A Visual Imprint of Moving Air: Methods, Models, and Media in Architectural Sound Photography, ca. 1930

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The recent turn toward studies of the environment as part of architectural history puts in question the discipline's emphasis on the visual and challenges us to include phenomena that are physical but not necessarily recognizable by the eye.[1] Environmental histories expand the scale and media of subjects commonly thought of as "architectural."[2] For example, architectural sound photography from the 1920s and 1930s is a remarkable and overlooked reference for the noise maps and climate registers circulated currently. In this article, I examine the photography of sound in architectural models, placing it at the intersection of the history of architecture, modern architectural acoustics, and media for visualizing physical phenomena. I will show how this photographic method links the sensory and the scientific in architectural reasoning. The models and apparatuses used to study the acoustics of spaces expose the material stakes involved in simulating architecture. While mathematical calculations of architectural acoustics, such as the reverberation formula, are still in use, visual representations of sound created with photography were soon declared obsolete. Today, the study of photography of sound propagation from the archives allows us to understand the role of the senses both in the conception and perception of scientific experiments and in architectural reasoning.

During the final months of my doctoral research, I discovered a crimson loose-leaf binder containing more than a hundred photographic prints, dated from 1930 through 1933, mounted onto fifty-six sheets of mostly brown paper.[3] The binder had lain forgotten in the basement archive at the acoustics department of Empa, the Swiss Federal Laboratories for Materials Science and Technology, near Zurich, as part of the meager archive of Franz Max Osswald (1879–1944). Osswald was Switzerland's first expert in architectural acoustics and founder of the first applied acoustics laboratory at ETH, the Swiss Federal Institute of Technology, in Zurich. The photographs in the album depict sound waves propagating, reflecting, and diffracting in sectional models of various geometries. I was looking at shadowgraphs of moving air, superposed pressure wave fronts imprinted on the photographic paper as gray lines and tones, all shimmering streaks capturing a moment of sound passing through space (Figure 1). The physical transfer of acoustic energy to scientific imagery as an expert's representation of sound, and the translation of the gray shadows back into what we can hear but not see, challenges our understanding of physics and the environment. Sound no longer appears ineffable but is transcribed in graphic representation. I realized that such images are crucial for communicating environmental phenomena such as the movement of air, temperature, and sound. Architectural sound photography, as this essay will show, was as much about dispelling the mysteries surrounding sonic phenomena as it was about implanting architectural design in the impenetrable registers of the science of physics.

Visual representations have accompanied the acoustic sciences since the Vitruvian analogy of the sound wave with the water wave in antiquity, when the visible movement in water was employed to explain the invisible movement in air. In the seventeenth century, Athanasius Kircher illustrated sound as straight lines reflecting off of walls and buildings. Shadowgraph techniques also go back to the seventeenth century, as part of the larger field of scientific observation using microscopes, telescopes, and glass lenses: the air flow of warm air

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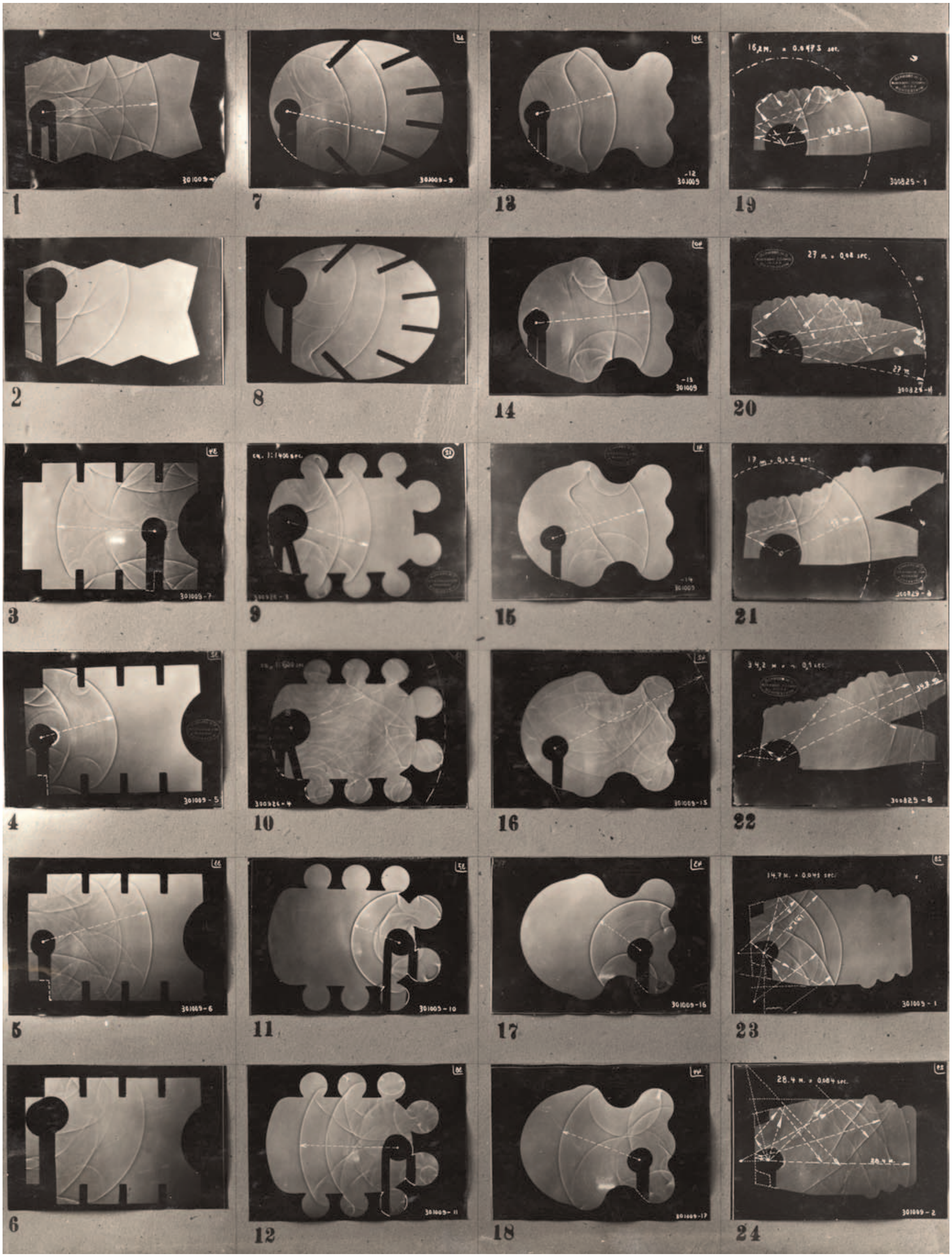

Figure 1 Franz Max Osswald, contact print of sound photographs in architectural models, from Osswald's applied acoustics laboratory at ETH Zurich, 1930–33 (Image Archive, ETH Library Zurich, http://doi.org/10.3932/ethz-a-000986437).

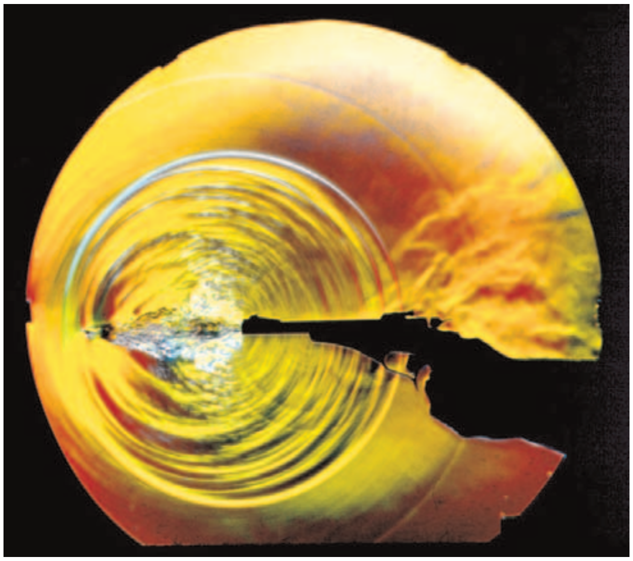

Figure 2 Shock wave visualization from a bullet fired from a pistol as a reenactment of a schlieren technique experiment from the late nineteenth century (photo by Gary S. Settles).

rising from a candle, or a hand, caught the attention of scientists. Architectural sound photography was developed from direct shadowgraphy without instruments (e.g., the hot air of a candle represented in a drawing) and the schlieren technique, which involved a shock wave from a gunshot and prismatic effects from lenses (Figure 2).[4] Both the wave and the line characterize the movement of sound and remained models for understanding sound in parallel; the photographic method explained in this essay was the first technique that held the promise of capturing the performance of sound in space in a comprehensive, objectified way, taking into account both wave and line characteristics. In architectural applications, often in studies of theaters and auditoriums, shadowgraphy and the schlieren technique aimed at capturing the spatial propagation of sound. They coexisted with other forms of visual representation through spectrography, phonophotography, melography, and oscillography, which captured specific parameters of sound, such as loudness and frequency.[5] The names of some of these techniques allude to photography, although the visualizations were produced mechanically or electrically. The products of Osswald's experiments in the early 1930s at his Institut für Angewandte Akustik (Institute of Applied Acoustics) at ETH indeed deserve to be called "sound photographs." Osswald in his schlieren imaging captured shadows of inhomogeneity in air, caused by sound waves traveling in space, on photo plates photochemically. He took blurry photographs inside sectional models, at a scale that fit into the experimenter's hand, and exposed them onto photographic paper that fit into the photo album.

Studying representations of sound brings forward the architectural consequences of media transfers and model scaling, as well as the ambiguities of expert reading and lay interpretation. The process of photographing sound raises a number of interesting questions about the relation between the visual and the auditory: The tyranny of the eye over the ear is a prevailing assumption in the hierarchy of the senses, but in these photographs the visual clearly serves the aural. While for Osswald the appeal of the schlieren technique may have lain in its (arguably unrealized) promise of objectivity, I will argue that its appeal was as an interface that incorporated the human sensorium in modern science. This may be the reason Osswald continued to pursue this method well after 1930, when others had abandoned it for its lack of precision and failure to represent all three dimensions of space accurately. In the 1930s, electroacoustic testing superseded photography and became indispensable in the automation and standardization of modern acoustic measurement. At Osswald's institute at ETH Zurich, electroacoustic testing coexisted with photographic methods, never replacing them completely.

The acoustic sciences and their applications are subject to not one but multiple epistemic traditions—physics, psychophysiology, anthropology, engineering, aesthetics, and others. Osswald's relentless pursuit of sound photography is a case study in the role of images in the construction of scientific authority in architectural design. I believe Osswald's sound photographs give insight into epistemic changes in the modern era, analogous to the "medical gaze" that Michel Foucault links to changes not only in medicine but also in society at large.[6] They also relate to what Lorraine Daston and Peter Galison have written about the ways the "scientific self" has disciplined the "scientific gaze" in pursuit of objectivity.[7] The history of photography is more than a history of constructing objectivity through a lens. It deals with vague imagery from close up, shown so memorably in Michelangelo Antonioni's 1966 movie *Blow-Up* and also described as the "dark side of photography" in "black boxes and dark rooms" in studies of so-called ghost and thought photography, in which shadows of the dead were seen as emerging from the photochemical process.[8] While the intentions of shadowgraphy and schlieren photography were far from such metaphysics, sound and ghost photography share the ambiguity produced by the photochemical process.

The term *soundscape* has been criticized because of its assumed origin in the realm of the visual, a perspective opposed especially by anthropologist Tim Ingold, who recuperates *scape* for a discourse related to topography and materiality.[9] What physicists and engineers photographed in the images studied here belongs to the materiality of sound: the acoustic energy visualized in architectural sound photography had been acknowledged for decades before these images visualized the phenomena. Architectural sound photography could thus be interpreted as an afterimage of acoustic reasoning, in the sense of a confirmation of knowledge gained previously. I argue that, while architectural sound photography claimed to represent "mechanical objectivity," it simultaneously and implicitly included and activated the human sensorium.

The story of the production of photographs of the temporal, ephemeral phenomenon of sound brings together objective method and the experience of learning through the senses. The schlieren technique and its architectural applications rendered visual what could be heard, engaging the visual sense. The mechanical process qualified the technique as affirmation, proof, and a means of quantifying acoustic phenomena. The acousticians discussed in this essay, especially Osswald, used photography in their search for a multisensory approach, in anticipation of future sciences that would link the physics and the psychophysiology of sound.

Wallace C. Sabine's Search for Sound Localization

In his relentless experimentation with architectural applications of sound photography, Osswald appropriated the methods of the American physicist Wallace C. Sabine (1868–1919). Osswald began his career as an acoustic consultant in 1922, the same year his role model's posthumous *Collected Papers on Acoustics* was published—a coincidence established retroactively by the disciple himself.[10] Osswald corresponded for many years with Wallace Sabine's successor at Riverbank Laboratories in Geneva, Illinois, Wallace's distant cousin Paul E. Sabine (1879–1958).[11] A photograph dated 1925 and stamped by the Riverbank Laboratories, included among Osswald's papers in the crimson binder, may well have inspired Osswald's photographic experiments in Zurich.

Wallace Sabine's reverberation theory—first published in the article "Architectural Acoustics" in the *American Architect and Building News* in 1898—is widely considered the catalyst for modern architectural acoustics.[12] Osswald was among the following generation who relied on Sabine's methods almost exclusively. In 1913, Sabine had illustrated his essay "Theatre Acoustics" in the journal *American Architect* with architectural sound photography, describing the origins of his technique as "what may be called the Toeppler-Boys-Foley method of photographing air disturbances."[13] What Sabine refers to is the optical rendering of inhomogeneity in transparent media. It was physicist August Toepler (1836–1912) who, between 1859 and 1864, while earning his PhD at the Agricultural College of Pappelsdorf, invented, named, and refined what is now commonly referred to as the schlieren technique.[14] The German word *Schlieren*, which means striation, streak, or smear, was previously used to describe inhomogeneities in glass. Toepler observed pressure wave fronts and drew what he saw in ink; his drawings were so fine that many mistook the images for photographs.[15] Toepler's wife had his tombstone inscribed with the words "He was the first to see sound."[16] While Toepler did not see sound as such, he observed a variation of density in air caused by candles, electric sparks, and shock waves from gunshots and made drawings of what he had seen (photographic techniques of sufficient speed for his schlieren imaging were not yet available). In 1887, Ernst Mach (1838–1916), who entered the physics of sound with a background in physiology, together with Peter Salcher of the Naval Academy in Fiume, developed Toepler's method further so that the fluid dynamics of projectiles traveling through air at ultrasonic speeds, and ultimately the wave characteristics of sound, could be captured photographically. Both Toepler's and Mach's schlieren imaging was visual and thus qualitative, rather than numerical or theoretical, as physicist Gary S. Settles notes; it was Toepler's "excellent physical 'feel' for his subject" that triggered the experiments later integrated into the canon of objective scientific methods that can be expressed quantitatively.[17]

In 1912, physicist Arthur L. Foley and his junior teaching fellow Wilmer H. Souder adapted Toepler's method to confined shapes, though not yet architectural models (Figure 3). They published a paper that included a drawing and a detailed description of the apparatus they used.[18] In the paper, they describe the challenges of obtaining a source of light sufficient to create a photographic image and the difficulty of controlling the interval between the first spark to set off a sonic pressure wave and the second spark to expose the photographic plate. The line drawing of the apparatus illustrates the mechanisms for timing the gap between the electric spark causing the sound wave and the light spark (L) that then exposes the photographic plate: "When the interval between the two sparks is properly timed the sound wave at S casts its shadow on the photographic dry plate P" (Figure 4).[19] Foley and Souder dispensed with the lenses previously used by Toepler, which enabled them to produce images inside confined spaces such as circles and ellipses. The experimenters photographed the sound wave as it reflected back from straight and bent surfaces, some of them perforated, using what they themselves referred to as the "point source shadow method."[20]

Photographic experiments with sound waves in confined objects enabled the visualization of refraction (breaking) and diffraction (bending). This technique complemented the geometric modeling of sound as rays, which Adolf Loos had explained as "straight lines from the sound source to the ceiling, assuming the sound would bounce off at the same angle, like a billiard ball from the cushion, and continue on its way."[21] Loos's judgment that this method was "nonsense" is certainly wrong.[22] However, it is correct that it is not true for all spatial conditions, especially as sound waves have the capacity to bend around obstacles. Geometrical ray constructions rely on the analogy with optics, rendering only the directionality of sound. Although modeling sound propagation as rays provides useful approximations for outdoor areas and large spaces,

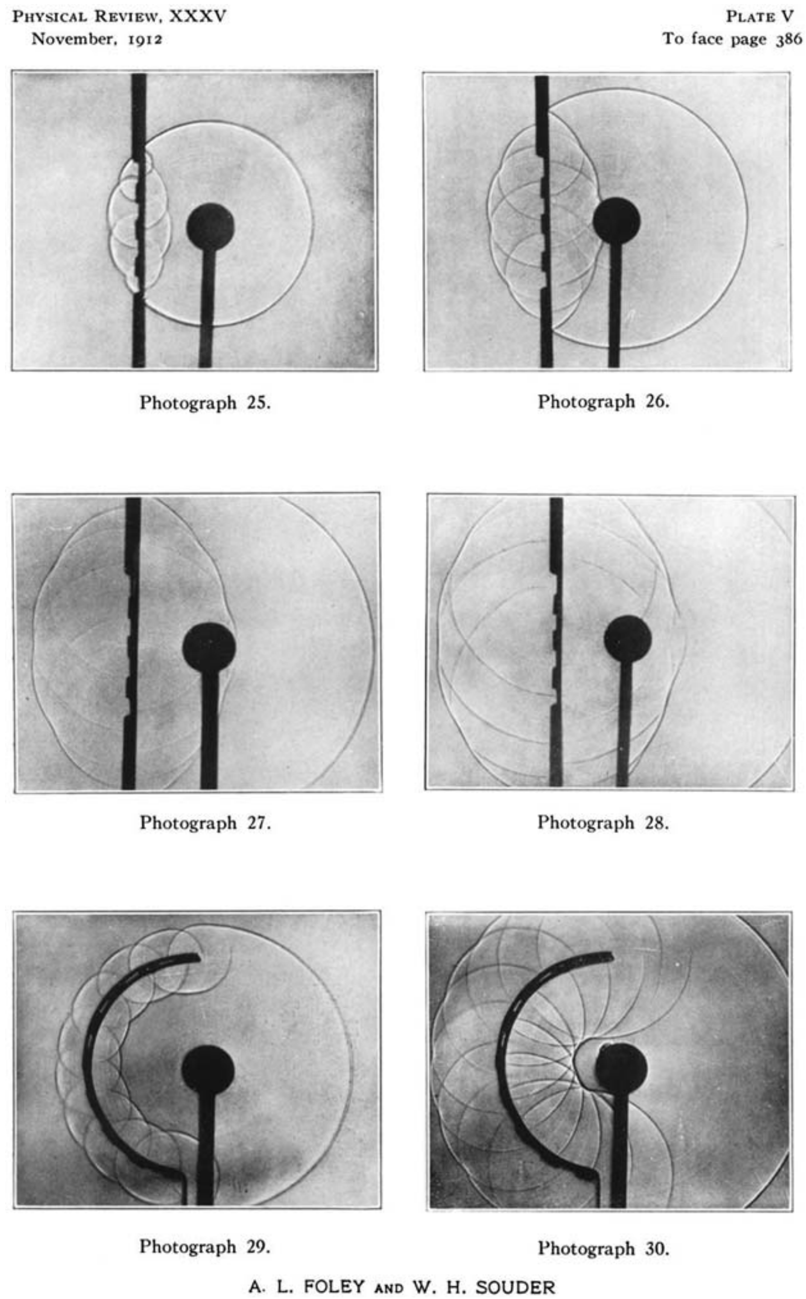

Figure 3 Arthur L. Foley and Wilmer H. Souder, experiments with schlieren photography in enclosed geometries, 1912 (Arthur L. Foley and Wilmer H. Souder, "A New Method of Photographing Sound Waves," *Physical Review* 35, no. 5 [1912], plate V).

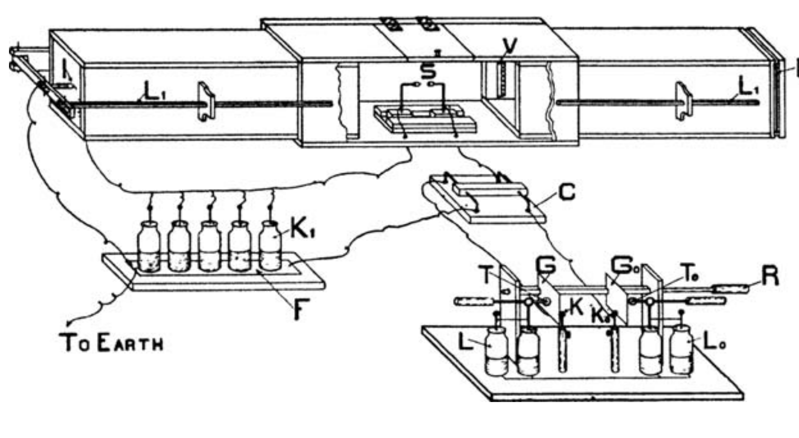

Figure 4 Apparatus for architectural sound photography, 1912 (Arthur L. Foley and Wilmer H. Souder, "A New Method of Photographing Sound Waves," *Physical Review* 35, no. 5 [1912], 374).

scientists looked for further ways of modeling sound. Especially in auditorium and theater design in the nineteenth century, the conflicting requirements of lighting and sound design were increasingly recognized, as the straight lines representing light worked for illumination but not for acoustics.[23]

In the early twentieth century, sound was a contested public issue. The building industry launched new products for sound insulation and absorption, newspapers debated noise abatement, and citizens sought increased silence and privacy. In churches and auditoriums, audience sizes increased, and with them the distance sound had to travel; sound reflectors, both those already created by the enclosing walls, floor, and ceiling and additional reflectors, were studied in depth. At this time, then, both drawings and photographs were useful and welcome tools for communicating the emerging field of architectural acoustics. While concepts and goals could be spelled out loudly, scientific explanations for sound lacked words and notations. Further models, other than mere line drawings, were needed to show the diffraction of sound waves.

The analogy of sound waves with water waves had been used since the time of Vitruvius, who described the expanding waves caused by a stone thrown into water. In 1787, the German physicist and musician Ernst Florens Friedrich Chladni (1756–1827) created the famous Chladni figures, patterns of sand resulting on metal or glass plates from vibrations at specific frequencies. Media historian Jonathan Sterne considers Chladni's technique "the founding moment of modern acoustics, and it embodies this connection between objectification, visualization, and the reversal of the general and the specific in theories of sound."[24] If we include Chladni's sound visualization in modern science, it predates what is considered the modern era of architectural acoustics.

According to Emily Thompson's influential history of architectural acoustics, the modern soundscape evolved in the nineteenth century, culminating with Wallace Sabine's reverberation formula, which gave architects unprecedented control over the acoustic performance of auditorium spaces.[25] At the beginning of the twentieth century, Sabine expanded the parameters of architectural design using a range of methods. His formula for reverberation time was the most influential; it is still used with little mathematical adjustment. In papers published from 1898 onward, Sabine explains how the geometry, volume, and material of a space determine its capacity to absorb or reflect sound.The formula $k = 0.171 \cdot V$ calculates the overall average of sound's energy in a space.[26] It describes quantitatively what we define in words as sound qualities such as "dead" or "dry" (with no or short reverberation) or full and echoing (with long reverberation). What Sabine's formula cannot explain is the local distribution of the sound's energy, which is crucial in auditoriums, where speech and music from the stage should be heard at all seats.

Sabine's subsequent 1913 paper on theater acoustics was extensively illustrated with schlieren technique sound photographs, as appropriated from Foley and Souder. The schlieren method promised a simulation of the differing intensities of sound—such as focal points and dead corners—across a space. Sabine announced that the "details of the adaptation of the method to the present investigation will be explained in another paper."[27] So far, however, this second paper has not been found, and Sabine makes no further mention of sound photography in his writings. Despite his disinterest in further photographic experiments, his 1913 paper is worth a closer investigation. It begins with a quote from Vitruvius's *Ten Books on Architecture*: "All this being arranged, we must see with even greater care that a position has been taken where the voice falls softly and is not so reflected as to produce a confused effect on the ear."[28] This emphasis on the "position taken" by the audience underlines the pertinence of describing the spatial geometry of sound distribution, of which Sabine's reverberation method had left out. The time and the intensity of sound were not the only things at stake in speech intelligibility and musical listening experience—the locality of the sound was also important. The excerpt from Vitruvius's treatise goes on to describe natural obstructions to the projection of the voice: those that reflect sound into the succeeding sound (creating dissonant sound), those that spread sound in all directions and reflect it into an indistinct field of sound (creating circumsonant sound), and those that reflect the voice, "producing an echo and making the case terminations double" (resonant sound). The last of Vitruvius's categories describes acoustic conditions "in which the voice is supported and strengthened, and so reaches the ear in words which are clear and distinct" (consonant sound).[29] In an effort to distinguish modern physics from practices based on traditional knowledge, Sabine updates Vitruvius's terminology with his own: "But to adapt it to modern nomenclature, we must substitute for the word dissonance, interference; for the word circumsonance, reverberation; for the word resonance, echo. For consonance, we have unfortunately no single term, but the conception is one which is fundamental."[30] Sabine's revision of acoustic method departed from ideas of proportion or universal harmony. It did so through a new terminology, complemented by new modes of representation. If reverberation measurements in milliseconds were a decisive step toward a mathematically precise description of sound in space, schlieren photography was a step toward mechanical objectivity in visual terms.[31]

The first illustration in Sabine's 1913 essay is a photograph of a small model of the Greek Theatre at the University of California, Berkeley (architect John Galen Howard), opened in 1903 and designed according to Mariano Fortuny's brand-new "Kuppel-Horizont" system. Sabine illustrates the problematic sound focalization in domed ceilings that were

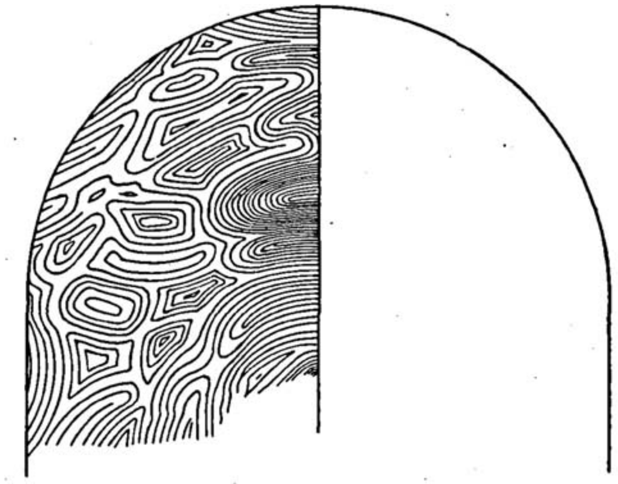

FIG. 5. INTERFERENCE SYSTEM FOR TENOR C IN THE KUPPEL-HORIZONT, HAVING A THIRTY-SIX FOOT PROSCENIUM OPENING. THE INTENSITY OF SOUND IS REPRESENTED BY CONTOUR LINES. THE MAXIMUM VARIATION BEING FORTY-SEVEN FOLD.

Figure 5 Wallace C. Sabine, contours of sound intensity, 1913 (Wallace C. Sabine, "Theatre Acoustics," *American Architect* 104, no. 1984 [31 Dec. 1913], 261).

designed to reflect light by tracing the contours of sound intensity, showing that the sound's energy is concentrated in the focal area of the dome and not reflected to the audience in any way analogous to the way light is reflected, as the designers had assumed (Figure 5). The graphic representation of contours of sound intensity served as proof for Sabine: the theater was designed for light projection effects, not for sound.

Sabine complemented the plans and interior views of the Little Theatre in New York (designed by the firm Ingalls & Hoffman and opened in 1912; now Helen Hayes Theatre) with a reverberation diagram. He illustrated his subsequent examples by means of photographs, including fifteen taken inside models of the longitudinal and cross sections of New York's New Theatre (designed by the firm Carrère and Hastings and opened in 1909) (Figures 6 and 7) and seven photographs taken during his experiments for Boston's Scollay Square Theatre (architect Clarence H. Blackall, 1912). For the latter, Sabine compared the longitudinal sections of the initial sketch (with a dome ceiling over the stage) to the built project with a flat plane over the stage.

After Sabine's premature death in 1919, the 1913 essay was included in his *Collected Papers on Acoustics*, published in 1922.[32] This collection of his revised papers led to the dissemination of modern acoustic theory and laid the ground for the formation of architectural acoustics as a discipline of its own on both sides of the Atlantic. In the comprehensive 1922 edition, a photograph of the open-air amphitheater in Orange, France—presented as the epitome of theater acoustics—was added as a full-page title image before the 1913 essay, even though it is hardly discussed in this paper on modern, enclosed theaters. Indeed, Sabine heaps scorn on the accounts of those who visit the Greek and Roman ruins and praise their acoustics. He claims that such praise is based on mystification and mocks the prejudiced ear, when the visitor in the ruins "makes a trial wherever opportunity permits . . . always with gratifying results and the satisfaction of having confirmed a well known fact. . . . The difficulty with such casual evidence is that it is gathered under wholly abnormal conditions," in "scant reminders of the original structure" (which had more reflecting enclosures than the present ruins) and in "absence of a large audience" (and their absorbing bodies and clothes).[33]

Sabine illustrates his article with sound photographs of contemporary enclosed theaters, establishing his reasoning as based in mechanically derived, objectified fact. The nuances of light and shadow inside scale models of modern theaters must have appeared mysterious to many of the article's readers, and yet it was exactly the "mystery of acoustics" that Sabine meant to expel from the discourse on sound. Despite the extensive use of photographic illustrations in his 1913 paper, Sabine never published such images, or referred to the technique, again. This seems to support Emily Thompson's contention that Sabine found the photographic method unrewarding and so did not pursue it further. Thompson restricts her discussion of his photographic experiments to a few lines, saying merely that "limitations of the available sources and detectors impelled Sabine to reconsider the utility of techniques for visually representing sound."[34]

Thompson links Sabine's interest in visual technique to eighteenth- and nineteenth-century practices, regarding it as an anachronistic move accounted for by his frustration with the fact that sound could be measured only relative to the hearing threshold of the human ear. However, the rich illustrations in Thompson's 2002 benchmark account on modern architectural acoustics demonstrate a consensus on the capacity of images to communicate scientific objects and phenomena. In his 1913 discussion, Sabine observes that images do not expose the "factors in determining the acoustical quality of the theatre, but the photograph affords excellent opportunity for showing the manner in which reflections are formed."[35] It is in "showing" more than in "knowing" that the founder of modern acoustics appreciates the photographic method.

Despite Sabine's abandonment of the technique, the fascination with sound photography among acoustic scientists persisted for another two decades, and beyond: At the beginning of the 1920s, German engineer Eugen Michel experimented extensively with acoustical water wave photography in ripple tanks. Michel preferred photographing ripples of

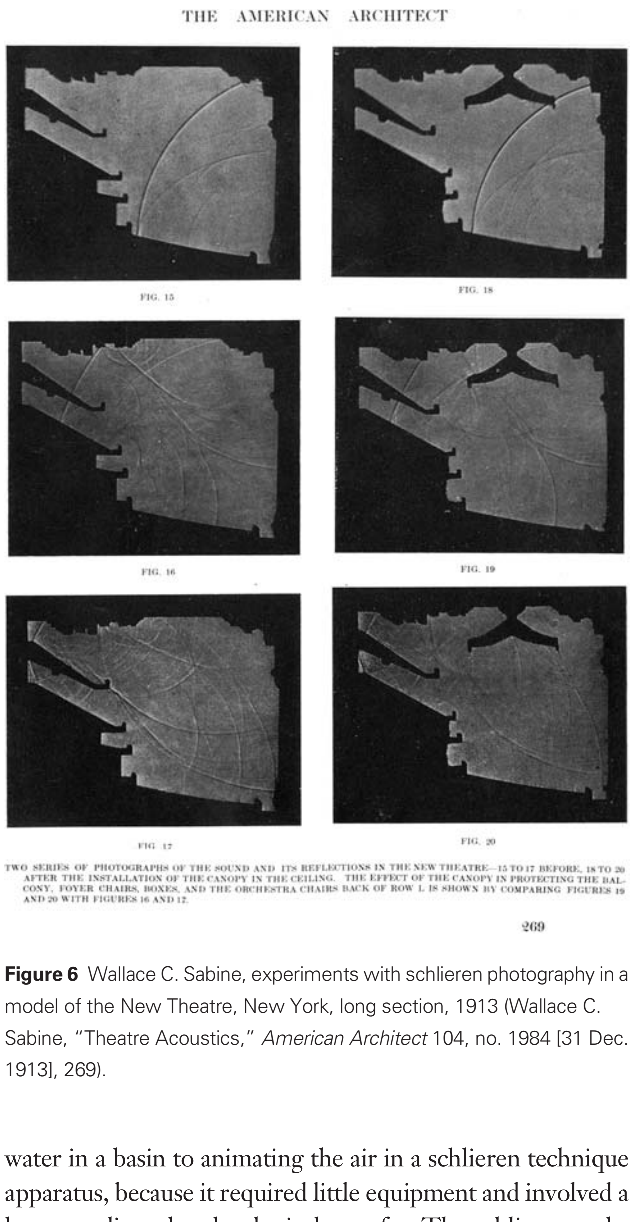

Figure 6 Wallace C. Sabine, experiments with schlieren photography in a model of the New Theatre, New York, long section, 1913 (Wallace C. Sabine, "Theatre Acoustics," *American Architect* 104, no. 1984 [31 Dec. 1913], 269).

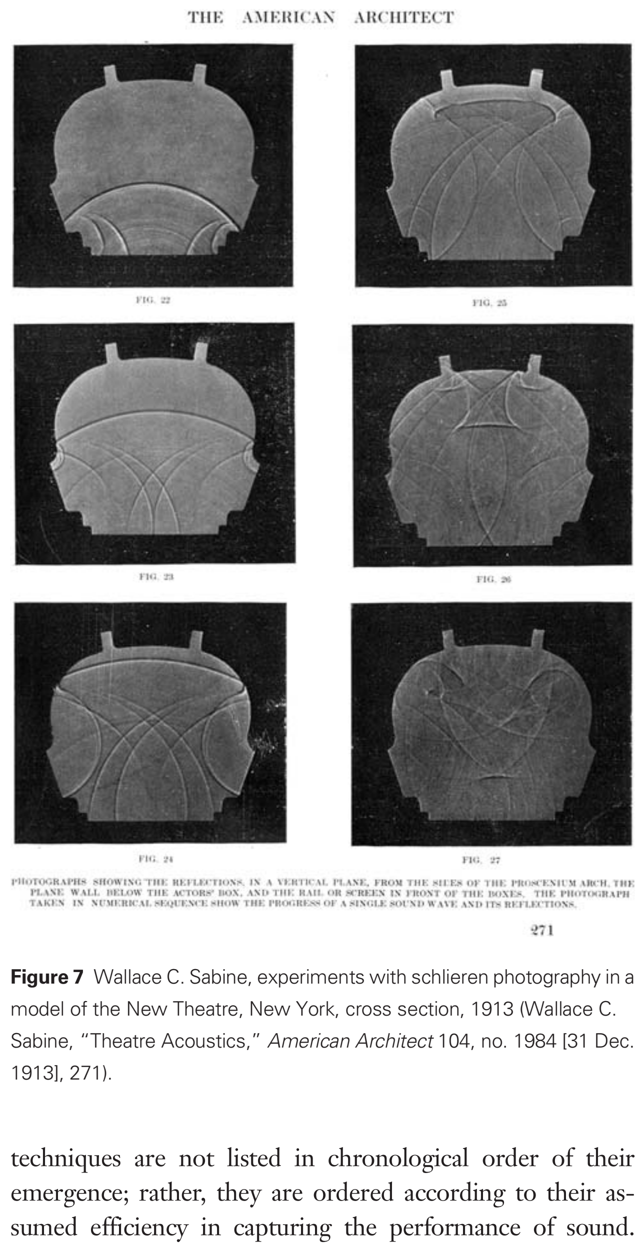

Figure 7 Wallace C. Sabine, experiments with schlieren photography in a model of the New Theatre, New York, cross section, 1913 (Wallace C. Sabine, "Theatre Acoustics," *American Architect* 104, no. 1984 [31 Dec. 1913], 271).

water in a basin to animating the air in a schlieren technique apparatus, because it required little equipment and involved a less complicated technological transfer. The schlieren technique asks for electrical equipment and, due to the necessary intensity of light, a rather small sectional model set vertically into the photographic apparatus. Water wave photography was easier: one simply put a model, of practically any scale as long as it fit into the basin, horizontally into water and photographed the surface of animated water, or the reflections thereof on a screen.[36] Water and air are both fluid media. In the ripple tank, the propagation of sound in air was simulated in water; the ease of handling, in Michel's assumption, compensated for their differing physical properties.

In 1927, scientists Alfred H. Davis and George W. C. Kaye of the National Physical Laboratory in Teddington (on the outskirts of London) published a comprehensive overview of the different methods for studying sound, three of which they described in detail: the geometrical method, the sound-pulse method, and the ripple-tank method.[37] The techniques are not listed in chronological order of their emergence; rather, they are ordered according to their assumed efficiency in capturing the performance of sound. Over three pages, Davis and Kaye introduce the method of geometrically constructing line drawings as a "first approximation."[38] In this section they quote from Michel's 1921 benchmark publication and reproduce several of the meticulous drawings preceding his photographic ripple-tank experiments (Figure 8). They remark, however, that "the diagram gives no indication of the relative intensities of the various portions of the wave-front."[39] Next is a description of the electrical "pulse" or "spark method" of architectural ultrasound photography as derived from the schlieren technique. Davis and Kaye then discuss the ripple-tank method in four pages of text and four pages of plates that culminate in a kinematographic series of fifty-five images (Figure 9). They reinforce the importance of studying not only single moments but also sequences of sound propagation. The limitations of schlieren sound photography are more severe than simply the

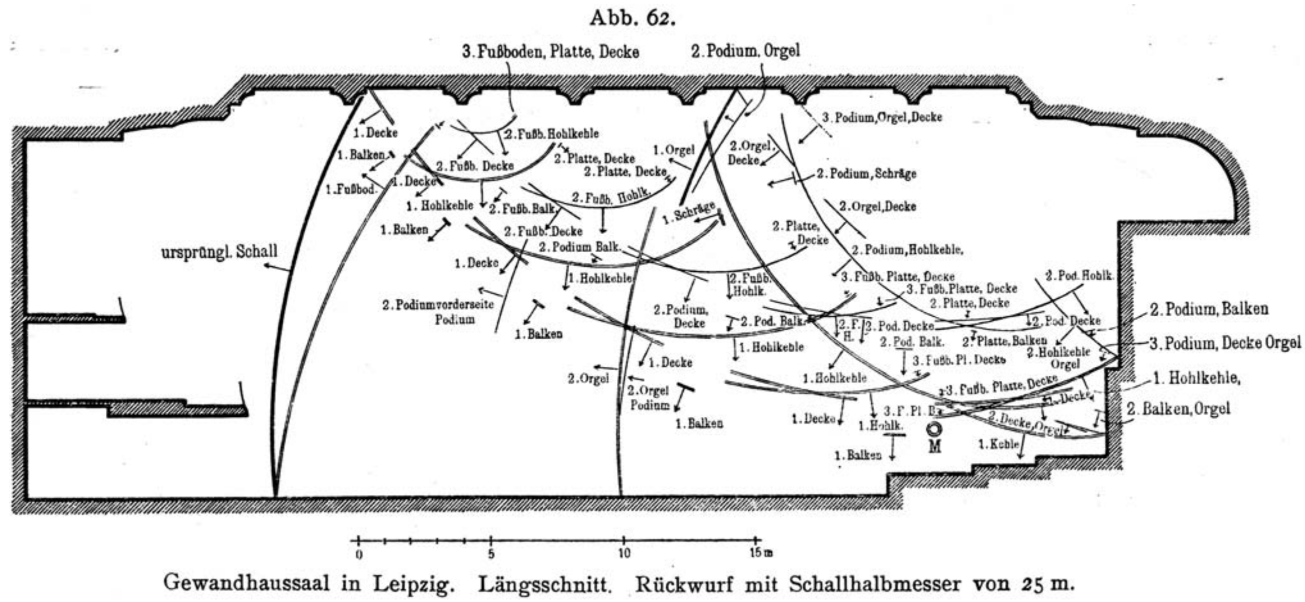

Figure 8 Eugen Michel, geometrical construction of sound propagation in the Gewandhaussaal, Leipzig, 1921 (Eugen Michel, *Hörsamkeit grosser Räume* [Braunschweig: Vieweg, 1921], 32).

two-dimensionality of the model sections. These photographs lack not only the third dimension of space—a problem Sabine addressed by always studying both long and cross sections of theater spaces—but also the fourth dimension of time, a necessary consideration in the study of sound that the kinematographic image recordings were able to capture.

Thanks to its practicality and simplicity, and despite the fact that acousticians acknowledged the blurry pictures and lack of precision, water wave photography outlived the laborious schlieren applications in architectural acoustics.[40] Experiments are documented into the post–World War II period and beyond, as I have discussed elsewhere.[41]

Franz Max Osswald's Sound Photography as Scientific Practice

In 1924, Franz Max Osswald began installing his research at ETH Zurich, Switzerland's first polytechnic university. ETH was his alma mater; he graduated with a degree in mechanical engineering in 1905 (Figure 10).[42] In 1929, he received his *venia legendi*—permission to teach at university level—and was given two spaces in which to set up his own laboratory: a larger one to be used as a reverberation chamber and a smaller one for his apparatuses.[43] In the smaller space, from 1930 through 1933, he produced hundreds of sound photographs. The remaining prints of Osswald's sound photography experiments are kept in the crimson loose-leaf binder that I discovered among the materials from the antecessors of contemporary acoustics. The binder is part of a system patented in 1909 by a British manufacturer; inside it, Osswald's 124 remaining photographs are mounted on fifty-six sheets of blue and brown paper.[44] I mention the folder's origin because it indicates Osswald's international orientation. He was a pioneer in his field and corresponded with other experts in Europe, as well as with Paul E. Sabine at the Riverbank Laboratories in the United States.

The photographs in the binder show the propagation of sound wave fronts in architectural models by illuminating the changes in the density of air, sometimes at a specific moment, sometimes in a sequence milliseconds apart, tracing how the waves expand and reflect inside the model space. It is likely that Osswald developed his plates in the ETH photography facility, founded in 1886 and located in the natural sciences building from 1916 onward. From 1926 to 1947, ETH's Photographisches Institut (Institute of Photography) was headed by Ernst Rüst. While there is no indication that Osswald relied on Rüst's expertise, their careers show interesting parallels. They both failed to position their small institutes in the debates over the "split" between pure and applied science of the time.[45]

In a class he taught on architectural acoustics, Osswald explained his "ultrasound photography apparatus" (another name for schlieren photography), constructed according to Foley and Souder's publication (see Figure 4), to the students in great detail, as is documented in a diagram included in the transcript of a lecture he gave during the winter semester of 1932–33 (Figure 11). In the apparatus, milliseconds after the sound spark from the shotgun (8 in Figure 11, triggered by 3 and 4), a light spark (9 in Figure 11, triggered by 5) was ignited, the timing of which required extremely advanced electrical

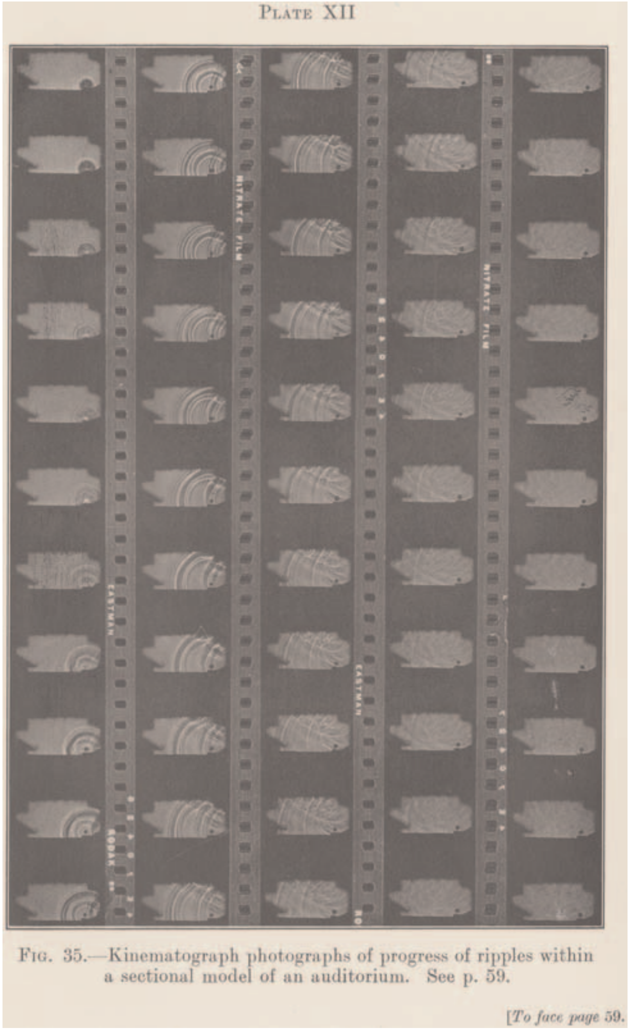

Figure 9 Alfred H. Davis and George W. C. Kaye, kinematographic visualization of sound propagation in a ripple tank, 1927 (Alfred H. Davis and George W. C. Kaye, *The Acoustics of Buildings* [London: G. Bell and Sons, 1927], plate XII).

Figure 10 Franz Max Osswald, portrait on the occasion of his graduation from ETH Zurich, 1905 (photo by Johannes Meiner; Image Archive, ETH Library Zurich, http://doi.org/10.3932/ethz-a-000271413).

controls (1 and 2 in Figure 11). The shadow of the air's inhomogeneity caused by the sound spark was then projected onto a photographic plate (7 in Figure 11).[46] Osswald was taken by the technique to the extent that he built a second, improved version of the device in which, he claimed, the timing of the sparks was much more precise (Figures 12 and 13).

Precision, here, is a relative term. The schlieren technique in aircraft and rocketry research of the late 1930s, as in the German wind tunnels in Peenemünde, was part of costly wartime techniques.[47] Experiments of the same origin in the Institute of Applied Acoustics at ETH in Zurich, in contrast, operated with practically Osswald alone, at times with a part-time assistant and with little interest and funding from the university, addressing architectural questions in auditorium design.

The first of Osswald's schlieren apparatuses is shown in a print dated 21 October 1930 (Figure 12). The second Osswald photographed on 11 July 1933 and published in 1936 (Figure 13).[48] Both versions appear in photos on the initial sheets in the loose-leaf album. The photograph of the first version also shows eleven small sectional models with different wall and ceiling geometries in the lower right-hand corner (see Figure 12). These were cut from hard rubber and inserted in the middle of the long apparatus. Osswald's second version of the apparatus controlled the time gap between the two sparks and thus the accuracy of the simulation, with a range from 0.00005 to 0.0005 seconds, which corresponds to sound traveling the distance of 2.5 to 25 centimeters in a model at scale 1:400, or 10 to 100 meters in real space.

The scale ratio of 1:400, which Osswald seems to have used as a standard for this method, was most likely determined by the intensity of light he could generate for the photographic exposure. The scale given by Davis and Kaye in Britain is roughly the same: 1 inch = 32 feet, which translates to 1:394 in the metric system.[49] A scale of 1:400 is actually

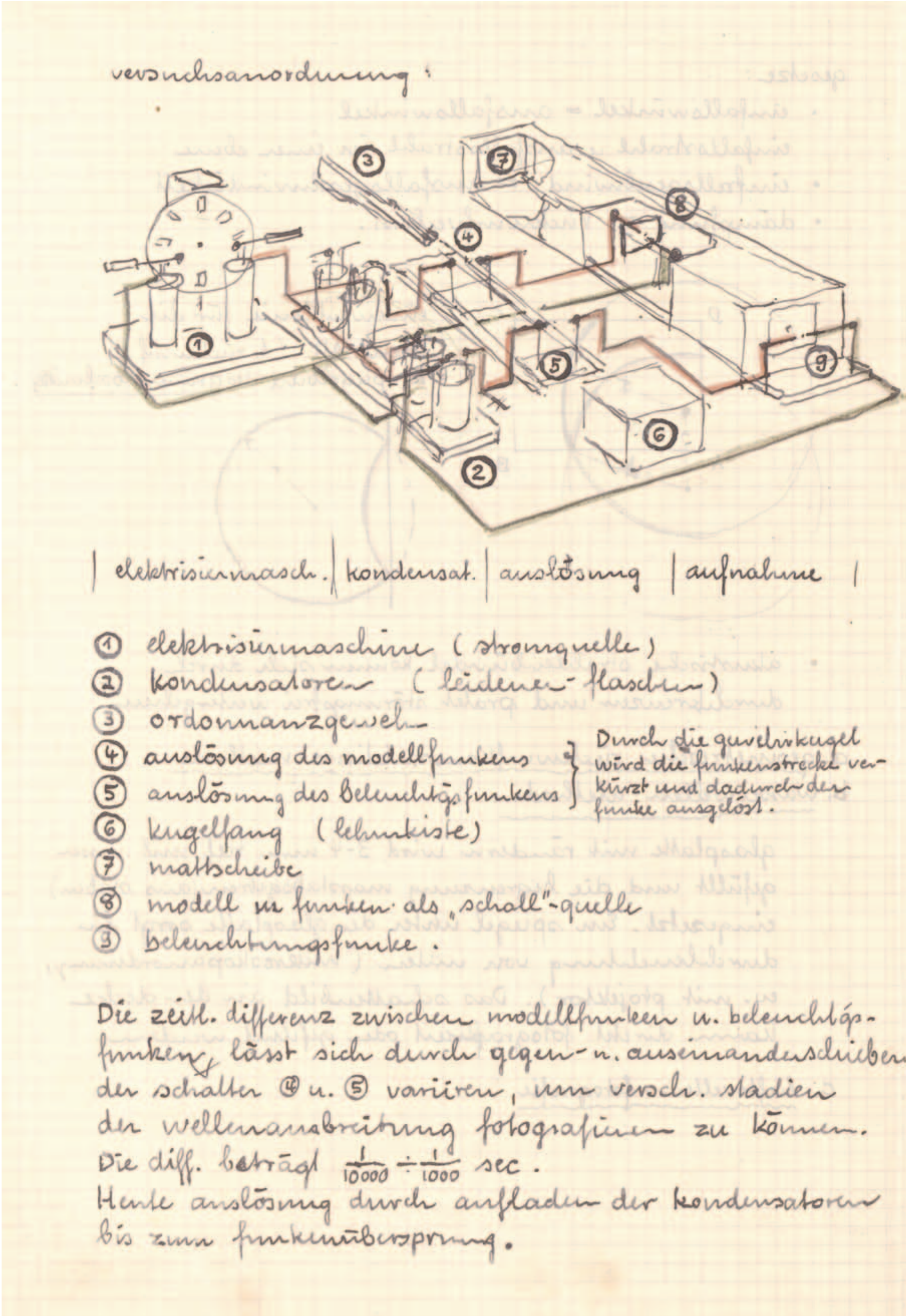

Figure 11 Franz Max Osswald, diagram of an "ultrasound photography apparatus" from the transcript of his lecture on architectural acoustics, winter semester 1932–33 (University Archives, ETH Zurich).

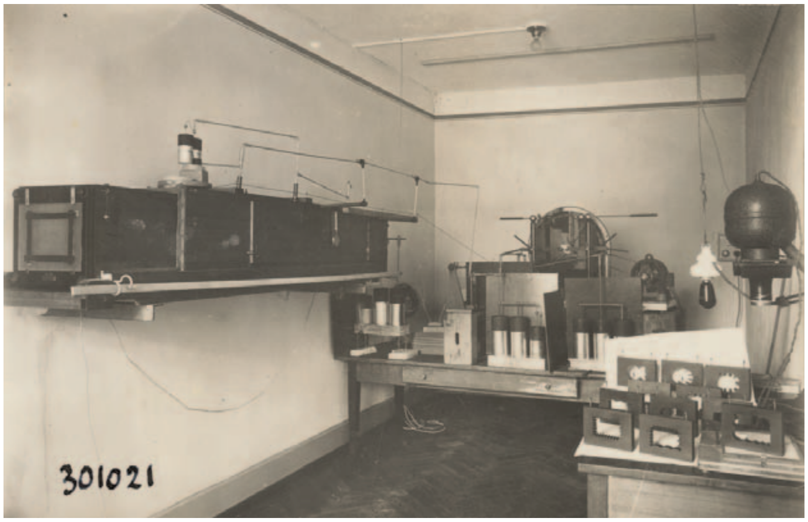

Figure 12 Apparatus room at Franz Max Osswald's applied acoustics laboratory at ETH Zurich, 1930 (Image Archive, ETH Library Zurich, http://doi.org/10.3932/ethz-a-000986421).

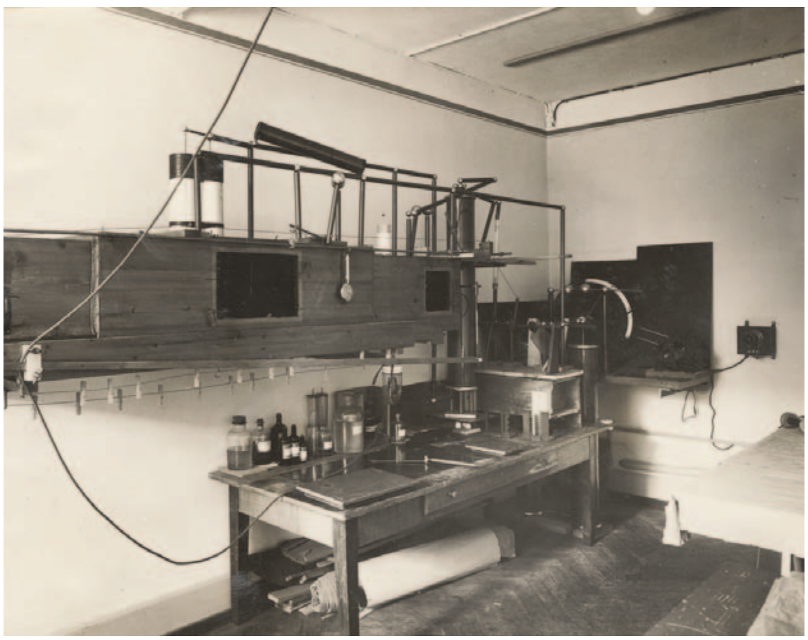

Figure 13 Franz Max Osswald, revised and improved apparatus for ultrasound photography, 1933, published in 1936; see note 48. (Image Archive, ETH Library Zurich, http://doi.org/10.3932/ethz-a-000986422).

very small compared to other architectural working models showing interiors, often built during the design process to enable evaluation of the volume and proportion of spaces; an auditorium model at that scale would, in most cases, fit into the palm of the experimenter's hand.

Osswald indicated the scale of the models on two of the photos in the crimson binder, both considerably larger than 1:400. A photograph dated 8 December 1930 of an unidentified study model marked "Luzern" has the note "1:254." The scale of the model of Gottfried Semper's Stadthaus Winterthur auditorium (discussed below), photographed on 4 July 1933, is noted as "1:183." The issue of scaling is especially pertinent in relation to today's practice of measuring sound in concert hall models at a scale ratio of 1:10. In Osswald's technique for sound photography, enlarging the model to 1:10 would have rendered the procedure impossible. The principal problem being the intensity of the light spark, greater distances to the photographic plate weakened the photographic imprint. Because of this, in 1936 Osswald recommended photographing sound propagation at distances of a maximum of 15 centimeters within the model, which corresponds to approximately 60 meters in the actual space. The scale of the model was thus chosen at a critical distance for auditorium acoustics. Osswald concluded that "ultrasound air wave photography is a precise and revealing means to recognize the reflecting effect of enclosures, which may then need to be shaped differently, or dampened," that is, redesigned in a different form, or clad with absorbing material.[50]

All of these measurements are based on the premise that a sound within the hearing range, when scaled down to an inaudible frequency, can simulate an audible phenomenon. In Osswald's 1930s experiments, different densities of air resulting from a sonic impulse become perceptible as an image on paper. His method, however, neglects the material properties of the air inside the apparatus and of the spatial enclosures, which were rendered in a section cut out of hard rubber. The experiment pretends to take place in a vacuum of abstract geometry without atmosphere, even though it was well known at the time that temperature and humidity change the propagation of sound. Aside from the problem of the model's reduced scale and its standardized material, there is also the issue of scaling in the photographic process itself, where further social, technical, aesthetic, and affective scales come into play.[51] While Osswald's apparatus was larger than many photographic devices of the period, the models he used for testing sound performance were miniaturized.

Geometric Studies of Auditorium Design

Like other experts at the time, Osswald focused much of his attention, in both teaching and research, on modern auditorium design. One of the highly controversial designs of this period was the large assembly hall at the League of Nations headquarters in Geneva, Switzerland, which was projected to have a capacity of 2,700—a size unheard-of in auditorium design at the time. After the jury had ruled on the 377 entries in the design competition for the auditorium in 1927, Osswald published his expert opinion of the large assembly hall both in Switzerland and in the United States, stating his doubt that loudspeakers could resolve the problem of amplification in very large auditoriums: "as experience has shown," they would "amplify at the same time the disturbing reverberation, thus failing to alleviate the difficulty."[52] His work was quoted by the leading proponents of modernism, such as Peter Meyer and Sigfried Giedion.[53] Auditorium design posed a pressing problem both for speech and for music in the 1920s. Audiences had grown larger, but loudspeaker technologies were not yet able to reproduce sound in interior spaces to a quality that was comfortable to listen to, or was even intelligible.

When Osswald first immersed himself in the technique of architectural sound photography, he built a model of the type of auditorium that he thought could best enable sound to travel to all positions in the audience. Thanks to a large gallery, sound would be reflected up to the very last row without becoming too reverberant. Photographs that Osswald took on 29 August (in a model of the vertical section) and on 9 October 1930 (in a model of the horizontal section) were published in *Schweizerische Bauzeitung* on 1 November 1930 (Figure 14).[54] They show two variations of the room: one with an open gallery and one with the gallery closed off. The variable internal volume of the space was key and allowed the users to accommodate differing requirements for speech and music. To reduce the volume when a shorter reverberation time was required, Osswald proposed, the gallery should be closed off. Thus, without the gallery extension, the space would serve more intimate performances and lectures. When enlarged from 6,100 cubic meters to its full capacity of 8,750 cubic meters, the space would be suited to orchestral music, with more seating and a longer reverberation time.[55]

The contemporary approach to controlling reverberation time was to rely on the many new absorbing materials promoted by industry. By contrast, Osswald continued to work on manipulating the volume parameter of the reverberation formula and paid little attention to the use of materials for sound control. After its publication in *Schweizerische Bauzeitung*, Osswald's idea of the variable volume was appraised in the 1932 American handbook *Acoustics and Architecture*, one of the most comprehensive works on architectural acoustics at the time. Its author, Paul E. Sabine, repudiated Osswald's reasoning:

> Osswald of Zurich has suggested a scheme whereby the volume term of the reverberation equation may be reduced by lowering movable partitions which would cut off a part of a large room when used by smaller audiences and for lighter forms of music. . . . In connection with Osswald's scheme, one must remember that in shutting off a recessed space, we reduce both volume and absorbing power and that such a procedure might raise instead of lower the reverberation time.[56]

Without specification of the walls' and partitions' materials or thickness, it is impossible to judge which of the acoustic experts was right, since they relied on different parameters. Nevertheless, this contemptuous mention in an international publication may have become an obstacle to Osswald's further career, which had advanced significantly after he voiced his expert opinion on the 1927 League of Nations competition. Throughout the 1930s, and until his death in 1944, he continued to work in his laboratory, but he received less acclaim and attention than he had in the late 1920s.

In the fall of 1936, Osswald submitted his architectural sound photography to the *Zeitschrift fur technische Physik*. The short article was accepted and published as three pages of text, exceptionally richly illustrated with glossy plates containing eleven samples of sound wave photography and photographs of the built theater spaces on which the models were based. The photographic experiments showed sound propagation and reflections not only in familiar types of modern auditorium geometry but also in extravagantly shaped models with folded, curved, and undulating walls. These models feature geometries that were unlikely to represent actual spaces; rather, Osswald probably created them to study certain wall angles or the curvature of a room's enclosure. These unusual sections were presented in the context of existing and

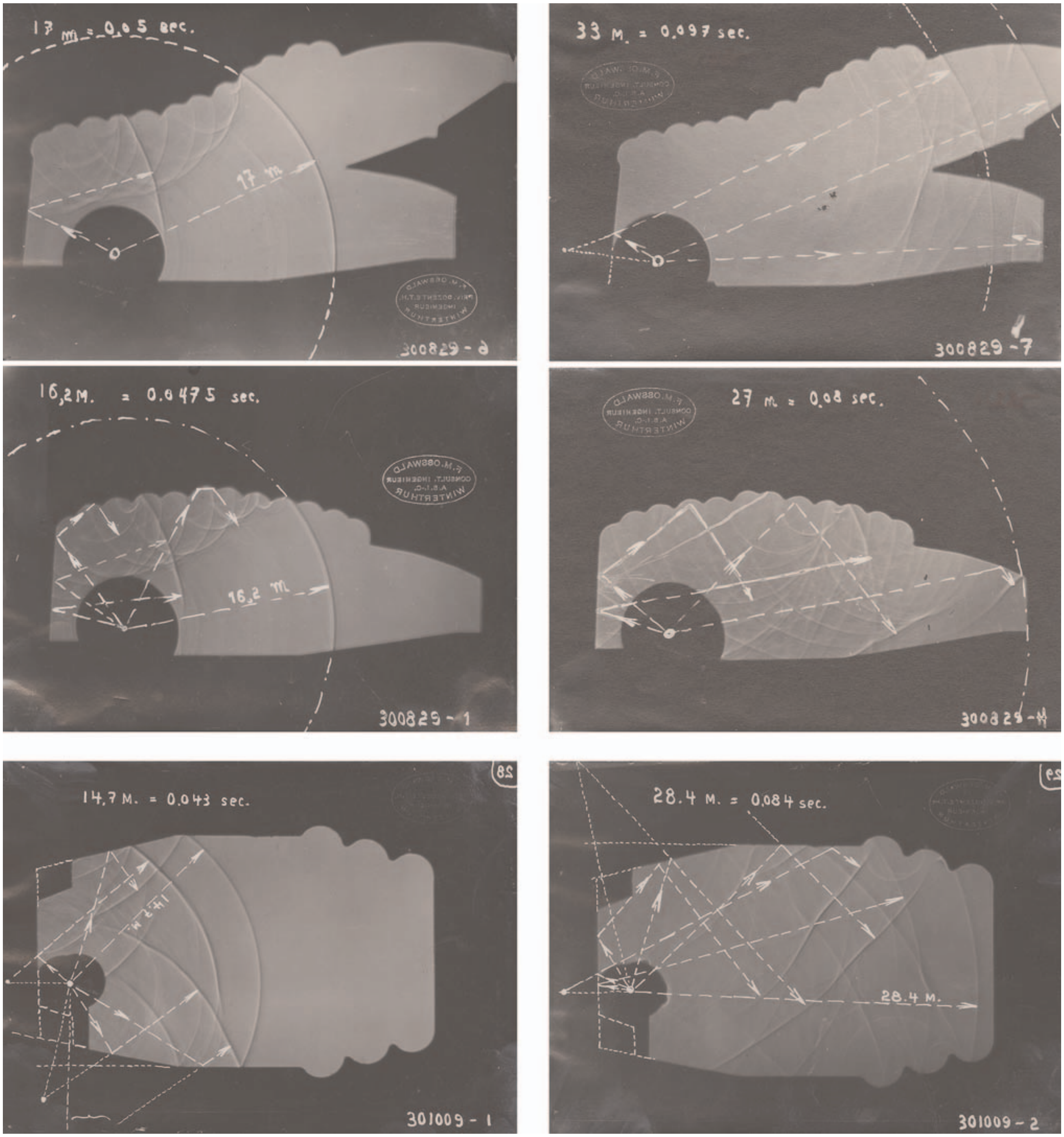

Figure 14 Franz Max Osswald, sound tests in the model of an auditorium with variable volume, published in 1930; see note 54 (Image Archive, ETH Library Zurich, http://doi.org/10.3932/ethz-a-000986428; http://doi.org/10.3932/ethz-a-000986429; http://doi.org/10.3932/ethz-a-000986430; http://doi.org/10.3932/ethz-a-000986431; http://doi.org/10.3932/ethz-a-000986432; http://doi.org/10.3932/ethz-a-000986434).

alternative shapes for film theaters (Figure 15).[57] In this most extensive publication of his photographic reasoning, Osswald included many of his 1930s experiments and a few of the photos taken for the doctoral thesis of Hans Frei, Osswald's only doctoral student, in 1933.[58]

Osswald's profound fascination with photographing sound was untimely, and he received scant reward for his time-consuming method of firing a rifle and illuminating moving air in a small two-dimensional model. His most direct critic was his student, Hans Frei. With funding by the wood construction industry, Osswald produced his improved apparatus and a second large series of photographs. Many were published in Frei's doctoral thesis on electroacoustic investigations in reverberation chambers, for which Osswald acted as

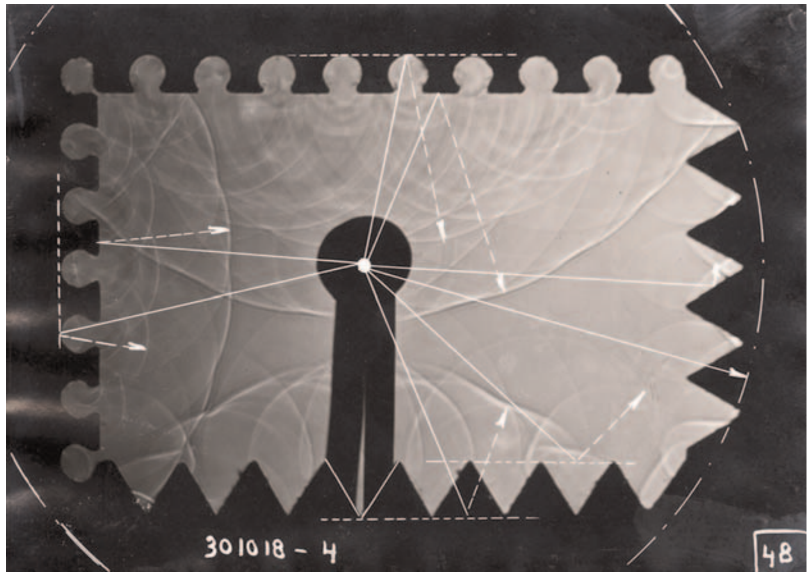

Figure 15 Franz Max Osswald, acoustic studies for wall shapes in film theaters, 1930, published in 1936; see note 48. (Image Archive, ETH Library Zurich, http://doi.org/10.3932/ethz-a-000986436).

coadviser. The primary adviser, the ambitious physicist Franz Tank, seems to have had little sympathy with the objective of a visual exploration of acoustic phenomena. The dissertation's criticism of the photographic experiments was crushing. Frei's critique cited the method's neglect of absorption, phase shifts, and its two-dimensional reduction, rejecting it as reductive, vague, accidental, and not suited to modeling a "theoretically precise image of the situation in real space."[59] Rather than valuing its aesthetic or communicative value, Frei seems to have judged Osswald's photographic technique as a comprehensive theoretical model, by which standard it was unable to deliver.

Fluting, folding, triple pocket moldings, cannelures, cavities, and waveforms were built into the walls of Osswald's sectional models of round, elliptical, rectangular, and potato-shaped spaces. While these imaginary spaces were certainly of no use in proving the "objectivity" of the method, the treatment of the walls was a practical concern in the context of sound film. Film theaters in the 1920s were designed for silent film, usually accompanied by music from a single live instrument. With changes in film technology and the advent of sound film, many theater spaces had to be remodeled to distribute sound more evenly through the audience and to be less reverberant. Of the three plates published by Osswald in 1936, two showed former silent film theaters that had been adapted to accommodate talking movies. The third was Gottfried Semper's Winterthur city hall of 1869, which had undergone several acoustic corrections before and after Osswald's consultancy (Figure 16). Osswald even photographically examined model sections of the Ear of Dionysius, a space that is supposed to have perfect sound conductivity (Figure 17). This ear-shaped Sicilian cave had long been a mecca for acousticians; that it still holds such interest is an indication of the "hard" natural science of acoustics' long tradition of engaging with psychophysiological and sociocultural mysteries of sound in space and in the ear.

While Osswald called for architectural designs that could distribute sound by spatial form and for methods of measurements that included the ear, the discipline of architectural acoustics, which he had helped to establish, had shifted interest to electroacoustics. Members of this next generation focused their attention on electrical methods for amplifying as well as for measuring sound. Osswald remained undeterred, devising other apparatuses intended to improve the practice of sound measurements and to correct the drawbacks of early loudspeaker technologies. For example, a huge spiral through which reverberation could be produced and added to the amplified sound from loudspeakers—another speculative proposal—speaks more of Osswald's sensitivity to spatial sound than of physical expertise (Figure 18).[60]

In a book published in 1939, the German acoustician Joseph Benedict Engl reproduced Osswald's two photographic sound tests for Semper's auditorium (Figure 16). Engl acknowledged the explanatory value of the visualizations and remarked that "not everything can be expected of this method."[61] Despite continuing criticism of the method by scientists, its explanatory value may be the reason that images of sound persisted throughout the twentieth century. Architectural acousticians in various countries and contexts embraced sound wave photography both for its promise of scientific objectivity (by means of the mechanical apparatus) and for its inclusion of the visual sense. The modern technique of photography, even though it did not satisfy physicists' theoretical desires, did enable scientists to communicate the experience of hearing in modern terms.

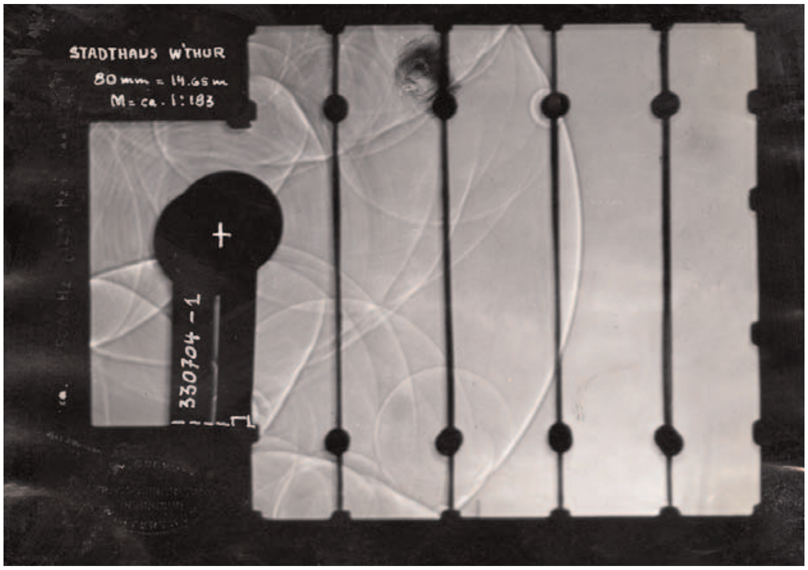

Figure 16 Franz Max Osswald, sound test in a horizontal model of Gottfried Semper's Stadthaus Winterthur auditorium, 1933 (Franz Max Osswald, "Raumakustik in geometrischer Betrachtung," 1930, published in 1936; see note 48. Image Archive, ETH Library Zurich, http://doi.org/10.3932/ethz-a-00098644).

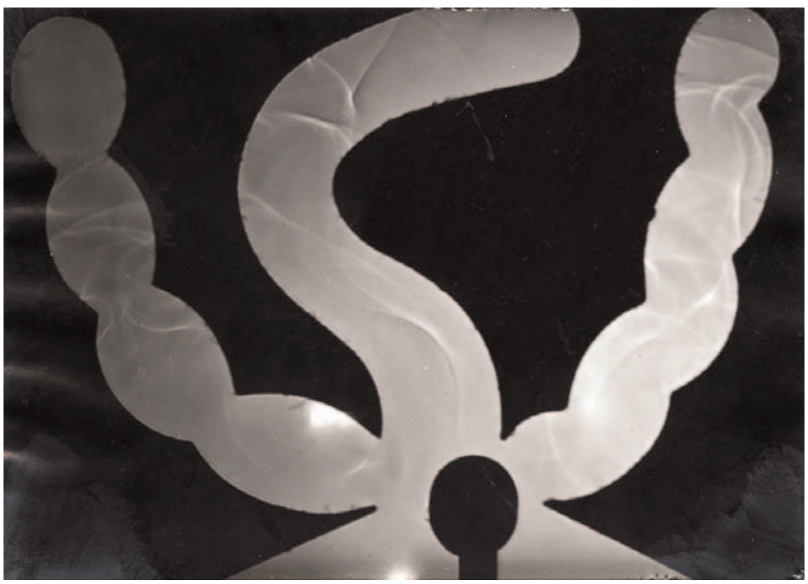

Figure 17 Franz Max Osswald, sound test in a model of the Ear of Dionysius, a Sicilian cave that is surrounded by a myth of perfect sound conductivity, 1930 (Image Archive, ETH Library Zurich, http://doi.org/10.3932/ethz-a-000986441).

In his paper on theater auditorium design, Wallace C. Sabine discussed the "inadequacy of the discussion of the subject of architectural acoustics by the construction of straight lines" and directed readers' attention to the areas of the photographs that exposed "waves reflected from the screens in front of the boxes, of the balcony, and of the gallery." He concluded, "The method of rays, although a fairly correct approximation with large areas, is misleading under most conditions," especially when it came to theaters.[62] Sabine thus hoped that the knowledge gained from a photograph could exceed the geometric ray method and praised the method for incorporating the effects of diffraction into the acoustical rendering. Osswald's extensive practice with sound photography, however, exposes an enthusiasm that cannot be found in Sabine's skeptical description: "The system of reflected waves in the succeeding photograph in the series is so complicated that it is difficult to identify the several reflections by verbal description. The photograph is therefore reproduced a second time, marked and annotated with an extensive caption."[63] Osswald's annotations seem less reluctant, often superposing lines of white to explain the direction in which the sound waves propagated through the sectional models and reflected from the walls (see Figures 14, 15, 19, and 20). That both Sabine and Osswald needed such elaborate annotation hints at their struggles to interpret in words the vagueness of the visual imprint of sound from moving air.

When, in the 1930s, Osswald traced his own photographs with white ink, indicating the directions in which the sound waves propagated, the superposed, simplified lines were intended to highlight the evidence provided by the photographs

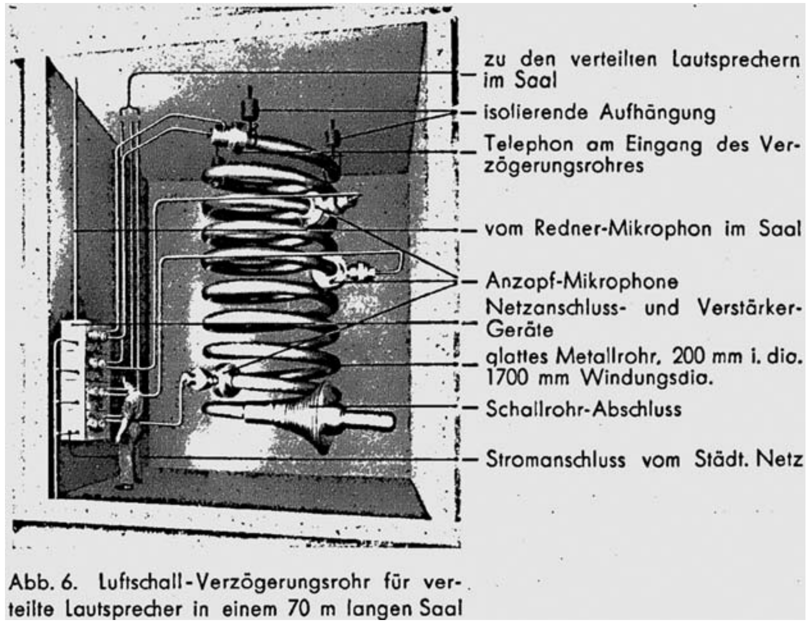

Figure 18 Franz Max Osswald, *Luftschall-Verzögerungsrohr*, a pipe for delaying airborne sound, proposed to enable spatially adequate loudspeaker transmission in large auditoriums, 1937 (Franz Max Osswald, "Zur akustischen Gestaltung von Grossräumen," *Schweizerische Bauzeitung* [4 Sept. 1937], 69).

and to communicate his findings to lay audiences; yet at the same time, the hand-drawn lines subverted the objectivity granted by his schlieren apparatus. Though Osswald's lines were meant to clarify the trajectories of sound, in fact they obscure more than they reveal. They trace what the experimenter himself expected, and what he saw. While helping lay viewers of Osswald's photographs understand where the blurry wave fronts might be moving, the hand-drawn lines also acted as markers of where the photographs failed, and as an affirmation of Osswald's expertise.

Sound photography proved effective for communicating expert knowledge to lay audiences. In the case of acoustic sciences, the lay audience includes many, from engineers to designers and architects. While providing a valuable tool for communicating findings to this audience, photographic images also assisted the experts in reiterating the processes they investigated and reevaluating their results. To the architect who sought the advice of the acoustician, the image was explanation and proof. And the confidence of the audience reassured the experts of their own expertise.

Despite their limited scientific usefulness, the sound photographs resurfaced. Lothar Cremer used Osswald's photography in his seminal *Geometrische Raumakustik* of 1949. Cremer juxtaposed an example of Osswald's photographic tests with a simple drawing constructed geometrically, although he concluded that the photographic technique offered no additional information (Figure 19).[64] In Cremer's book, as in Frei's thesis, the photographs were published without arrows to indicate the directions of the sound waves; the audience was considered expert enough to understand the photographs without explanation. Possibly, Cremer and Frei thought Osswald's markings were a simplification, a "pandering" to nonexpert readers with no relevance for contemporary science. The hand-drawn lines did not survive within the new practice—and paradigm—of pattern recognition, which ultimately required expert understanding. Certainly, Osswald's markings hardly fulfill Daston and Galison's criteria for the third period of objectivity, when "trained judgment" allows information to be highlighted or reduced by an expert but not to be added or superimposed from preexisting knowledge.[65] The geometrical lines that Osswald superposed onto the blurry shadows of sound waves in the photographs—which I have classified as belonging to Daston and Galison's second periodization, "mechanical objectivity"—were conceived in the logic of "truth-to-nature," the first of Daston and Galison's three periodizations, when preconception was not opposed to scientific knowledge. Different concepts of modern objectivity collided in the applied acoustics laboratory at ETH Zurich.

Osswald's hand-drawn lines counteract the intended modern objectivity—granted by the mechanical process of his photographic technique—with a modernity that is subjective and, in the words of Hilde Heynen, "refers to the typical features of modern times and to the way that these are experienced by the individual."[66] These lines assert the relevance of Osswald's untimely image making by exposing the simultaneity of scientific and aesthetic intentions; they oscillate between intuition and simplification. The modern assumption that photography could capture a more comprehensive range of physical phenomena than could mathematical formulas collided and merged with the tradition of engineers thinking with pictures.

As historian of science Hans-Jörg Rheinberger describes it, scientific findings require "a kind of attention with a sharp sense for subtle tones, thus an attention which seems to hover

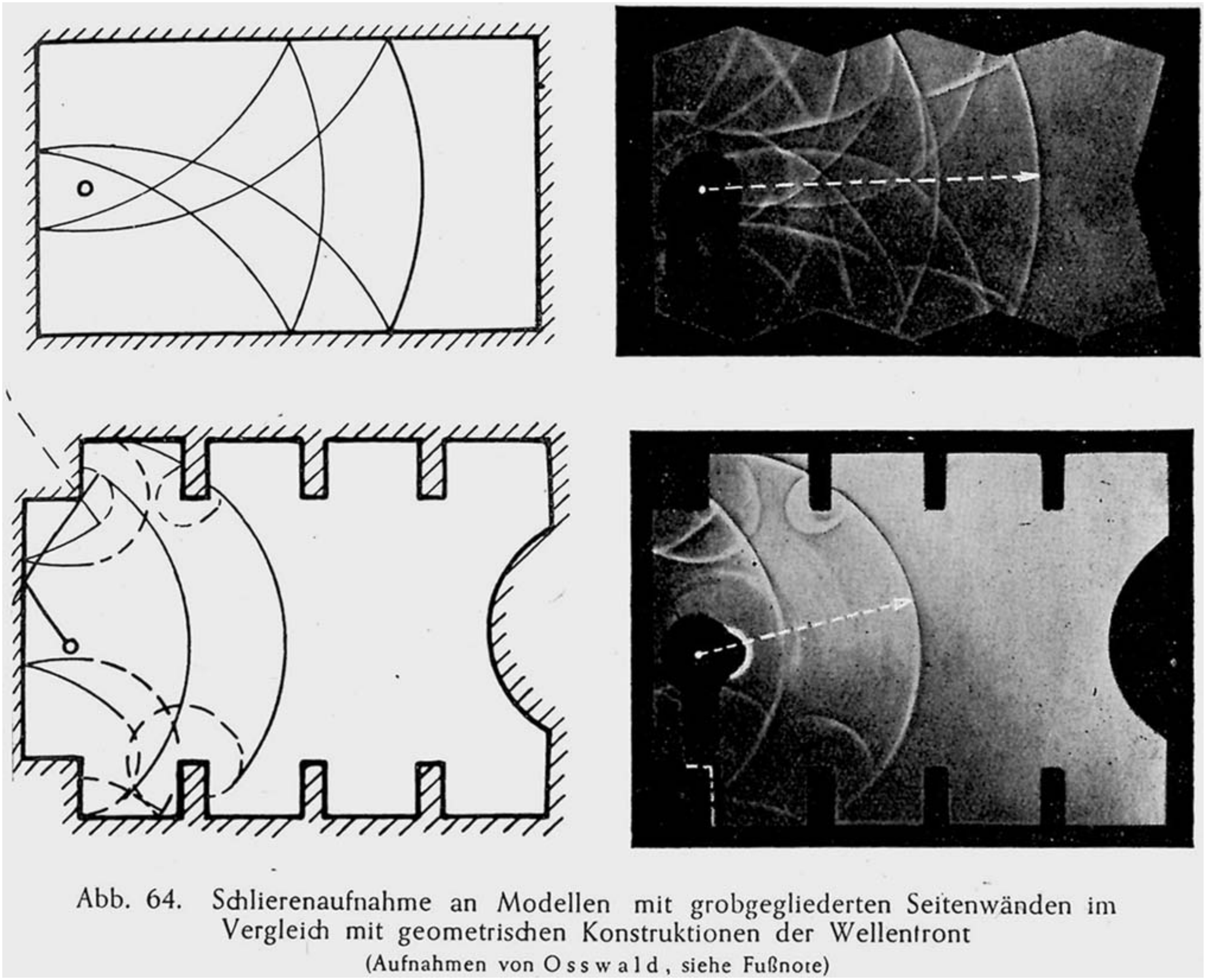

Figure 19 Lothar Cremer's comparison of the geometric construction of sound reflection and Franz Max Osswald's experiments with schlieren technique, 1949 (Lothar Cremer, *Geometrische Raumakustik* [Zurich: Hirzel, 1949], 147).

above" and does not steer the viewer rigidly toward a predefined result.[67] The kind of attention that comes with Osswald's tracing over areas of subtle grays with blurry contours gets in the way of his ambition to create an "objective" image of the phenomena of sound; intuition then is inseparable from the kind of subjectivity that science calls prejudice. Osswald traced the lines of his own forecast onto the grayish print, as many scientists in the medical sciences and in applied acoustics had done before him and would do after him. Perhaps the motivation for the laborious schlieren technique was more than the production of evidence. One of the questions explored in this article relates to visual reasoning in acoustics, when engineers combined scientific photography with the experience of hearing.

In 1961, Willi Furrer (1906–85), Osswald's successor at ETH Zurich, claimed that the insights offered by sound photography were "relatively limited" and had "no relationship to the efforts necessary," therefore the technique was not used after 1930 (the year of Osswald's most extensive photography experiments).[68] While the first edition of Furrer's book *Raum- und Bauakustik*, *Lärmabwehr*, published in 1956, does not refer to the technique at all, in the 1961 edition he uses Osswald's reproductions of British sound photography from the National Physical Laboratory in his discussion of modeling sound. Despite Furrer's disparagement of the method, it is most likely because of him that the crimson binder survives; the album was one of the few objects left by Osswald that Furrer might have thought worth keeping. French architectural acoustics, too, remained fascinated with sound photography in the postwar period: a 1952 handbook dedicated seven out of twelve pages of illustrations to sequences of water wave photography, one page to photographs of light reflections in a model, and none to the tedious method of ultrasound photography with the schlieren method.[69]

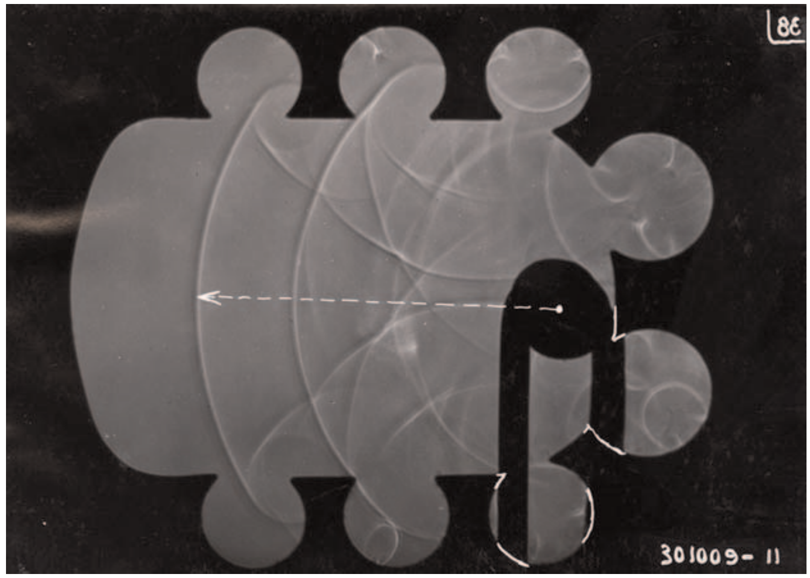

Figure 20 Franz Max Osswald, acoustic studies for wall shapes in film theaters, 1930, published in 1936; see note 47. (Image Archive, ETH Library Zurich, http://doi.org/10.3932/ethz-a-000986433).

Osswald's eager and relentless experimenting was at once ahead of and behind its time, both pioneering and too late. This was the moment when architectural acoustics gained momentum and formed a discipline, and when specialists across the globe appropriated its techniques.[70] But by the mid-1930s, when electroacoustics entered the scene, most of Wallace C. Sabine's cohort had already left the field. Such shifts in scientific attention accompanied the realization that the information conveyed in architectural sound photography was not sufficient. Sound propagation, like many other phenomena, could be more precisely rendered by electroacoustic techniques than by the photographing of air movements. Nevertheless, the images kept appearing in journals. Lay audiences and experts alike were fascinated by the elucidation of acoustic phenomena, so little understood and so hard to explain.

Unlike many of his contemporaries, Osswald never suspended his belief in the role of the senses in his experiments, abandoning neither the visual—illuminated by the photographs he produced—nor the auditory sense. When he devised a tapping machine with variable loudness as part of a new "method for measuring impact sound" in 1936, he did so by including hearing as a means in scientific measurement. Doing so, he reversed the point of reference in the scientific experiment, declaring the sound to be the variable parameter against the constant of the physiological threshold of hearing: "It is necessary only that the 'threshold' of the detecting instrument be constant. Nature has provided a wonderful threshold instrument, the human ear," he noted as he explained his apparatus in the *Journal of the Acoustical Society of America*.[71] Osswald's claim must have sounded absurd to other scientists in the 1930s, when automated acoustic measuring had finally obliterated the unsatisfactory subjective judgment of sound levels by the ear. Nevertheless, Osswald's paper propagating the human hearing threshold as an instrument of standardization was accepted for publication in the *Journal of the Acoustical Society of America* in 1936. The human ear, as a "wonderful threshold instrument," seemed to be a viable part of acoustic measurement methods.

Eyes, Ears, Experts, and Oracles: Conclusion

Osswald's success as researcher and consultant in architectural acoustics coincided with the proliferation and institutionalization of architectural acoustics. Recognition of his work was propelled by his expert judgment of contemporary auditorium designs during the 1920s and peaked in 1929—the founding year of the Acoustical Society of America and the year of Osswald's promotion at ETH.[72] His efforts in photographing sound in architectural models during the 1930s, when electroacoustics and loudspeaker amplification were increasingly applied to architectural designs, were rather untimely. Studying these photographs now, when the rivalry between ocular-centric and sonic positions is superseded by more comprehensive, multisensory interests, however, seems timely.

In the endeavor to capture, measure, describe, and control sound, what emerges in the study of photographic practices in architectural acoustics is a strange ambivalence regarding sensory perception. Inserting visual techniques into the study of sound raises many issues, such as that of "technologically inflected vision," when manipulation becomes a condition for objectivity.[73] In regard to Osswald's photographs, we can no longer be sure whether the scientist's hand acts as an extension of or imposes his intention on the machine he has created.

Architectural sound photography, like almost all photography in the natural sciences of the epoch, did not speak for itself; it required explanation. For example, British physicists Davis and Kaye instructed readers to interpret the image series of sound traveling with their attention "directed to the progress of only one of the waves of the train" of the many reflections photographed in the ripple tank.[74] As shown here in examples from Osswald (Figure 20; see Figures 14, 15, 19, and 20), many sound photographs are marked with lines to guide the eye of the observer, indicating the directions in which these singled-out "waves of the train" propagated. As Jennifer Tucker emphasizes, the veracity of photographs was often suffused by claims of subjective intervention: the production of images of invisible phenomena required exceptional skill and knowledge, thus exposing the authority of the expert to contestation.[75]

The photographs captured blurry, and to an extent accidental, nuances of the light and dark of inhomogeneous air caused by the movement of sound pressure. These patterns complemented scientific inquiry in that they included some of the intricacies of sensory perception that the natural sciences otherwise exclude. If nonintervention lies at the heart of photography, the manual interventions on the photographs interfered with the goal of mechanical objectivity as defined by Daston and Galison. The relation of sound photography to the "unprejudiced, unthinking, blind sight" of mechanical objectivity raises questions of method, model, and media; of the relationship of visual and auditory cultures; and of the authority of the expert.[76] Hand-drawn lines and arrows, as Athanasius Kircher had etched three centuries earlier, seem anachronistic but remind us how verisimilitude as well as intuition persisted in the age of mechanical objectivity, and beyond. I argue that such hand-drawn interventions also show how the visual representation of sound raises the question of media and visibility per se. The photographs relate to an epistemology of modern architecture both in the setting of the experiments, in the laboratory, and in the technique of representation, schlieren photography, borrowed from the natural sciences. They remind us that the amplification of sound once depended largely on the geometry of a room, together with its materials and size, as expressed in the reverberation formula, when spatial form and not electroacoustic amplification shaped the sounds of the environment.

The youngest generation of sound-mapping systems has appropriated a name pertaining to photography: market leaders such as Norsonic (Norway), Brüel & Kjær (Denmark), and CAE Systems (Germany) currently promote "acoustic cameras." These register sound levels at different frequencies using microphone arrays of varying sizes. The "noise maps" thus produced are superimposed onto photographs of the sites where the sound intensities were measured, expecting remedy for the auditory while communicating by visual media.

Osswald's practice around 1930 seems to lie at a crossroads of modern science. He was persistent in observing the blurry shadows cast by sound waves but eager to mark the images with his hand-drawn lines, simultaneously rigid in copying Sabine's methods and blinded by the visual magic of the patterns emerging. In the expert culture in architectural acoustics of the 1930s, architectural sound photography restated the geometry and the volume of physical space, thus spatial form, as the decisive parameter for architectural acoustics and enforced this concept—against the increasing application of electronic amplification—by means of a representational technique borrowed from the natural sciences. Yet at the same time, the aesthetic appeal of the photographs plunged them into the realm of sensory magic. It seems that Osswald consulted his apparatus like an oracle, to bring out an image that explained more than a mathematical formula could. Yet we might suspect that, through his self-constructed oracle, Osswald sought only to confirm what he already knew.

Sabine von Fischer is research associate in the Department of Architecture at the Zurich University of Applied Science and visiting scholar at the Max Planck Institute for the History of Science in Berlin. Her current research focuses on standards and standardizations of climate in architecture, representations in building physics, and architectural acoustics as an argument and parameter in design. sabine.vonfischer@zhaw.ch

Notes

1. This essay was written on the occasion of my postdoctoral stay at the Max Planck Institute for the History of Science, Berlin, in 2015. Thanks to Viktoria Tkaczyk and her research group Epistemes of Modern Acoustics for their responses to an early draft, and for the invitation to serve as visiting scholar in 2016–17. I am grateful to the *JSAH* editorial team and the anonymous reviewers for their encouraging and helpful comments on earlier versions of this article. Dear colleagues have inseminated the essay with their comments: Carlotta Daro, Brenda Edgar, and many others, and I owe a debt to the expert reasoning of physicists Robert Hofmann and Gary S. Settles. Initially, the research for my Swiss National Science Foundation–funded doctoral thesis "Hellhörige Hauser: Akustik als Funktion der Architektur" (2013), supervised by Prof. Laurent Stalder, Prof. David Gugerli, and Ing. Kurt Eggenschwiler of ETH Zurich, gave me the opportunity to study Franz Max Osswald's previously unstudied contribution to architectural acoustics. I am especially indebted to Kurt Eggenschwiler, head of acoustics at Empa Duebendorf, for opening the basement of his department to my research. Further thanks to the Max Planck Institute's library and ETH Library Zurich for help with digitizing and archiving the photographic materials.

2. See "Field Notes: Architecture and the Environment—A Questionnaire," ed. Sophie Hochhaeusl and Torsten Lange, *Architectural Histories* 5 (2017). This position paper with statements by fifteen scholars reflects methods and themes of "environmental histories of architecture." Daniel Barber has also recognized this as an expanding subdiscipline; see Daniel Barber, "Introduction," in "Architectural History in the Anthropocene," ed. Daniel Barber, special issue, *Journal of Architecture* 21 (2016), 1165–70.

3. The 124 photographs from the crimson binder have, in the meantime, been archived at the Image Archive of ETH Library Zurich; they are available online there and in the Max Planck Institute's database Sound & Science: Digital Histories, created by the Epistemes of Modern Acoustics research group.

4. Gary S. Settles, *Schlieren and Shadowgraph Techniques: Visualizing Phenomena in Transparent Media* (Berlin: Springer 2001), 8. A brief explanation of schlieren imaging is available at Gary Settles, "High-Speed Imaging of Shock Waves, Explosions and Gunshots," *American Scientist*, Jan./Feb. 2006, http://www.americanscientist.org/issues/feature/high-speed-imaging-of-shock-waves-explosions-and-gunshots/1 (accessed 21 Apr. 2017).

5. Susanne Holl, "Strahl und Welle: Bilder des Schalls um 1800," in *Über Schall: Ernst Machs und Peter Salchers Geschossfotografien*, ed. Christoph Hoffmann and Peter Berz (Göttingen: Wallstein, 2001), 171–98; Douglas Kahn, "Concerning the Line: Music, Noise, and Photography," in *From Energy to Information: Representation in Science and Technology, Art, and Literature*, ed. Bruce Clarke and Linda Dalrymple Henderson (Stanford, Calif.: Stanford University Press, 2002), 178–94; Patrick Feaster, *Pictures of Sound: One Thousand Years of Educed Audio: 980–1980* (Atlanta, Ga.: Dust-to-Digital, 2012).

6. Michel Foucault, *The Birth of the Clinic: An Archaeology of Medical Perception*, trans. A. M. Sheridan (1963; repr., New York: Pantheon, 1973).

7. Lorraine Daston and Peter Galison, *Objectivity* (New York: Zone Books, 2010), 16. See also Lorraine Daston and Peter Galison, "The Image of Objectivity," *Representations*, no. 40 (Fall 1992), 81–128; Lorraine Daston, "Wordless Objectivity" (Preprint 1), Max Planck Institute, Berlin, 1994.

8. Peter Geimer, "Noise or Nature? Photography of the Invisible around 1900," in *Shifting Boundaries of the Real: Making the Invisible Visible*, ed. Helga Nowotny and Martina Weiss (Zurich: vdf Hochschulverlag, 2000), 121. See also Tom Gunning, "Invisible Worlds, Visible Media," in *Brought to Light: Photography of the Invisible*, ed. Corey Keller (New Haven, Conn.: Yale Architectural Press, 2008), 51–63; Anthony Enns, "Vibratory Photography," in *Vibratory Modernism*, ed. Anthony Enns and Shelley Trower (Basingstoke: Palgrave Macmillan, 2013), 177–97.

9. In parallel to the critique of the term *landscape*, *soundscape* has been criticized and recuperated as derived not from "looking at" (Greek: *skopein*) but from land formation (Old English: *sceppan* or *skyppan*); see Tim Ingold, "Four Objections to the Concept of Soundscape," in *Being Alive: Essays on Movement, Knowledge and Description* (London: Routledge 2011). The term has also been exposed as inherently related to sound reproduction; see Jonathan Sterne, "The Stereophonic Spaces of Soundscape," in *Living Stereo*, ed. Kyle Devine, Tom Everett, and Paul Théberge (New York: Bloomsbury, 2015), 65–84. Further, it has been criticized for its vagueness and ubiquity; see Ari Y. Kelman, "Rethinking the Soundscape: A Critical Genealogy of a Key Term in Sound Studies," *Senses and Society* 5, no. 2 (2010), 212–34. This ubiquity and similarity to *landscape* make *soundscape* useful, too. "Like a landscape," Emily Thompson argues, "a soundscape is simultaneously a physical environment and a way of perceiving that environment; it is both a world and a culture constructed to make sense of that world." Emily Thompson, *The Soundscape of Modernity: Architectural Acoustics and the Culture of Listening in America, 1900–1933* (Cambridge, Mass.: MIT Press, 2002), 1. Buckminster Fuller's 1964 conference talk "The Music of the New Life," published first in 1966 in a journal (and discovered there by my colleague Olga Touloumi, with whom I am engaged in a lasting discussion on this matter) and later in Fuller's best-selling paperback *Utopia or Oblivion*, has three uses of the word *soundscape* within only two paragraphs, as in a firework of words. See R. Buckminster Fuller, "The Music of the New Life: Thoughts on Creativity, Sensorial Reality, and Comprehensiveness, Part I," *Music Educators Journal* 52, no. 5 (1966), 52; R. Buckminster Fuller, *Utopia or Oblivion: The Prospects for Humanity* (New York: Bantam Books, 1969), 43. Utopia was out there, broadcast by radio and loudspeaker systems, in a media frenzy that could possibly lead to oblivion (which probably was Fuller's take on immersion). The "paranoiac state" to which Marshall McLuhan referred in a 1974 letter to R. Murray Schafer was a state of confusion in which a term like *soundscape* held a promise of totality; see Marshall McLuhan to R. Murray Schafer, 16 Dec. 1974, in *Letters of Marshall McLuhan*, ed. Matie Molinaro, Corinne McLuhan, and William Toye (Toronto: Oxford University Press, 1987), 508. The overview inherent in the term is continuous with modernist trajectories of technological control and electronic stratification. See Sabine von Fischer, "Soundsphere: Electronic Dispositives in Acoustic Space," in *Staging Space: The Architecture of Performance in the 21st Century*, ed. Jeffrey Huang, Anton Rey, and Sabine von Fischer (Zurich: Park Books, forthcoming), 78–84.

10. This was a coincidence that Osswald emphasized, even altering his professional résumé to match the dates. Franz Max Osswald to the board of ETH, 12 Jan. 1934, item 14 of the board meeting of 3 Feb. 1934, SR3:1934/232.14, University Archives, ETH Zurich.

11. For a comprehensive history of the different generations of Sabines at Riverbank, see John W. Kopec, *The Sabines at Riverbank: Their Role in the Science of Architectural Acoustics*, ed. Acoustical Society of America (Woodbury, N.J.: Peninsula, 1997).

12. Wallace C. Sabine, "Architectural Acoustics," *American Architect and Building News* 62, no. 1196 (1898), 71–73. In 1900, a seven-part article series ("Architectural Acoustics I" through "Architectural Acoustics VII," from 7 April to 16 June), also in *American Architect and Building News*, expanded on the 1898 publication. See also note 26 below.

13. Wallace C. Sabine, "Theatre Acoustics," *American Architect* 104, no. 1984 (31 Dec. 1913), 268. Sabine erroneously spells August Toepler's name with two *p*s.

14. Settles, *Schlieren and Shadowgraph Techniques*, 8.

15. Peter Krehl and Stephan Engemann, "August Toepler: 'Er sah als erster den Schall,' " in Hoffmann and Berz, *Über Schall*, 200, 204.

16. "Er sah als erster den Schall" (my translation; all translations are my own unless otherwise noted). See ibid., 223. In an earlier English publication of Krehl and Engemann's essay on Toepler, *Schall* was translated as "shock waves." Peter Krehl and Stephan Engemann, "August Toepler—The First Who Visualized Shock Waves," *Shock Waves* 5 (1995), 1–18. Toepler's investigation of gunshots at a young age, in which he did not consider frequency, is often referred to as a study of "shock waves." The epitaph undoubtedly alludes to the broader phenomenon of sound.

17. Settles, *Schlieren and Shadowgraph Techniques*, 10.

18. Arthur L. Foley and Wilmer H. Souder, "A New Method of Photographing Sound Waves," *Physical Review* 35, no. 5 (1912), 373–86 (followed by five plate pages). A later, shorter publication on the technique made it familiar in the architectural community: Arthur L. Foley, "Sound Wave Photography in the Study of Architectural Acoustics," *American Architect–Architectural Review* 122, no. 2406 (1922), 415–18.

19. Foley and Souder, "A New Method," 374.

20. Ibid., 382.

21. Adolf Loos, "Das Mysterium der Akustik," *Der Merker: Österreichische Zeitschrift fur Musik und Theater* (Jan. 1912), 9–10. A revised version of this work was published in Adolf Loos, *Trotzdem: Gesammelte Schriften 1900–1930*, ed. Adolf Opel (1931; repr., Vienna: Prachner, 1997), 116–17. An English translation titled "The Mystery of Acoustics" appears in Adolf Loos, *Adolf Loos: On Architecture*, trans. Michael Mitchell (Riverside, Calif.: Ariadne Press, 2002), 108–9. On this text, see Sabine von Fischer, "From Seat Cushions to Formulae: Understanding Spatial Acoustics in Physics and Architecture," in *Germany in the Loud Twentieth Century: An Introduction*, ed. Florence Feiereisen and Alexandra Merley Hill (New York: Oxford University Press, 2011), 63–77.

22. Loos, "Das Mysterium der Akustik."

23. Viktoria Tkaczyk, "Listening in Circles: Spoken Drama and the Architects of Sound, 1750–1850," *Annals of Science* 71, no. 1 (2014), 299–334.

24. Jonathan Sterne, *The Audible Past: Cultural Origins of Sound Reproduction* (Durham, N.C.: Duke University Press, 2003), 43–44.
25. Thompson, *The Soundscape of Modernity.*
26. "Being equal to about .171*V* in the present experiments, but dependent on the initial intensity of the sound." Wallace C. Sabine, "Architectural Acoustics III," *American Architect and Building News* 68, no. 1271 (5 May 1900), 35–37. *V* stands for volume in cubic meters, and the constant (*k*) is composed of reverberation time (*T*) and total absorption in square meters (*A*). In later calculations, the constant of 0.171 was slightly lowered to 0.163, which is still used in the contemporary formula for reverberation time: $T = 0.163 \cdot V/A$.
27. Sabine, "Theatre Acoustics" (1913), 268.
28. Vitruvius, *De architectura*, bk. 5, chap. 8, "De locis consonantibus ad theatra eligendis," quoted in Sabine, "Theatre Acoustics" (1913), 257.
29. Ibid., 258.
30. Ibid.
31. Absolute accuracy was not achieved during these measurements, however, which still involved the experimenter's hearing threshold; rather, accuracy was achieved through mathematical calculation: "Each determination being the mean of about twenty observations under conditions such that the audible duration of the residual sound was 4 seconds, the average deviation of the single observations from the mean was .11 seconds, and the maximum deviation was .31. The computed 'probable error' of a single determination was about .02 seconds; as a matter of fact, the average deviation of ten determinations from the mean of the ten was .03 seconds, and the maximum deviation was .05." Wallace C. Sabine, "Architectural Acoustics II," *American Architect and Building News* 68, no. 1269 (21 Apr. 1900), 19.
32. Wallace C. Sabine, "Theatre Acoustics," in *Collected Papers on Acoustics by Wallace Clement Sabine*, ed. Theodore Lyman (Cambridge, Mass.: Harvard University Press, 1922), 163–97.
33. Sabine, "Theatre Acoustics" (1913), 274–76.
34. Thompson, *The Soundscape of Modernity*, 64.
35. Sabine, "Theatre Acoustics" (1913), 268–70.
36. Eugen Michel, *Hörsamkeit grosser Räume* (Braunschweig: Vieweg, 1921).
37. Alfred H. Davis and George W. C. Kaye, *The Acoustics of Buildings* (London: G. Bell and Sons, 1927), 46.
38. Ibid., 47.
39. Ibid., 48.
40. Eugen Michel, *Akustik und Schallschutz im Hochbau* (Berlin: De Gruyter, 1938), 50.
41. Anselm Lauber, *Wasserwellenversuche*, report no. 22.160 (Bern: Generaldirektion P.T.T., Forschungs- und Versuchsanstalt, 1951). For discussion, see Sabine von Fischer, "Refractions Reflected in a Ripple Tank, Reconsidered (1951)" (paper presented at the Fourth International Meeting of the European Architectural History Network, Dublin, 2–4 June 2016).
42. The work and career of Franz Max Osswald form a key narrative in Sabine von Fischer, *Das akustische Argument* (Zurich: gta Verlag, forthcoming).
43. Osswald asked for the two rooms numbered 39A and 35/36A. Habilitations—Gesuch Osswald an den Schweizerischen Schulrat, 2, SR3:1928/170, University Archives, ETH Zurich.
44. U.S. Patent US931819 A, granted 24 Aug. 1909, for "Walker's Loose Leaf" to the manufacturer John Walker Jr., London, England. Walker sold paper refills specifically to fit Osswald's binder (Refill Size No. 1299), but instead Osswald filled it with custom-cut brown craft paper and thin, pale-blue cardboard.
45. In her thesis, Lea Haller investigates the history of the ETH Photographisches Institut within the larger framework of the separation between basic and applied science. Lea Haller, "Reine und angewandte Forschung: Zur Praxis einer Grenzziehung. Eidgenössische Technische Hochschule Zürich, 1918–1952" (MA thesis, Universitat Zürich, 2006).
46. Franz Max Osswald, "Akustik in der Architektur" (lecture presented during the winter semester 1932–33), Hs 1412:20 (bequest of Rolf Meyer-von Gonzenbach), University Archives, ETH Zurich.
47. Settles, *Schlieren and Shadowgraph Techniques*, 19.
48. Franz Max Osswald, "Raumakustik in geometrischer Betrachtung," *Zeitschrift fur technische Physik* 17, no. 12 (1936), 562–63. Figures 15 and 20 in this essay are published on plate XI, Figure 16 on XIII.
49. Davis and Kaye, *The Acoustics of Buildings*, 52.
50. "Ultraschall-Luftwellenphotographie ist ein genaues und anschauliches Mittel zur Erkennung reflektorisch einflussreicher Begrenzungsteile, die nötigenfalls anders zu formen oder zu dampfen sind." Osswald, "Raumakustik in geometrischer Betrachtung," 563.
51. See Andy Fisher, "Photographic Scale," in *On the Verge of Photography: Imaging beyond Representation*, ed. Daniel Rubinstein, Johnny Golding, and Andy Fisher (Birmingham, England: ARTicle Press, 2013), 151–57; this essay was also published in *Philosophy of Photography* 3, no. 2 (2012), 310–29.
52. Franz M. Osswald, "The Acoustics of the Large Assembly Hall of the League of Nations, at Geneva, Switzerland," *American Architect* 84, no. 2559 (20 Dec. 1928), 838.
53. On the debates concerning the League of Nations auditorium, see Sabine von Fischer, "Debating Volume: Architectural vs. Electrical Amplification in the League of Nations, 1926–28," in "Sound Modernities," ed. Sabine von Fischer and Olga Touloumi, special issue, *Journal of Architecture* (forthcoming).
54. Franz Max Osswald, "Akustischer Konzert- und Vortragsaal mit veranderlichem Volumen," *Schweizerische Bauzeitung* 96, no. 18 (1930), 224–25.
55. Ibid., 225.
56. Paul E. Sabine, *Acoustics and Architecture* (New York: McGraw-Hill, 1932), 163.
57. Osswald, "Raumakustik in geometrischer Betrachtung," plates XI, XII, XIII.
58. Hans Frei, "Elektroakustische Untersuchungen in Hallraumen" (Electroacoustic experiments in reverberation chambers; PhD diss., ETH Zurich, 1935).
59. Ibid., 79.
60. With the theoretical suggestion of the *Luftschall-Verzögerungsrohr* (pipe for delaying airborne sound) Osswald (naively) asserted that resonances could be somehow eliminated in the context of large auditoriums, especially churches, where the amplified sound reached the audience before, instead of after, the direct sound, thus creating misorientation and sound perceived as a monstrosity. Franz Max Osswald, "Zur akustischen Gestaltung von Grossraumen," in Schweizerischer Ingenieur- und Architektenverein Centennial special issue, *Schweizerische Bauzeitung* (4 Sept. 1937), 69. For a general reference on the history of the reproduction of reverberation, see Axel Volmar, "Auditiver Raum aus der Dose," in *Klangmaschinen zwischen Experiment und Medientechnik*, ed. Daniel Gethmann (Bielefeld: Transcript-Verlag, 2010), 153–74.
61. Joseph Benedict Engl, *Raum- und Bauakustik* (Leipzig: Akademische Verlagsgesellschaft, 1939), 224.
62. Sabine, "Theatre Acoustics" (1913), 270, 272.
63. Ibid., 270.
64. Lothar Cremer, *Geometrische Raumakustik* (Zurich: Hirzel, 1949), 147.
65. Daston and Galison, *Objectivity*, 46, 371.
66. Hilde Heynen, *Architecture and Modernity: A Critique* (Cambridge, Mass.: MIT Press, 1999), 10.
67. Hans-Jörg Rheinberger, "Über Serendipitat—Forschen und Finden," in *Imagination: Suchen und Finden*, ed. Gottfried Boehm, Emmanuel Alloa, Orlando Budelacci, and Gerald Wildgruber (Paderborn: Wilhelm Fink, 2014), 235. The focus on serendipity in science is attributed to Royston M. Roberts, *Serendipity: Accidental Discoveries in Science* (New York: John Wiley, 1989).
68. Willi Furrer, *Raum- und Bauakustik*, *Lärmabwehr*, 2nd ed. (Basel: Birkhauser, 1961), 112.

69. Auguste Constant Raes, *Acoustique architecturale* (Paris: Eyrolles Editeur, 1952), plates I–XII.
70. "Architectural Acoustics" was the title of a journal article in 1898 and then of a series of articles in the *American Architect and Building News* of 1900, all by Wallace C. Sabine. It was not until three decades later, when the Acoustical Society of America and its journal were founded, that the field asserted a wider presence as an academic discipline.
71. Franz Max Osswald, "Method for Measuring Sound Isolation, in Particular of Impact Sound," *Journal of the Acoustical Society of America* 7 (Apr. 1936), 261. This article and its unpublished German manuscript are discussed in von Fischer, *Das akustische Argument*; and in Sabine von Fischer, "Tapping Machines: Listening to Difference, 1928–1956," in *Architecture / Machine*, eds. Moritz Gleich and Laurent Stalder (Zürich, gta Verlag, 2017), in print.
72. See von Fischer, *Das akustische Argument*.
73. Corey Keller, "Sight Unseen: Picturing the Invisible," in Keller, *Brought to Light*, 35.
74. Davis and Kaye, *The Acoustics of Buildings*, 58.
75. Jennifer Tucker, "The Social Photographic Eye," in Keller, *Brought to Light*, 44. Tucker foregrounds the history of visualization as a history of material culture. See also Jennifer Tucker, "The Historian, the Picture, and the Archive," *Isis* 97, no. 1 (2006), 111–20.
76. Daston and Galison, *Objectivity*, 16.