PROCEDURE

The experiment was performed twice, on the second and fifth days of the cosmonauts' stay in the space station; 25 minutes were available for each trial. Measured data will be compared to data obtained from reference tests done on the earth before and after the flight.

The first phase of the experiment was designed to determine localization accuracy, particularly for sounds from the front. The cosmonaut heard short-duration signals (300-ms noise bursts for horizontal-plane tests, 500-ms bursts for median-plane tests) coming from center front, left front, or right front. A second test series presented signals that moved from center toward the left or right.

The cosmonaut was required to describe his judgment as left, center, or right. The answers were entered into the DATAMIR system, which processed them for further control of the experiment. The initial target azimuth

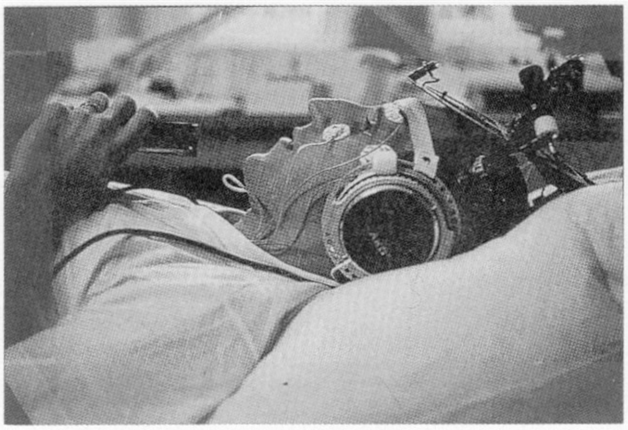

Fig. 6. AUDIMIR headphones.

range was relatively wide (±20°), but narrowed continuously as long as the answers were correct. Incorrect answers increased the azimuth range. Target azimuths were thus controlled in such a way that they eventually stabilized around the limits of localization error. In this way, optimum results were obtained in spite of the short time available for the experiment. Fig. 7 is a graphic representation of one test series. The evaluation of the data will show any changes in localization performance as well as any lateral displacement of center-front localization toward the left or right. Median-plane elevation judgment tests were performed analogously.

Following 1 min of silence, the second phase of the experiment simulated sound sources that initially stood still and then began to move around the head of the subject. The sense of rotation was reversed once. The objective was to determine to what extent the cosmonaut developed a sensation of movement, in other words, whether he believed to be spinning while the sound source was at rest. The first series of test stimuli used white noise. In order to evoke the desired association more easily, the second series drew on the familiar experience of waltzing. The cosmonaut was presented with a passage from the waltz "Viennese Chocolates" by Johann Strauss, with a simulation of the orchestra moving around the cosmonaut's head.

During and after the experiment the cosmonaut recorded his sensations on a dictaphone (such as "the orchestra is circling my head" or "I am wheeling as if I were waltzing"). Also recorded was an EOG for measuring the characteristic eye movements (nystagmi) that indicate the response of the orientation system. The intensity of the spinning sensation is a measure of the importance of auditory orientation.

5 PRELIMINARY RESULTS

The results of the first phase of AUDIMIR show that the azimuth localization error at microgravity is within the same range as on earth, that is, between 1 and 2° (Fig. 8). During the second in-flight experiment, azimuth judgments slightly shifted to the left.

Due to the absence of interaural cues, median-plane elevation judgments are necessarily more difficult than azimuth judgments. Localization error values were commensurately high and did not change significantly during the flight (Fig. 9). However, a significant downward shift in elevation judgments by approximately 10° was observed.

In the second phase of the experiment, perceived orientation was first measured without presenting a sound signal. The subject reported the sensation of a slight clockwise rotation. Presenting a stationary sound did not affect perceived orientation. The presentation of a sound that was moving counterclockwise, however, reinforced the perceived clockwise rotation significantly. This sensation was stronger with the waltz than with white noise. Both a subjective illusion and the corresponding eye movement activity were observed. Reversing the sense of rotation of the sound reversed the direction of the eye movements but not the perceived sense of rotation of the subject.

The responses to stimulation by a revolving sound source clearly show that dynamic orientation can be influenced by an audiokinetic stimulus, both in terms of a subjective illusion of movement and by objective eye movement measurements. Thus the existence of this phenomenon was proven for the first time.

The results cannot be interpreted before the data have been fully analyzed and further reference experiments

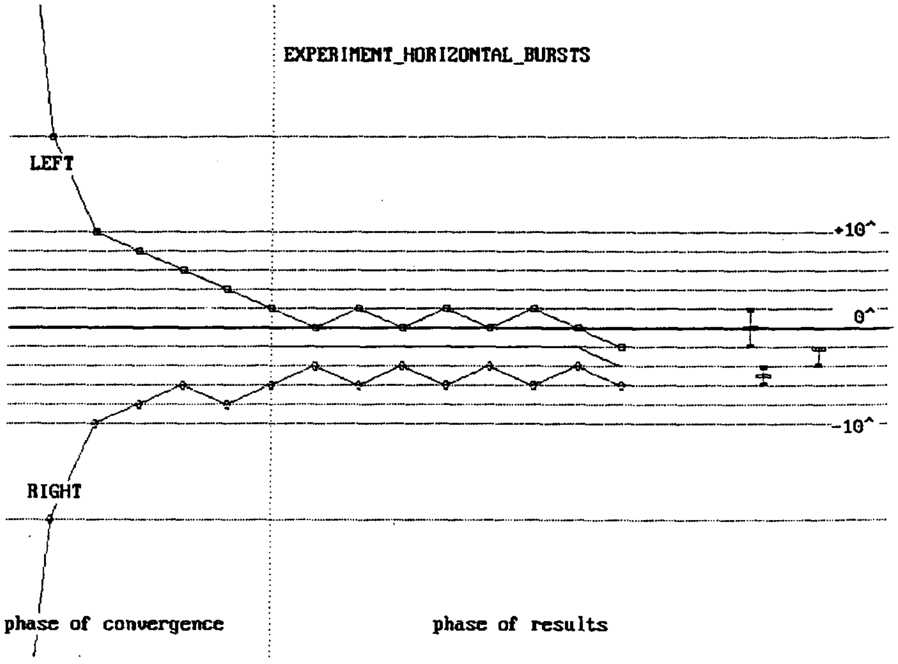

Fig. 7. Evaluation.

have been performed on earth. Also, another series of AUDIMIR experiments ending in summer 1992 will be performed by the Russian crew aboard the space station in order to obtain long-term data.

6 OBJECTIVES

Our immediate scientific objective was to measure the localization error and the importance of auditory orientation at microgravity. The AUDIMIR experiment was also intended to show how communications systems for space travel can be improved and how these improvements can be implemented.

The situation of a space walker talking over the radio with the commander in the space station or a ground station on earth illustrates how the technique could be used to aid orientation. The voices could be processed such that they seem to come from the "correct" direction—from the space station or from earth—and thus provide the cosmonaut with a point of reference.

The elimination of the auditory mismatch is expected to have a positive effect on the orientation system, which may counteract space sickness.

The binaural processing of audio signals for headphone reproduction provides not only orientation cues at microgravity, but the following positive effects as well. In conventional headphone listening the voice of a caller is heard inside the head, an unnatural situation that causes stress. Binaural processing creates a more natural situation with reduced stress.

In certain extreme situations, such as increased gravitational stress during the liftoff of a space ship, the field of vision may be reduced so that lateral visual stimuli that normally would be seen may not be perceived. There is no similar effect on hearing. Important information could therefore be presented to astronauts in this phase by three-dimensional audio.

Binaural sound restores the listener's ability to con-

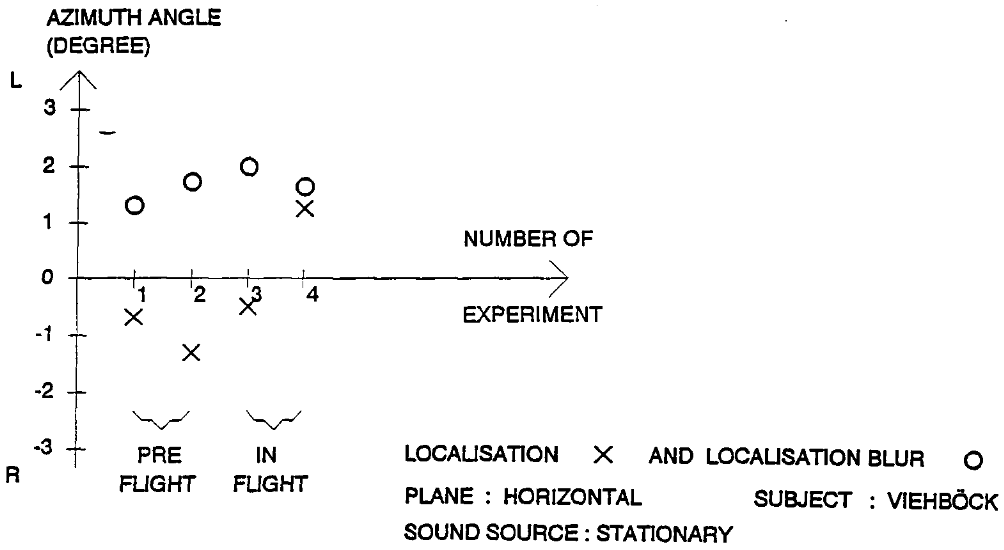

Fig. 8. Localization in horizontal plane.

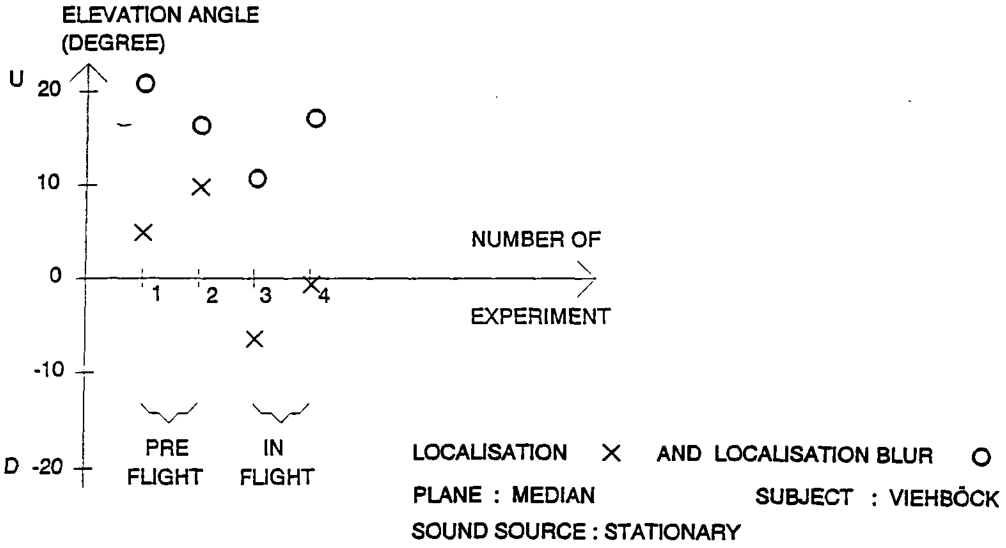

Fig. 9. Localization in median plane.

centrate on one specific voice out of many talking at the same time (cocktail party effect). The cosmonaut could therefore listen to several radio channels over headphones at once if each channel is assigned a different direction. He can always concentrate on one channel without having to switch the others off.

Speech intelligibility is improved, that is, the noise level at which the voice signal is still intelligible may be about twice as high as with no binaural processing (binaural intelligibility level difference).

7 SUMMARY

The AUDIMIR experiment was the first investigation of the auditory system as part of the human orientation system at microgravity. The technical realization of the project was based on the presentation of binaurally processed signals over headphones. For the horizontal plane, no significant localization errors were found, while a downward displacement was observed in median-plane elevation judgments.

The second phase of the experiment proved for the first time the phenomenon that human dynamic orientation can be influenced by audiokinetic stimulation.

At microgravity, auditory orientation evidently is of special significance. Starting from the results of AUDIMIR, further research will have to show whether this discovery will be of any use for future space travel.

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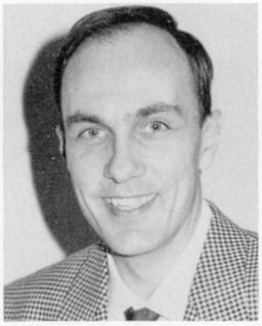

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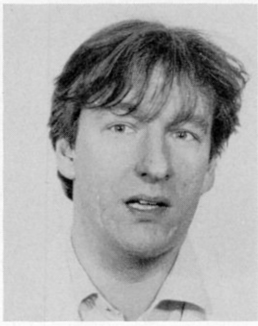

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Alexander Persterer was born near Salzburg, Austria, in 1958. He studied electronics specializing in sound engineering at the Technical University of Graz, Austria, from which he graduated in 1984, and from which he received a Ph.D. degree in 1989.

Dr. Persterer has been with AKG since 1985, where he has been involved in the fields of digital signal processing and psychoacoustics. His work has included the development of the binaural signal processing system CAP340M. He has initiated and led the AUDIMIR project. Since 1990 he has been head of AKG's DSP development team.

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Martin Opitz was born in Vienna, Austria, in 1953. He studied technical physics at the Technical University of Vienna, from which he graduated in 1977 and received a Ph.D. degree in 1980.

Since 1980 Dr. Opitz has been with AKG, where he has been working on the computation of acoustic and magnetic fields and in the fields of digital signal processing and psychoacoustics. His work included the installation and use of techniques for the measurement of acoustic transducers and outer ear transfer functions. He is currently working on algorithms to compute binaural digital filters to be used in binaural processing devices such as the CAP340M or BAP1000.

He is currently evaluating the results of the AUDIMIR research project, which includes experimentation on several aspects of directional hearing under microgravity conditions and was performed by several crews on board the Russian space station MIR.

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Christian Koppensteiner studied electronics with specialization in sound engineering at the Technical University of Graz, Austria, from which he graduated in 1991. Mr. Koppensteiner was with AKG from 1989 to 1991, where he was engaged in the development of the AUDIMIR DSP-System for the generation of binaural test patterns.

Since 1992 he has been with Micro Analog, Graz, where he is involved in the design of a digitally controlled audio matrix.

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Maria Nefjodova was born in Kokand, Usbekistan, on August 5, 1942. She graduated after studying medicine from the 2nd Moscow Medical College in 1969. Since 1961 she has worked as a medical advisor to space flight projects. Since 1969 she has been with the Institute of Medical/Biological Problems of the Russian Ministry of Health in Moscow. In 1979 she received an M.D. degree in aerospace medicine.

Dr. Nefjodova is a highly qualified expert on space audiology. She has published more than 50 scientific papers on examinations of the functional condition of the auditory system under space flight conditions and on the development of preventive measures to protect the auditory system from the effects of space travel. In 1990 she received the title of Senior Scientist.

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Christian Müller was born in Vienna, Austria, in 1957, and studied medicine at the University of Vienna, from which he graduated in 1982. He currently works at the Clinic for Neurology as a clinical neurologist where he leads the oculomotor research group.

Dr. Müller has published several papers in the field of the oculomotor system. He also has been interested in multisensory psychophysics and was PI in a microgravity experiment dealing with visuo-vestibular interaction. His current research interests concentrate on the physiological basis of sensory multichannel use in virtual environments.

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Meinhard Berger was born 1943 in Neuwied, Germany. After studying at the Medical Faculty of the University of Innsbruck and Graz he graduated with an M.D. degree in 1969. His further specialization was in neurology and neuroorthopedics. He has developed methods for motion analysis, especially head motion (cervicomotography), and achieved habilitation for neurology in 1986 after studies on the effect of head motion on neurological diseases and whiplash injury.

Since 1986 Dr. Berger has been involved in space medicine. He was the principal investigator on the Projekt MONIMIR and coordinator of the medical experiments of the Austrian-CIS space missions AUSTROMIR in 1991 and 1992. During three missions the sensori-motor control of eye–head–arm movement and the ability of spatial hearing and pointing to acoustic targets was investigated. The acoustical part of these experiments was conducted in cooperation with Fa.AKG/Vienna.

Dr. Berger has published 93 papers in his areas of interest.