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Acoustics Today

Sounds in Space
Sounds of the Eiffel Tower
Environment for Auditory Research
Hearing Aid Terminology
and more

A publication of the Acoustical Society of America

United States Army's Environment for Auditory Research Laboratory

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FUTURE ARTICLES

The "Technical Committee on Noise" Theme Issue

Pitch Circularity

Bow Bells

Cavitation and Cetacean

Marine Mammals

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Acoustics Today

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Volume 5, Issue 3 **July 2009**

Cover: Army personnel are required to perform missions while immersed in a wide range of ambient sounds. Acoustic recreations of rural and urban soundscapes mixed with relevant military sounds need to be presented to warfighters in controlled laboratory spaces to quantify the effects of auditory environments on listening tasks. For this reason, the Environment for Auditory Research (EAR) facility was conceived and constructed at the U.S. Army Research Laboratory (ARL) at Aberdeen Proving Ground, Maryland. This new facility will be used to study the ability of soldiers to detect, identify, and localize sounds in realistic operational sound fields and to develop equipment to maximize human communication performance.

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WHAT IS THE SOUND OF THE EIFFEL TOWER?

China Blue
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How the intersection of audio technology, architecture and art can change our perception of what we thought we knew

The sound of human spaces is defined by human expectations. Architects consider sound based on how vibrations affect the structural integrity and the acoustics of residential and performing spaces. Bioacousticians examine sound based on its effects on living organisms and how it affects their behavior in the environment. Musicians and artists judge it by how it impacts their creations and their listeners. However, as in many fields, crossing categories can generate a hybridized result, and allow new, enriched sonic experiences to emerge. In the pursuit of a new way to consider the intersection between structure, space and human sound, in September 2007, I went to Paris to reexamine the Eiffel Tower.

> *"Social impact operating in conjunction with the structural acoustic elements creates a complex and dynamic sonic ecology that helps to extend our knowledge of how we perceive our sonic world."*

My plan was to create a sound environment based on what I expected to hear—the sounds of traffic around the base, human voices and footsteps—the normal sounds we hear from any human urban space, the differences largely based on the linguistic mix of a tourist site in a foreign country. But shortly before receiving authorization by the Societe d'Exploitation de la Tour Eiffel to do the recording, by chance I had come upon some near-infrasonic sound recordings based on seismic events—earthquakes, temblors, underwater recordings of tsunamis—and I was intrigued with the possibility of trying to expand my recordings to including what I previously had thought of as beyond human hearing—infrasonic recordings. I managed to obtain some "can" geophones from a surplus house and after some test trials, decided to include the infrasonic and near-infrasonic in my recordings of the tower. I realized that I had no idea of what I would capture (possibly nothing useful). But, following in the path of Gustave Eiffel, the builder of the Eiffel Tower who used it as his private laboratory for his scientific research, it was an experiment.

My goal was to record using two different methods. One would be to use the geophones to record the actual vibrations of the iron of the structure, the other was to record the social experience of being there. People usually specialize and record either the subsonic or the ambient soundscape, but normally not both. Yet, from my prior recording work I concluded that to capture the full acoustic environment, it was important to sample both ranges of the structure. By doing this I would collect not only the physical impact of the structure but also the social impact. For this work I had the help of 8 technicians, 6 from France and 2 from the United States. Seth Horowitz, a member of the Acoustical Society of America's Technical Committee on Animal Bioacoustics, came on board as the Chief Technical Officer for the project.

The process

The multiple levels of the Eiffel Tower were the inspiration to try out multi-level recording—examining various points in the tower using multiple recording techniques. To achieve this, we used two types of microphones. The first was the can-type geophones (with resonant frequencies of ~14 Hz) connected to 100 meter cables. These sensors are normally used for monitoring seismic activity, but we adapted them for this purpose because they would successfully capture the subsonic vibrations. We recorded from two geophones simultaneously on separate channels onto a single 4-channel digital recorder (Zoom H4) to allow us a hardwired method to avoid any differences in time of the arrival of sounds across the potential span of 200 meters. The next method we used was recording via in-ear stereo binaural microphones. These microphones pick up sounds that have a very human feel based on their position in the ear canal and allow the external ears to shape the sounds to be similar to what a person normally hears and create a very personalized and "human" sounding recording. The binaural recordings were captured on a Sony portable DAT deck. In addition, a third "wandering" team member carried an additional Zoom recorder using built-in microphones configured for long distance (shotgun-style) recording to capture any additional ambient or transient sounds. All recordings were done at 48.1 kHz/16 bit sampling.

The planning and transporting of the equipment was an extensive and stressful process. We were traveling from the US to Paris, France with two Zoom H-4s, one Sony Digital Audio Tape (DAT) recorder, six 100 meter lengths of XLR cables, 6 customized geophones, a pile of Secure Digital (SD) memory cards and DAT tapes, and of course the inevitable rolls of electrical and duct tape. I was primarily concerned whether the equipment would pass security inspection since there was a likelihood that the equipment might look like material to create a bomb. So to avoid any problems, I placed instruction manuals for everything in the suitcase and the authorization to record the Eiffel Tower in hopes that if anyone opened the case, they would have complete description of what was inside. Fortunately we had no trouble with authorities until we were actually on site.

We arrived at the Eiffel Tower that fall morning at 9:00 a.m. with all of the equipment ready to do a test recording

Fig. 1. Some of the equipment. The Zoom H4 is not shown. Credit: China Blue.

(Fig. 1). That morning just as Dr. Horowitz and I were first setting up the equipment, a lead to one of the geophones broke. This was my worst nightmare because although I brought 6 sensors, that morning only two were on site and the rest were at the hotel a few miles away. Additionally, the one thing I didn't pack was a soldering gun and I had no idea of how to say "solder" in French, much less where to find the equivalent of a Radio Shack in Paris. I looked down at the situation and then Dr. Horowitz and I just looked at each other in agony as attempts at wrapping the geophone in electrical tape were clearly not going to work. Dr. Horowitz happened to be chewing gum at that moment; I paused and then it came to me. I asked him for his gum. He looked a bit tentative but handed it to me and we used it to try to repair the connection. I didn't think it would work but fortunately it worked perfectly for the entire duration of the recordings, and even as I am writing this today the gum is still connected to the sensor. Perhaps the lesson learned was to always travel with an extra pack of peppermint gum (Fig. 2).

With our recording gear working, we had to consider the best plan to capture the full range of sound and vibrations of the tower. We were expecting to record infrasonic and sonic vibrations based on the movement of the elevators as they transport the visitors up and down, and the vibrations of the tens of thousands of feet that walk across it every day, as well as the whining of the wind through the tower and the human sounds of her visitors. These are the forces that transfer energy to the 2,500,000 rivets and 18,038 pieces of iron of the tower. We originally planned to record at each level using both the geophones and the binaural microphones, but my original plans to record with a geophone planted on separate pillars of the tower on the ground level was logistically impossible so it was not going to work out. Aside from construction going on at one of the entrances that blocked our access, the wind and rain on that September day was blowing at up to 10 km/hour, the temperature was a chilly 12°C and the rain was shifting from a constant mist to a near-horizontal deluge. However, breaks in the weather allowed us to carry out the alternate recordings designed. While members of our team walked about on the ground level with the in-ear binaural recorders and the additional shotgun microphones, Dr. Horowitz and I set about the first geophone recordings (Fig. 3).

We decided to set up the geophones on two separate legs that enter the stone at the base of the North pillar (Fig. 4). This seemed the simplest technique but did in fact cause some minor havoc—a miscommunication between the tower's security manager and the local *gendarmes* led a squadron of startled French soldiers to start yelling at Dr. Horowitz in high speed French to come down and put down what clearly must have looked like a small wired bomb. The raised machine guns made the point and our recording session was over until the manager who fortunately was nearby came and cleared up the issue.

Once in position, via clambering on the stone supports with rolls of duct tape, the two geophones were calibrated and tested to see if we would get signal crossover from one leg to another. As soon as we started recording, we found that even with a best frequency in the near-infrasonic range, we were able to hear a rich acoustic signal. During the 20 minute recording session we captured both the wind's force against the structure as well as the elevator's intermittent movements as it passed from floor to floor. If you have downloaded the audio material (Editor's note: see "Directions to download the *interactive* Audio Clips and Track Samples" at the end of the article) you will hear the ground-level near-infrasonic

Fig. 2. Peppermint gum used successfully to repair broken solder joint Credit: China Blue.

Fig. 3. China Blue monitoring the recording in front of the Jules Verne Restaurant on the ground level. Credit: Seth Horowitz.

recording that was produced (Clip 1).

We also used this same method to record in the sub-basement. This area that is out-of-bounds to visitors is a room where all of the motors, gears, pulleys and accumulators are housed that run the whole system some of which are original and now over 120 years old. We placed the geophones on the metal foot bridge that amplified and resonated with the vibrations of the machinery housed on the floor below. There we monitored the chassis that pull the elevator gears and cables and the accumulator that makes a spewing sound as it spills oil to let the elevator ascend (Figs. 5, 6). We also heard the emergency alarm that went off when one of the elevators temporarily stopped and the workers running and yelling as they responded to the alarm. That was when Dr. Horowitz said that I broke the Eiffel Tower. Here a sample of the geophone recording of the carriage in the machine room can be heard. (Clip 2).

Ascending from the sub-basement via a service elevator, we next decided to record from the summit, just in case the weather would prevent such recordings later in the day. At the summit, we positioned the seismic sensor system on the outside railing that runs continuously around the tower on this level. There we captured a separate recording of the wind blowing against the summit at the elevation of about 1,000 feet (Fig. 7).

We also applied this method to the service stairwell landing (just under the summit—another area closed to tourists).

Fig. 4. Seth Horowitz placing the seismic sensor on the iron at the base of the Eiffel Tower Credit: China Blue.

In this region are the fire escape stairs and service access areas that are adjacent to the open elevator cages. There we placed the geophones on a metal grating to capture the sound of the elevators going by as they moved within inches of our faces (Fig. 8, Clip 3).

For the ambient sonic recordings, we primarily used the in-ear binaural microphones attached to the DAT for a period of 20 minutes at each location. I assigned a team member to monitor the binaural system and whenever possible, the individual would walk in a snail shell or circular pattern moving from the inside out to capture the ambient acoustics on each level. On the ground level this was an easy walking pattern. This is a large open area where people clustered in groups and we were able to capture street sounds, the sounds of the on-going construction on the lower level of the Eiffel Tower, and visitors queuing up to get into the tower. Listen here to the binaural recording at the ground level (Clip 4).

The snail-shell recording pattern could not be applied in the machine room area because our work area was limited to two narrow staircases and the metal service bridge that overlooks the floor below where the elevator equipment is housed. Although this recording area was physically limited there were fascinating mechanical sounds that we were able to capture (including the emergency alarm). The sounds of the emergency in the machine room were caught on the binaural recording (Clip 5).

The area just under the summit is a narrow metal main-

Fig. 5. Chariot pulling the cables in the subbasement. Credit: France Languérand.

Fig. 6. Another view of the sub-basement equipment with a portion of the large orange accumulator on the left. Credit: France Languérand.

tenance staircase surrounded by the open geometric patterning of iron that forms the structure. There again, the binaural recording method was limited to the staircase, but what was captured by both the geophones and binaural microphones was remarkably dynamic: regular metallic clattering of the ascending and descending elevators, second harmonics of the wind through the infrastructure, and of course the occasionally radical changes in noise as wind screens were blown off by gusts (Fig. 9, Clip 6).

On a clear day the summit provides spectacular views of the city—up to 40 miles away. That day, however, there was a taxi protest so when we looked down we saw the taxis lining the streets for hours protesting for a wage increase. While we were told that this was not that unusual, the semi-constant tones of French taxi horns were fleetingly picked up, even miles away and 300 meters up, underneath the more local sounds of the wind, rain and of course human voices. One of the more interesting moments sampled was a group of children seeing the Eiffel Tower for the first time. Their enthusiasm was contagious (Fig. 10, Clip 7). In this clip you will also hear the geophone recording of the high-pitched whistling of the wind. This is an exciting example of the wind's energies sending waves and vibrations through the tower's structure.

Fig. 7. Placement of the geophone on the railing with a view of the Champ de Mars below. Credit: Seth Horowitz.

Fig. 8. Geophone positioned on the metal grating in the service stairwell underneath the summit. Credit: France Languérand.

How does recording beyond the normal sonic range change how we understand sound?

Vibrations are anywhere there is energy and a medium to transfer it. The sources are from the forces of the wind, rain and snow, the machines that operate in or around the structure, and from people moving through the space. Materials used in the construction of structures respond differently to these sources, and although we do not hear them all, it is the vibrations that create the total sound field of a structure. To experience and perceive this full range, we need to extend our own sensory range and bring those below (or above) it into the realm of human experience.

At a practical level, as the goal of this project was to create a sound art/musical piece, I needed to be sure that the entire range of acoustic signals, even those below the normal range of human hearing (not to mention speaker performance) would be audible to listeners. While the geophones picked up sounds in the range of 1-40 Hz, analysis and editing software showed some of the more interesting vibrational signals were, as expected, well below 20 Hz. To bring these sounds into the listener's range, I inverted a method from bioacoustics that allows humans to listen to ultrasonic bat signals and used a pitch shifting algorithm to bring the lowest frequencies into the audible range.

A good example of the usefulness of extending our acoustic range can be found in the seemingly unrelated field of animal behavior. Animal behavior has often been studied by using the most basic (and useful) of tools—our own eyes

Fig. 9. Service stairwell underneath the summit. Credit: France Languérand.

and ears. However, this works best when we observe animals like ourselves—daytime dwellers whose sounds we can hear. But relying on these techniques causes problems when the subject of study is more exotic. For example, it was largely thought that big brown bats (*Eptesicus fuscus*) hunted insects at night in clearings; however, it was not until studies were carried out using thermal vision cameras, allowing real-time tracking of the animals' movements in total darkness at a distance outside of the lab, that these limitations were found to be artifacts. Big brown bats in fact carry out highly acrobatic maneuvers even in thick vegetation.[1] In this paper, James Simmons pointed out that the limitations of the usual methods of observation restricted how behavior was assessed. The "system proved superior for making observations of bat behavior at night because the bats are nearly always visible and can be followed for as long as they remain in line-of-sight out to 50-100 m or so." [2] And, what he concluded is that new technology enables us to come to new understandings of the world around us. This is what we discovered with the new equipment used to record at the Eiffel Tower. We were able to understand it and see it in a new way, through her sounds.

Throughout history few scientists have studied sound in relationship to structures. Christiaan Huygens in 1692 was possibly the first to map the movement of sound in space based on reflections. His discovery, "l'Echo" later became known as a Repetition Pitch, was discovered when Huygens "noticed that the noisy sound from a fountain produced a certain pitch. He was able to determine the height of this pitch by matching it with the pitch produced by a 'closed organ pipe.'" This work was later confirmed by Bilsen in 1993, with contemporary methods and equipment.[2] Similar architectural pitch shifting was discovered at the Kukulkan pyramid at Chichen Itza, a Mayan ruin in Mexico in 1998 by David Lubman.[3,4] There he discovered that hand claps are heard as chirps as they reflect off of the pyramid stairs. Lubman determined that these were periodic reflections off of the stair surfaces. In addition, Anish Kumar described the interesting musicality of the Vitthala Temple in Hampi in South India. If you strike a column with your finger it produces a sound, with the frequency varying, depending on the column struck.[5] The increasing interest in this crossover between architecture and acoustics has also led to a steady growth in both research and practical applications of architectural acoustics for design of human spaces ranging from symphony halls to quiet work areas.[6]

What is compelling about these viewpoints on sound and architecture is that they analyze the physical nature of sound movement in relationship to the surface of a structure—rooms in the case of Salter, stairs in the case of Huygens and Lubman, and columns in the case of Kumar. The difference between these works and what we accomplished was that we recorded the actual vibrations trans-

ferred through the iron, in addition to those in the air around it. By adding the subsonic range to our acoustic perception, we uncovered another dimension to consider in listening to a building: the unheard subsonic sounds that are reactions to environmental forces on the materials. This activity is what gives the Eiffel Tower the characteristic of a living fluxing organism: a dynamic system. And yet, its dynamic qualities are not based on just being a passive receiver of vibrational energies. The heavily-visited Eiffel Tower is not just a resonator of physical forces but impacts its environment by acting as a local attractor of human attention.[7] This effect is achieved by the increased density of observers and of local behavior both reactive, through the vibration of their feet on the surfaces and evocative and in the form of their exaltations. These physical and social sonic characteristics are ongoing ambient and subsonic noises that also play a part in the perception of a space. They also need to be considered in assessing the psychoacoustics of our environment. Even though these are the sounds that we selectively edit out as noise in our normal experience of a space these sounds are critical to our overall sense and perception of our world and part and parcel to our experience of the Eiffel Tower. This combination of the social impact operating in conjunction with the structural acoustic elements creates a complex and dynamic sonic ecology that helps to extend our knowledge of how we perceive our sonic world.

Fig. 10. China Blue monitoring the recording equipment placed on the railing on the summit. Credit: Seth Horowitz.

Conclusion

The acoustic environment of architectural structures is comprised of complex social and physical sonic characteristics. The human auditory sounds represent the sounds of the world around us based on our own acoustic viewpoint, whereas infrasonic vibrations represent the inherent movement and vibrations of the structure. Together they create an acoustic epiphenomenon, an energetic ecology based on time, human presence, and vibrational acoustics—a ~~spectro-~~temporal aesthetic. Using our senses to integrate the physical vibrations, social acoustics and auditory psychophysics extends our knowledge of how we perceive. The sound of a structure, a transparent yet primary component injects physical, social and time-based concepts into it, thus adds a human-related construct to the art that is produced from it. And, although the Eiffel Tower has no formal inside and outside, it is through usage of the structure that these ideas are established. As Roland Barthes said: "The tower is there incorporated into daily life…it is as literal as a phenomenon of nature whose meaning can be questioned to infinity but whose existence is incontestable."[8]

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Editor’s note: Directions to download the *interactive* audio clips and track samples

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SOUND ART AND SCIENTIFIC TECHNOLOGY

The sampled sounds from all of the areas of the Eiffel Tower became the basis of a final art piece, published on both a CD and a thumb drive—*Under Voices: Les Voix de la Tour Eiffel*. In this compilation, the recordings of the sonic space as well as the structural vibrations of the Eiffel Tower were used.

The six pieces on the CD were created from a diverse array of multi-level compositional influences that provided the structural envelope for the raw material. First and foremost the usage of ambient sound (noise) is a nod to *Musique concrèete*, a style created in the early 1950’s by Pierre Schaeffer; this is, a form of music that uses raw sound as a compositional device without the requirement for it to be traditionally “musical.” But as these are contemporary times with contemporary influences that cannot be ignored, the acoustic narrative style of Pink Floyd was the inspiration to provide a backbone while new technology based concepts are captured with the use of dial-tone multi-frequency (DTMF) i.e., touch-tone telephone tones. Samples of each of the tracks on *Under Voices: Les Voix de la Tour Eiffel* have been included on the download. The CD and thumb drive are available at www.chinablueart.com.

Under Voices: Les Voix de la Tour Eiffel (China Blue)

Under Voices: (Sous Voix) uses the recordings of the wind in full force on the summit. There on the summit, sometimes it takes more than your own strength to stand up against the wind as it blows through the iron beams. Yet, while you can feel and hear a high pitched whistling, most of the wind’s energy is spent in sending waves and vibrations through the tower’s structure. Largely unnoticed, the impact is very much there. This track is the unheard song of the tower in the wind.

The Wind and the Accordionist (Le Vent et le accordéoniste) and *The Wind and the Accordionist, Reprise (Le Vent et le accordéoniste)*. Edith Piaf is an icon of French music. Her voice, heard in combination with the tones of the accordion, are what evoke a classically romantic image of Paris. *The Wind and the Accordionist* weaves samples of her classic songs with sounds of wind through the tower to create a nostalgic sonic mosaic of French culture and architecture.

Crypto Keys (Les Messages Caché). The Eiffel Tower is not just a tourist attraction. It has been involved in communication and counterespionage in two world wars because it possesses one of the tallest radio towers in the world. During World War I for example, “the tower’s radiotelegraphic center was used to intercept enemy messages, one of which led to the arrest and execution of the infamous Dutch dancer and spy, Mata Hari.”[8] *Crypto Keys* captures the Eiffel Tower’s surveillance capability in wartime with shortwave spy messages from the era. Other hidden acoustic information is imbedded in the piece in the form of DTMF tones which were derived from statistics of the Eiffel Tower including features such as its height, how many pieces of iron were used to build it and how many rivets hold it together, etc.

Memory Strains (Les oreilles de l’ascenseur). The elevators are the vessels that have carried people up and down the tower’s living body for over a century, and the operators are their guardians. These people have heard snatches of millions of lives in numerous languages for over a hundred years. *Memory Strains* pays homage to these life stories with acoustic fragments that flicker by—in a vertical flow of sound.

Iron Rhythms (Les Rhythmes de la fer forgé) ring throughout the whole tower but rise from the structure unseen by almost everyone. A mechanical underworld supports the complex building above. This piece is based on the rhythms and sounds of the machine room from the humming and pounding of the “chariots” to the sounds of the elevator motors that constantly push them up and then bring them back down the structure.

The Woeful Tale of Jack the Snail. In the style of multitrack sampling, I asked Lance Massey, the creator of the T-Mobile ring tone, if he would like to make a piece from the selection of raw files. From this material, he created *The Woeful Tale of Jack the Snail*. This wonderful pop piece tells the story of Jack the Snail’s short and tragic life.

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China Blue. Credit: France Languérand.

China Blue is an internationally exhibiting artist who is the first person to record the Eiffel Tower in Paris, France. She pursues the intersection of sound and architecture. Her work has been shown in galleries and non-profit spaces in Finland, Sweden, France, the United Kingdom, and the US. She was the United States representative at OPEN XI, Venice, Italy, an exhibition held in conjunction with the Architecture Biennale. Her work has also been shown at the Melbourne International Arts Festival in Australia and the Armory Fair in New York. Reviews of her work have been published in the *New York Times, Art in America, Art Forum, artCritical,* and *NY Arts* to name a few. She has been interviewed by France 3 (TV), for the film "Com-munity" produced by the Architecture Institute of America and was a featured artist for the 2006 meeting of the Acoustical Society of America. She has been an adjunct professor and Fellow at Brown University in the United States. Her work is represented by Galerie Barnoud, Dijon, France and Art Currents, New York, NY.