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(54) Title: REMOTE RECOVERY OF ACOUSTIC SIGNALS FROM PASSIVE SOURCES

(57) Abstract: Remote recovery of acoustic signals from passive sources is provided. Wideband radars, such as ultra-wideband (UWB) radars can detect minute surface displacements for vibrometry applications. Embodiments described herein remotely sense sound and recover acoustic signals from vibrating sources using radars. Early research in this domain only demonstrated single sound source recovery using narrowband millimeter wave radars in direct line-of-sight scenarios. Instead, by using wideband radars (e.g., X band UWB radars), multiple sources separated in ranges are observed and their signals isolated and recovered. Additionally, the see-through ability of microwave signals is leveraged to extend this technology to surveillance of targets obstructed by barriers. Blind surveillance is achieved by reconstructing audio from a passive object which is merely in proximity of the sound source using clever radar and audio processing techniques.

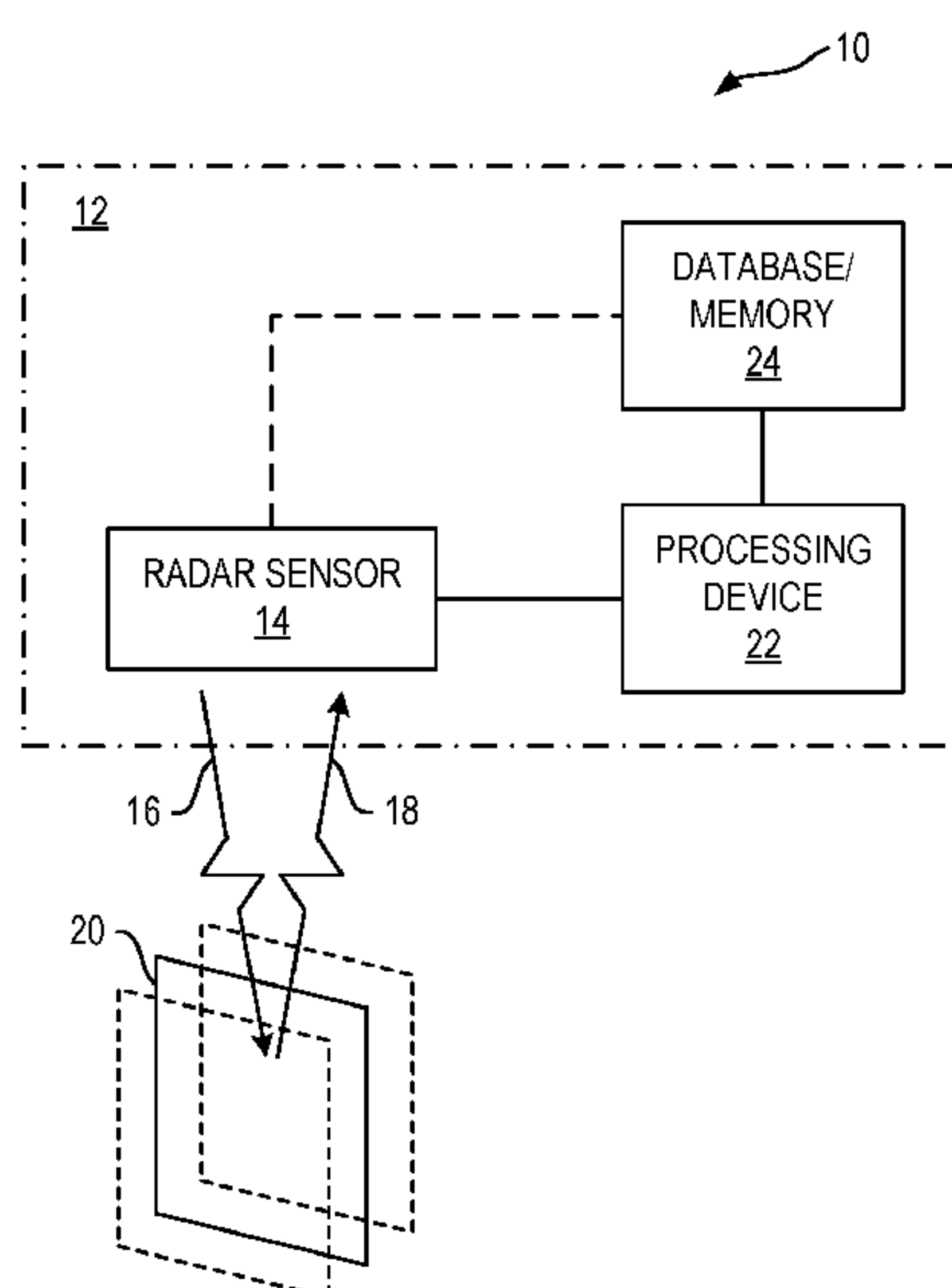


FIG. 2

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REMOTE RECOVERY OF ACOUSTIC SIGNALS FROM PASSIVE SOURCES**Related Applications**

[0001] This application claims the benefit of provisional patent application
5 serial number 62/929,140, filed November 1, 2019, the disclosure of which is
hereby incorporated herein by reference in its entirety.

Field of the Disclosure

[0002] The present disclosure relates to acoustic signal detection through
10 radio frequency (RF) signals.

Background

[0003] Radars have always been an integral part of industrial automation,
surveillance security and health monitoring systems. Previously, their ability to
15 detect minute surface displacements has been exploited for vibrometry
applications such as speech recovery. Similarly, surface skin motions have been
extracted for vital signs detection and even through-wall cardiac sensing.

[0004] Recovery of acoustic signals from surface vibrations using distinct
sensors has been a topic of interest for a few decades now. When sound
20 propagates through a medium, it creates pressure waves that induce surface
displacements. Feasibility of using radars to remotely sense sound has been
illustrated for speech retrieval. Radar sensing has also been illustrated for
generic acoustic signals using different millimeter wave radars and several
improvements have been proposed to radar receivers. A variety of speech
25 recovery methods have also been proposed to handle noisy backgrounds.

[0005] These previous approaches employed narrowband millimeter wave
Doppler radars for sound sensing and have been limited to single acoustic
source recovery in direct line-of-sight scenarios.

Summary

[0006] Remote recovery of acoustic signals from passive sources is provided. Wideband radars, such as ultra-wideband (UWB) radars can detect minute surface displacements for vibrometry applications. Embodiments described
5 herein remotely sense sound and recover acoustic signals from vibrating sources using radars. Early research in this domain only demonstrated single sound source recovery using narrowband millimeter wave radars in direct line-of-sight scenarios. Instead, by using wideband radars (e.g., X band UWB radars), multiple sources separated in ranges are observed and their signals isolated and
10 recovered. Additionally, the see-through ability of microwave signals is leveraged to extend this technology to surveillance of targets obstructed by barriers. Blind surveillance is achieved by reconstructing audio from a passive object which is merely in proximity of the sound source using clever radar and audio processing techniques.

[0007] Embodiments disclosed herein use a radio frequency (RF) radar sensor, such as a wideband radar sensor (e.g., X band UWB pulse Doppler radar sensor), to measure surface displacement of a vibrating surface. A radar response signal is received, from which a motion signal is extracted. An acoustic signal is reconstructed from the motion signal using signal processing
20 techniques, such as a fast Fourier transform (FFT)-based time-frequency signal processing technique. In some examples, the vibrating surface can be a passively vibrating source (e.g., one excited indirectly, such as by a non-line-of-sight active acoustic source). Some examples can isolate acoustic signals from multiple active sources. Some examples can also exploit a see-through ability of
25 the radar signal to recover acoustic signals.

[0008] An exemplary embodiment provides a method for remote recovery of an acoustic signal. The method includes transmitting a radar signal toward a vibrating surface and receiving an RF response signal corresponding to the radar signal. The method further includes extracting a motion signal from the RF
30 response signal, determining spatial information corresponding to the vibrating

surface from the motion signal, and reconstructing an acoustic signal from the motion signal using the spatial information.

[0009] Another exemplary embodiment provides an RF device. The RF device includes a radar sensor and a processing circuit coupled to the radar sensor. The radar sensor is configured to receive an RF response signal to a radar signal.

The processing circuit is configured to recover an acoustic signal by extracting a motion signal for one or more vibrating surfaces from the RF response signal, determining spatial information corresponding to the one or more vibrating surfaces from the motion signal, and using the spatial information to recover the acoustic signal from the motion signal.

[0010] Another exemplary embodiment provides a system for remote recovery of an acoustic signal. The system includes a radar sensor, a database, and a processing circuit coupled to the database. The radar sensor is configured to receive an RF response signal to a radar signal. The database is configured to store the RF response signal. The processing circuit is configured to extract a motion signal for a vibrating surface from the RF response signal, determine spatial information corresponding to the vibrating surface from the motion signal, the spatial information comprising at least one of a range to the vibrating surface, an angle to the vibrating surface, and a Doppler frequency shift associated with the vibrating surface, and reconstruct the acoustic signal from the motion signal using the spatial information.

[0011] Those skilled in the art will appreciate the scope of the present disclosure and realize additional aspects thereof after reading the following detailed description of the preferred embodiments in association with the accompanying drawing figures.

Brief Description of the Drawing Figures

[0012] The accompanying drawing figures incorporated in and forming a part of this specification illustrate several aspects of the disclosure, and together with the description serve to explain the principles of the disclosure.

[0013] Figure 1A is a schematic diagram of an exemplary system for remote recovery of an acoustic signal, illustrating observation of surface displacement of a passive object in the proximity of an active source.

5 [0014] Figure 1B is a schematic diagram of the system of Figure 1A, illustrating detection and isolation of acoustic signals by observing surface displacement of multiple sound sources separated in different ranges to the radar.

10 [0015] Figure 1C is a schematic diagram of the system of Figure 1A, illustrating recovery of an acoustic signal from a sound source obstructed by a dielectric medium.

[0016] Figure 2 is a schematic diagram of the system of Figures 1A-1C, which includes a radio frequency (RF) device for acoustic recovery using wideband radar.

15 [0017] Figure 3 is a graphical flowchart of an exemplary process for audio signal extraction from a backscattered radar return.

[0018] Figure 4 is a schematic diagram of a radar data matrix which includes micro-displacements corresponding to an acoustic signal.

[0019] Figure 5 is an image of a first evaluation setup, which recovers an acoustic signal by observing surface displacement of a passive source.

20 [0020] Figure 6A is a spectrogram of a radar result for remote recovery of the acoustic signal of Figure 5.

[0021] Figure 6B is a spectrogram of the original audio signal.

[0022] Figure 6C is a graphical representation of the radar recovered audio waveform from the radar result of Figure 5.

25 [0023] Figure 6D is a graphical representation of the original audio waveform.

[0024] Figure 7 is an image of a second evaluation setup, which recovers multiple acoustic signals by observing and isolating surface displacement of two active sources at different ranges.

30 [0025] Figure 8A is a spectrogram of a radar result for remote recovery of the acoustic signal from the closer sound source S_2 of Figure 7.

[0026] Figure 8B is a spectrogram of the original audio signal from sound source S_2 .

[0027] Figure 8C is a graphical representation of the radar recovered audio waveform $\hat{x}_2(t)$ from sound source S_2 .

5 [0028] Figure 8D is a graphical representation of the original audio waveform $x_2(t)$ from sound source S_2 .

[0029] Figure 8E is a spectrogram of a radar result for remote recovery of the acoustic signal from the further sound source S_1 of Figure 7.

10 [0030] Figure 8F is a spectrogram of the original audio signal from sound source S_1 .

[0031] Figure 8G is a graphical representation of the radar recovered audio waveform $\hat{x}_1(t)$ from sound source S_1 .

[0032] Figure 8H is a graphical representation of the original audio waveform $x_1(t)$ from sound source S_1 .

15 [0033] Figure 9 is an image of the third evaluation setup, which recovers an acoustic signal through a wall or other barrier.

[0034] Figure 10A is a spectrogram of a radar result for remote recovery of the acoustic signal from Figure 9.

[0035] Figure 10B is a spectrogram of the original audio signal.

20 [0036] Figure 10C is a graphical representation of the radar recovered audio waveform.

[0037] Figure 10D is a graphical representation of the original audio waveform.

25 [0038] Figure 11 is a flow diagram illustrating a process for remote recovery of an acoustic signal.

[0039] Figure 12 is a schematic diagram of a generalized representation of an exemplary computer system that could be used to perform any of the methods or functions described above, such as remote recovery of an acoustic signal.

Detailed Description

[0040] The embodiments set forth below represent the necessary information to enable those skilled in the art to practice the embodiments and illustrate the best mode of practicing the embodiments. Upon reading the following description
5 in light of the accompanying drawing figures, those skilled in the art will understand the concepts of the disclosure and will recognize applications of these concepts not particularly addressed herein. It should be understood that these concepts and applications fall within the scope of the disclosure and the accompanying claims.

[0041] It will be understood that, although the terms first, second, etc. may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. For example, a first element could be termed a second element, and, similarly, a second element could be termed a first element, without departing
10 from the scope of the present disclosure. As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items.

[0042] It will be understood that when an element such as a layer, region, or substrate is referred to as being "on" or extending "onto" another element, it can be directly on or extend directly onto the other element or intervening elements
15 may also be present. In contrast, when an element is referred to as being "directly on" or extending "directly onto" another element, there are no intervening elements present. Likewise, it will be understood that when an element such as a layer, region, or substrate is referred to as being "over" or extending "over" another element, it can be directly over or extend directly over
20 the other element or intervening elements may also be present. In contrast, when an element is referred to as being "directly over" or extending "directly over" another element, there are no intervening elements present. It will also be understood that when an element is referred to as being "connected" or
25 "coupled" to another element, it can be directly connected or coupled to the other element or intervening elements may be present. In contrast, when an element is

referred to as being "directly connected" or "directly coupled" to another element, there are no intervening elements present.

[0043] Relative terms such as "below" or "above" or "upper" or "lower" or "horizontal" or "vertical" may be used herein to describe a relationship of one element, layer, or region to another element, layer, or region as illustrated in the Figures. It will be understood that these terms and those discussed above are intended to encompass different orientations of the device in addition to the orientation depicted in the Figures.

[0044] The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the disclosure. As used herein, the singular forms "a," "an," and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises," "comprising," "includes," and/or "including" when used herein specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

[0045] Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure belongs. It will be further understood that terms used herein should be interpreted as having a meaning that is consistent with their meaning in the context of this specification and the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

[0046] Remote recovery of acoustic signals from passive sources is provided. Wideband radars, such as ultra-wideband (UWB) radars can detect minute surface displacements for vibrometry applications. Embodiments described herein remotely sense sound and recover acoustic signals from vibrating sources using radars. Early research in this domain only demonstrated single sound source recovery using narrowband millimeter wave radars in direct line-of-sight scenarios. Instead, by using wideband radars (e.g., X band UWB radars),

multiple sources separated in ranges are observed and their signals isolated and recovered. Additionally, the see-through ability of microwave signals is leveraged to extend this technology to surveillance of targets obstructed by barriers. Blind surveillance is achieved by reconstructing audio from a passive object which is
5 merely in proximity of the sound source using clever radar and audio processing techniques.

[0047] Embodiments disclosed herein use a radio frequency (RF) radar sensor, such as a wideband radar sensor (e.g., X band UWB pulse Doppler radar sensor), to measure surface displacement of a vibrating surface. A radar
10 response signal is received, from which a motion signal is extracted. An acoustic signal is reconstructed from the motion signal using signal processing techniques, such as a fast Fourier transform (FFT)-based time-frequency signal processing technique. In some examples, the vibrating surface can be a passively vibrating source (e.g., one excited indirectly, such as by a non-line-of-
15 sight active acoustic source). Some examples can isolate acoustic signals from multiple active sources. Some examples can also exploit a see-through ability of the radar signal to recover acoustic signals.

I. Introduction

20 **[0048]** Previous approaches employed narrowband millimeter wave Doppler radars to single acoustic source recovery in direct line-of-sight scenarios. Embodiments of the present disclosure instead use wideband radar sensors (e.g., a UWB radar operating at X frequency band) as an RF microphone but in much more complex environments.

25 **[0049]** Figures 1A-1C illustrate three unique evaluation setups used to demonstrate the success of the technology described herein. Figure 1A is a schematic diagram of an exemplary system 10 for remote recovery of an acoustic signal, illustrating observation of surface displacement of a passive object in the proximity of an active source. Figure 1B is a schematic diagram of
30 the system of Figure 1A, illustrating detection and isolation of acoustic signals by observing surface displacement of multiple sound sources separated in different

ranges to the radar. Figure 1C is a schematic diagram of the system of Figure 1A, illustrating recovery of an acoustic signal from a sound source obstructed by a dielectric medium. This disclosure analyzes the spectrum and waveform of a reference source and recovered signals to illustrate workings of proposed
5 processing techniques.

II. Radar Processing

[0050] Figure 2 is a schematic diagram of the system 10 of Figures 1A-1C, which includes an RF device 12 for acoustic recovery using wideband radar. In
10 an exemplary aspect, the RF device 12 includes a radar sensor 14 which transmits a radar signal 16 and receives an RF response signal 18 to the radar signal 16 after interaction with (e.g., reflection/refraction from) one or more vibrating surfaces 20. The vibrating surfaces 20 represent any surface which may
15 vibrate with an acoustic signal, such as an active acoustic source or a passive acoustic source, such as in the examples illustrated in Figures 1A-1C. The RF device 12 further includes a processing device 22 for processing and analyzing the RF response signal 18 to recover one or more acoustic signals. Generally,
the RF device 12 further includes a database or memory 24 for storing instructions and/or data, which is coupled to the processing device 22 (and
20 optionally coupled to the radar sensor 14). The RF device 12 may include additional components, such as discussed in Section VI below.

[0051] In an exemplary aspect, the radar sensor is a wideband radar, and the radar signal 16 is a wideband radar signal, such as an X band UWB impulse signal. It should be understood that other signals may be used (e.g., a non-
25 impulse radar signal) in an appropriate electromagnetic frequency (e.g., terrestrial radio, microwave, mmWave, optical, etc.). In some examples, the radar sensor 14 receives the RF response signal 18 without sending the radar signal 16 (e.g., the radar signal 16 is sent from another component of the RF device 12 or from another transmitter device).

30 **[0052]** In the illustrated embodiment, the system 10 for remote recovery of an acoustic signal primarily includes the RF device 12. In other embodiments, the

system 10 includes the components of the RF device 12 as two or more separate devices. For example, the processing device 22 and/or the database/memory 24 may be incorporated in a remote server, with minimal or no signal processing being performed at the radar sensor 14.

5 **[0053]** This section elaborates on proposed processing steps that make detection and recovery of audio signals using radars (e.g., the radar sensor 14) possible. First, models for radar return for an environment are established. Next, how radar processing alters the model analytically is described. Given that Doppler shift is extracted in slow time from the pre-processing stage, exemplary
10 audio recovery methods are elaborated.

A. *Signal Model*

[0054] An impulse radar emits same narrow pulse at every pulse repetition interval. When reflected off a vibrating target (e.g., the vibrating surface 20), the
15 received pulse is modulated in phase and magnitude. Inspecting and extracting meaningful information from such backscattered signal is termed radar ‘sensing’. The RF response of surface vibrations of the object is modeled as a superposition of responses from discrete, dynamic scattering centers. The i -th scattering center is parameterized by reflectivity coefficient $\rho_i(t)$ and radial
20 distance $d_i(t)$ from the radar sensor, which vary as a function of time t . The received composite signal is modeled as:

$$y(\tau, t) = \sum_i^N \rho_i(t) p(\tau - \tau_{d_i}(t)) \quad \text{Equation 1}$$

$$= \sum_i^N \rho_i(t) p(\tau - 2 \frac{d_i(t)}{c}) \quad \text{Equation 2}$$

where N is the number of scattering centers and $p(\tau)$ is the transmitted pulse, c
25 denotes the speed of light. Note that t and τ are two different time scales. The former is often referred as slow-time sampling interval and is related to the pulse repetition interval. The latter time scale is referred as fast-time sampling interval and is often associated with ADC sampling interval providing distance information.

30 **[0055]** The direct RF sampled signal is then down converted to the complex baseband and is represented as:

$$y_b(t) = y(t, \tau) e^{-j2\pi F_c \tau} \quad \text{Equation 3}$$

where F_c denotes the nominal operating frequency.

B. Radar Processing

5 **[0056]** Figure 3 is a graphical flowchart of an exemplary process for audio signal extraction from a backscattered radar return (e.g., the RF response signal 18). At a pre-processing stage (block 300), motion filtering is implemented to remove a static background. In an exemplary aspect, the received radar return is organized in two-dimensional (2-D) matrix format with one direction
10 corresponding to the slow-time samples t and the other direction to the fast-time/range samples τ . By stacking range samples column-wise (block 302), vibration profiles are revealed in a range-slow time heatmap. The most significant energy indicates where the surface motion occurs.

[0057] In order to capture all the local motions, multiple range bins of interest
15 are spatially combined into a single time series $y_b(t)$ (block 304) and a composite vibration profile (e.g., a Doppler profile) is obtained (block 306). Then, time-varying spectral features are inspected through time frequency analysis. For visualization purposes of this study, a few edited audio sound clips that have very distinct spectral and temporal features are selected as shown in the results
20 section. The radar recovered acoustic wave is constructed (block 308) by the proposed audio recovery method in Section III. The goal is to extract good quality audio samples from radar signals and then these audible samples are played out by an audio device so that human can hear and recognize it.

25 III. Audio Signal Processing

[0058] Sound is produced when molecules inside a medium are exerted by an internal or external force (certain embodiments consider only external forces). More elaborately, kinetic energy generated due to motion of an external object is transferred into surrounding molecules in vicinity of the object. This energy
30 travels through the medium as a longitudinal wave and is heard as sound. In the context of radar processing, rate of object displacement is the Doppler

frequency/velocity of object. The Doppler frequency is computed by taking a Fourier transform across slow time. In radar vibrometry, a short-time Fourier transform (STFT) is instead computed across slow time for a selected number of range bins.

5 **[0059]** Figure 4 is a graphical representation of an analogy of a radar data matrix (which includes micro-displacements corresponding to an acoustic signal) with sound production. Using this analogy, radar vibrometry can be interpreted as hearing Doppler frequency of the object in time.

[0060] During radar processing for a given slow time period, the received
10 complex baseband waveform for a closely spaced set of range bins contains all vibration information from detected sources. STFT is then operated on the spatially combined complex baseband waveform $\dot{y}_b(t)$:

$$S_y(t, f; h) = STFT(\dot{y}_b(t)) = \int \dot{y}_b(\kappa) h^*(\kappa - t) e^{-j2\pi f \kappa} d\kappa \quad \text{Equation 4}$$

Equivalently, it may be represented in the frequency spectrum as:

$$15 \quad S_y(t, f; h) = S_{(y,f)}(t, f; h) + S_{(y,-f)}(t, -f; h) \quad \text{Equation 5}$$

where $S_y(t, f; h)$ is the STFT of the signal $\dot{y}_b$ using a window function $h(t)$. It is to be noted that the bandwidth of $S_y(t, f; h)$ is always band limited by maximum measurable Doppler frequency. The band limited signal inherently reduces ambient noise to give high quality sound. However, the STFT of complex
20 baseband signal $\dot{y}_b(t)$ is generally not symmetric, $S_{(y,f)} \neq S_{(y,-f)}$. This poses a significant challenge in recovery. This symmetry issue is addressed by emphasizing that vibrations are physical phenomena and are transmitted/acquired as real signals. To this end, a conjugate symmetry is enforced such that $S_{(y,f)}(t, f; h) = S_{(y,-f)}^*(t, -f; h)$, and the resulting inverse
25 STFT transformed waveform is deemed to be a real-valued signal $x(t)$.

[0061] The chosen mirroring spectrum is based on power density comparison, higher power gives better audible sound. Thus, if $S_{(y,f)}(t, f; h)$ contains more energy than $S_{(y,-f)}(t, -f; h)$ in the spectral range of interest, such as:

$$\sum_t \sum_{f_1}^{f_2} |S_{(y,f)}(t, f; h)|^2 > \sum_t \sum_{f_1}^{f_2} |S_{(y,-f)}(t, -f; h)|^2 \quad \text{Equation 6}$$

then $S_{(y,f)}(t, f; h)$ is a better candidate for mirroring and vice versa. Hence Equation 5 reduces to:

$$x(t) = STFT^{-1}\{S_{(y,f)}(t, f; h) + S_{(y,-f)}^*(t, -f; h)\} \quad \text{Equation 7}$$

where $g(t)$ is a window function used in inverse STFT. Additional processing steps by using filters on $S_y(t, f; h)$ may be performed to reduce noise, however for clarity those details are omitted. Under the unity energy assumption on window functions $h(t)$ and $g(t)$, Equation 7 simplifies into:

$$x(t) = 2Re\{\dot{y}_b(t)\} \quad \text{Equation 8}$$

specifically when both STFT and inverse STFT (ISTFT) windows are identical the resulting sound waveform generated is the real part of $\dot{y}_b(t)$, $x(t) = 2Re\{\dot{y}_b(t)\}$. If $S_{(y,-f)}(t, -f; h)$ is used in for mirroring in Equation 7, the resulting sound waveform is the imaginary part of $\dot{y}_b(t)$, $x(t) = 2Imag\{\dot{y}_b(t)\}$. The resulting range averaged complex baseband waveform contains most of the vibration information for production of sound. Evaluations on passive and active sources as well as discussion of these results are in the next section.

IV. Evaluation Results

[0062] Successful radar vibrometry is demonstrated for a multitude of tests using a UWB radar with 2 gigahertz (GHz) bandwidth operating around 10 GHz with slow-time frame rate 1000 hertz (Hz). Three distinct evaluation setups are constructed – 1) recover source audio by observing a passive source, 2) detect and isolate signal from two sources separated in space and 3) retrieve audio from a source obstructed by a non-conductive barrier such as a wall (see Figures 1A-1C).

25

A. *Evaluation Setup 1: Passive Source*

[0063] Figure 5 is an image of the first evaluation setup, which recovers an acoustic signal by observing surface displacement of a passive source. A passive object is exposed to an audio source in a cluttered environment, and surface vibrations of the object as a result of its proximity to the source are studied via UWB radar. Here, the audio source is a speaker labeled S and the

30

object under observation is an empty aluminum soda can P , both of which are separated by a small distance of about 15 cm.

[0064] Figure 6A is a spectrogram of a radar result for remote recovery of the acoustic signal of Figure 5. Figure 6B is a spectrogram of the original audio
 5 signal. The micro-displacements dominated by the passive object are collected from the range bins of interest and processed. An improved radar spectrogram is obtained since all the major spectral features (bright dots at higher frequencies and square shapes at lower frequencies) seen in Figure 6B are recovered in Figure 6A. Additionally, higher order harmonic frequency components and
 10 intermodulations are observed.

[0065] Figure 6C is a graphical representation of the radar recovered audio waveform from the radar result of Figure 5. Figure 6D is a graphical
 representation of the original audio waveform. The radar recovered waveform is also consistent with the majority of the temporal structure of the original audio
 15 waveform.

B. Evaluation Setup 2: Multiple Sources

[0066] Figure 7 is an image of the second evaluation setup, which recovers multiple acoustic signals by observing and isolating surface displacement of two
 20 active sources at different ranges. This setup demonstrates the ability to isolate audio signals for different vibrating sources from the radar return signal in non-ideal environments by clever radar processing. An evaluation setup was constructed where two audio sources S_1 and S_2 , separated in space, are being illuminated by a UWB radar. To add interest, two sound sources (two
 25 commercially available speakers) are used, playing two pre-edited sound files. The two sources are loudly playing different audio signals $x_1(t)$ and $x_2(t)$ respectively, which are recovered using methods outlined earlier.

[0067] Figure 8A is a spectrogram of a radar result for remote recovery of the acoustic signal from the closer sound source S_2 of Figure 7. Figure 8B is a
 30 spectrogram of the original audio signal from sound source S_2 . Figure 8C is a graphical representation of the radar recovered audio waveform $\hat{x}_2(t)$ from sound

source S_2 . Figure 8D is a graphical representation of the original audio waveform $x_2(t)$ from sound source S_2 .

[0068] Figure 8E is a spectrogram of a radar result for remote recovery of the acoustic signal from the further sound source S_1 of Figure 7. Figure 8F is a spectrogram of the original audio signal from sound source S_1 . Figure 8G is a graphical representation of the radar recovered audio waveform $\hat{x}_1(t)$ from sound source S_1 . Figure 8H is a graphical representation of the original audio waveform $x_1(t)$ from sound source S_1 .

[0069] In particular, the closer sound source S_2 has a triangular temporal-spectral content since the loudness increases over time. More spectral harmonic structures show up at later time. The recovered radar spectrogram (Figure 8A) is very similar to the reference audio spectrogram (Figure 8B). The amplitude of the radar recovered sound wave (Figure 8C) increases over time as expected but not all details are recovered (Figure 8D). While the temporal-spectral content in the sound source S_1 has a square shape, both the radar spectrogram and the waveform resemble the audio reference. Better recovery of the acoustic waveform of S_1 is observed because this sound is played by a much larger/louder speaker resulting in a larger surface vibration though it is located at a slightly further distance.

C. Evaluation Setup 3: See-Through Barriers

[0070] Figure 9 is an image of the third evaluation setup, which recovers an acoustic signal through a wall or other barrier. Unlike light, microwave signals penetrate dielectric medium, such as clothes, glass, plastic, dry wood, wall, etc. This implies this setup can be utilized to surveil vibrating targets that are beyond line of sight (e.g., not directly observable through sound or light waves), a regime where cameras fail. Here, the ability to reconstruct an audio signal $x(t)$ where the source S is obstructed by a non-conducting barrier B is demonstrated.

[0071] Figure 10A is a spectrogram of a radar result for remote recovery of the acoustic signal from Figure 9. Figure 10B is a spectrogram of the original audio signal. Figure 10C is a graphical representation of the radar recovered

audio waveform. Figure 10D is a graphical representation of the original audio waveform.

[0072] Despite the non-line-of-sight environment, the major spectral features and the temporal features are recovered in Figure 10A and 10C by comparing to the audio reference in Figures 10B and 10D. There are nine sound symbols corresponding to the nine distinct peaks in the audio waveform (Figure 10D). Similarly, the radar recovered waveform (Figure 10C) has nine spikes with a significantly reduced signal signal-to-noise ratio (SNR) due to energy loss in this blocked environment compared to the previous two evaluations. It is interesting to see that the most significant energy in the radar spectrogram is the low frequency content around 190 Hz while in the audio spectrogram it is 2nd -order harmonics around 380 Hz.

V. Method for Remote Recovery of an Acoustic Signal

[0073] Figure 11 is a flow diagram illustrating a process for remote recovery of an acoustic signal. The process begins at operation 1100, with transmitting a radar signal toward a vibrating surface. The process continues at operation 1102, with receiving an RF response signal corresponding to the radar signal. In an exemplary aspect, the radar sensor 14 of Figure 2 sends a series of wideband radar impulses and receives the RF response signal. The process continues at operation 1104, with extracting a motion signal from the RF response signal. The process continues at operation 1106, with determining spatial information corresponding to the vibrating surface from the motion signal. The process continues at operation 1108, with reconstructing an acoustic signal from the motion signal using the spatial information.

[0074] Although the operations of Figure 11 are illustrated in a series, this is for illustrative purposes and the operations are not necessarily order dependent. Some operations may be performed in a different order than that presented. Further, processes within the scope of this disclosure may include fewer or more steps than those illustrated in Figure 11.

VI. Computer System

[0075] Figure 12 is a schematic diagram of a generalized representation of an exemplary computer system 1200 that could be used to perform any of the methods or functions described above, such as remote recovery of an acoustic signal. In some examples, the RF device 12 of Figure 2 is implemented as the computer system 1200 or a component of the computer system 1200. In this regard, the computer system 1200 may be a circuit or circuits included in an electronic board card, such as, a printed circuit board (PCB), a server, a personal computer, a desktop computer, a laptop computer, an array of computers, a personal digital assistant (PDA), a computing pad, a mobile device, or any other device, and may represent, for example, a server or a user's computer.

[0076] The exemplary computer system 1200 in this embodiment includes a processing device 1202 or processor, a main memory 1204 (e.g., read-only memory (ROM), flash memory, dynamic random access memory (DRAM), such as synchronous DRAM (SDRAM), etc.), and a static memory 1206 (e.g., flash memory, static random access memory (SRAM), etc.), which may communicate with each other via a data bus 1208. Alternatively, the processing device 1202 may be connected to the main memory 1204 and/or static memory 1206 directly or via some other connectivity means. In an exemplary aspect, the processing device 1202 could be used to perform any of the methods or functions described above.

[0077] The processing device 1202 represents one or more general-purpose processing devices, such as a microprocessor, central processing unit (CPU), or the like. More particularly, the processing device 1202 may be a complex instruction set computing (CISC) microprocessor, a reduced instruction set computing (RISC) microprocessor, a very long instruction word (VLIW) microprocessor, a processor implementing other instruction sets, or other processors implementing a combination of instruction sets. The processing device 1202 is configured to execute processing logic in instructions for performing the operations and steps discussed herein.

[0078] The various illustrative logical blocks, modules, and circuits described in connection with the embodiments disclosed herein may be implemented or performed with the processing device 1202, which may be a microprocessor, field programmable gate array (FPGA), a digital signal processor (DSP), an application-specific integrated circuit (ASIC), or other programmable logic device, a discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein.

Furthermore, the processing device 1202 may be a microprocessor, or may be any conventional processor, controller, microcontroller, or state machine. The processing device 1202 may also be implemented as a combination of computing devices (e.g., a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration).

[0079] The computer system 1200 may further include a network interface device 1210. The computer system 1200 also may or may not include an input 1212, configured to receive input and selections to be communicated to the computer system 1200 when executing instructions. The input 1212 may include, but not be limited to, a touch sensor (e.g., a touch display), an alphanumeric input device (e.g., a keyboard), and/or a cursor control device (e.g., a mouse). In an exemplary aspect, the radar sensor of Figure 2 is an input 1212 to the computer system 1200. The computer system 1200 also may or may not include an output 1214, including but not limited to a display, a video display unit (e.g., a liquid crystal display (LCD) or a cathode ray tube (CRT)), or a printer. In some examples, some or all inputs 1212 and outputs 1214 may be combination input/output devices. In an exemplary aspect, the radar sensor of Figure 2 is also an output 1214 of the computer system 1200.

[0080] The computer system 1200 may or may not include a data storage device that includes instructions 1216 stored in a computer-readable medium 1218. The instructions 1216 may also reside, completely or at least partially, within the main memory 1204 and/or within the processing device 1202 during execution thereof by the computer system 1200, the main memory 1204, and the

processing device 1202 also constituting computer-readable medium. The instructions 1216 may further be transmitted or received via the network interface device 1210.

[0081] While the computer-readable medium 1218 is shown in an exemplary embodiment to be a single medium, the term “computer-readable medium” should be taken to include a single medium or multiple media (e.g., a centralized or distributed database, and/or associated caches and servers) that store the one or more sets of instructions 1216. The term “computer-readable medium” shall also be taken to include any medium that is capable of storing, encoding, or carrying a set of instructions for execution by the processing device 1202 and that causes the processing device 1202 to perform any one or more of the methodologies of the embodiments disclosed herein. The term “computer-readable medium” shall accordingly be taken to include, but not be limited to, solid-state memories, optical medium, and magnetic medium.

[0082] The operational steps described in any of the exemplary embodiments herein are described to provide examples and discussion. The operations described may be performed in numerous different sequences other than the illustrated sequences. Furthermore, operations described in a single operational step may actually be performed in a number of different steps. Additionally, one or more operational steps discussed in the exemplary embodiments may be combined.

[0083] Those skilled in the art will recognize improvements and modifications to the preferred embodiments of the present disclosure. All such improvements and modifications are considered within the scope of the concepts disclosed herein and the claims that follow.

Claims

What is claimed is:

1. A method for remote recovery of an acoustic signal, the method
5 comprising:
transmitting a radar signal toward a vibrating surface;
receiving a radio frequency (RF) response signal corresponding to the
radar signal;
extracting a motion signal from the RF response signal;
10 determining spatial information corresponding to the vibrating surface from
the motion signal; and
reconstructing an acoustic signal from the motion signal using the spatial
information.
- 15 2. The method of claim 1, wherein the radar signal comprises a series of
wideband radar impulses.
3. The method of any of claims 1 to 2, wherein the spatial information
comprises at least one of an angle to the vibrating surface, a range to the
20 vibrating surface, and a Doppler frequency shift due to the vibrating surface.
4. The method of claim 3, wherein the Doppler frequency shift is a large-
scale Doppler frequency shift.
- 25 5. The method of claim 3, wherein the Doppler frequency shift is a micro-
Doppler frequency shift.
6. The method of any of claims 1 to 5, wherein:
the spatial information comprises a range to the vibrating surface; and

determining the spatial information corresponding to the vibrating surface from the motion signal comprises spectrally analyzing the motion signal to:

divide the motion signal into a plurality of range bins; and

5 determine one or more range bins corresponding to one or more potential vibrating surfaces.

7. The method of claim 6, wherein:

the spatial information further comprises a Doppler frequency shift

10 associated with the vibrating surface; and

reconstructing the acoustic signal from the motion signal comprises using the Doppler frequency shift by:

selecting an initial range bin around a physical position of the vibrating surface;

15 selecting nearby range bins in a vicinity of the physical position; and

determining a Doppler frequency shift for the initial range bin and the nearby range bins.

20 8. The method of claim 7, wherein reconstructing the acoustic signal from the motion signal further comprises performing a short-time Fourier transform (STFT) over the initial range bin and the nearby range bins over a frequency support.

9. The method of claim 8, wherein the frequency support is based on a spectral signal-to-noise ratio (SNR) of a magnitude of the Doppler frequency shift.

10. The method of any of claims 1 to 9, wherein extracting a motion signal from the RF response signal comprises pre-processing the RF response signal by filtering the RF response signal to remove a static background.

30

11. The method of any of claims 1 to 10, wherein:
the vibrating surface is a passively vibrating surface; and
the acoustic signal originates from an indirectly observed active acoustic
source.

5

12. The method of claim 11, wherein the indirectly observed active acoustic
source is a non-line-of-sight acoustic source.

13. The method of any of claims 1 to 12, wherein:
the acoustic signal originates from multiple active acoustic sources; and
the method further comprises isolating a respective acoustic signal for
each active acoustic source from the acoustic signal.

10

14. The method of any of claims 1 to 13, wherein reconstructing the acoustic
signal from the motion signal comprises extracting local motion information at
each of a plurality of regions of the vibrating surface.

15

15. The method of claim 14, wherein reconstructing the acoustic signal from
the motion signal further comprises spatially combining the local motion
information at each of the plurality of regions of the vibrating surface into the
motion signal.

20

16. A radio frequency (RF) device, comprising:
a radar sensor configured to receive a radio frequency (RF) response
signal to a radar signal; and
a processing circuit coupled to the radar sensor and configured to recover
an acoustic signal by:
extracting a motion signal for one or more vibrating surfaces from
the RF response signal;
determining spatial information corresponding to the one or more
vibrating surfaces from the motion signal; and

25

30

using the spatial information to recover the acoustic signal from the motion signal.

17. The RF device of claim 16, wherein the radar sensor is further configured
5 to transmit the radar signal comprising a wideband radar signal.

18. The RF device of claim 16, wherein the spatial information comprises at least one of an angle to each of the one or more vibrating surfaces, a range to each of the one or more vibrating surfaces, and a Doppler frequency shift due to
10 each of the one or more vibrating surfaces.

19. The RF device of claim 18, wherein:
the RF response signal comprises a plurality of acoustic signals each from a different acoustic source; and
15 the processing circuit is further configured to recover each one of the plurality of acoustic signals by:
determining at least one of a range or an angle to a respective vibrating surface associated with the one of the plurality of acoustic signals;
20 determining a Doppler frequency shift at the at least one of the range or the angle to the respective vibrating surface; and
recovering the one of the plurality of acoustic signals using the Doppler frequency shift.

25 20. A system for remote recovery of an acoustic signal, comprising:
a radar sensor configured to receive a radio frequency (RF) response signal to a radar signal;
a database configured to store the RF response signal; and
a processing circuit coupled to the database and configured to:
30 extract a motion signal for a vibrating surface from the RF response signal;

- 5 determine spatial information corresponding to the vibrating surface
 from the motion signal, the spatial information comprising at
 least one of a range to the vibrating surface, an angle to the
 vibrating surface, and a Doppler frequency shift associated
 with the vibrating surface; and
 reconstruct the acoustic signal from the motion signal using the
 spatial information.

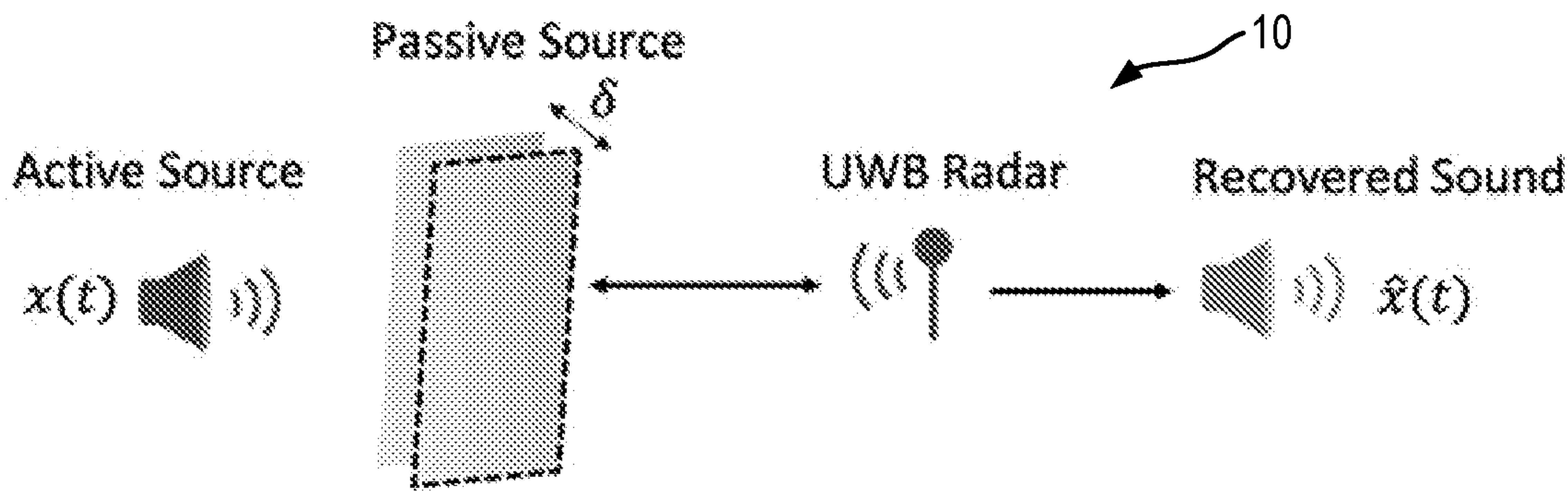


FIG. 1A

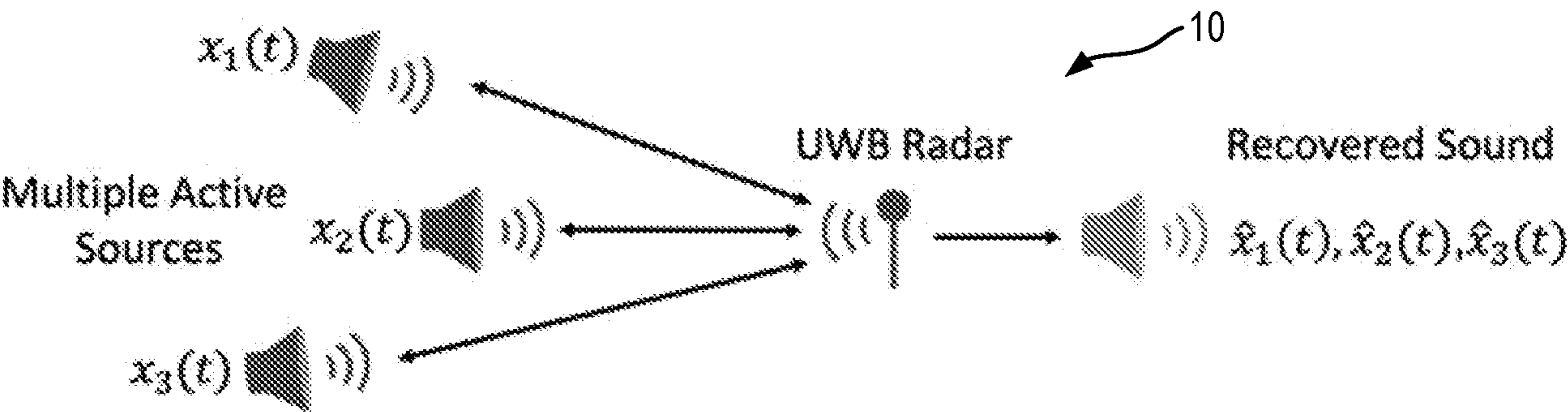


FIG. 1B

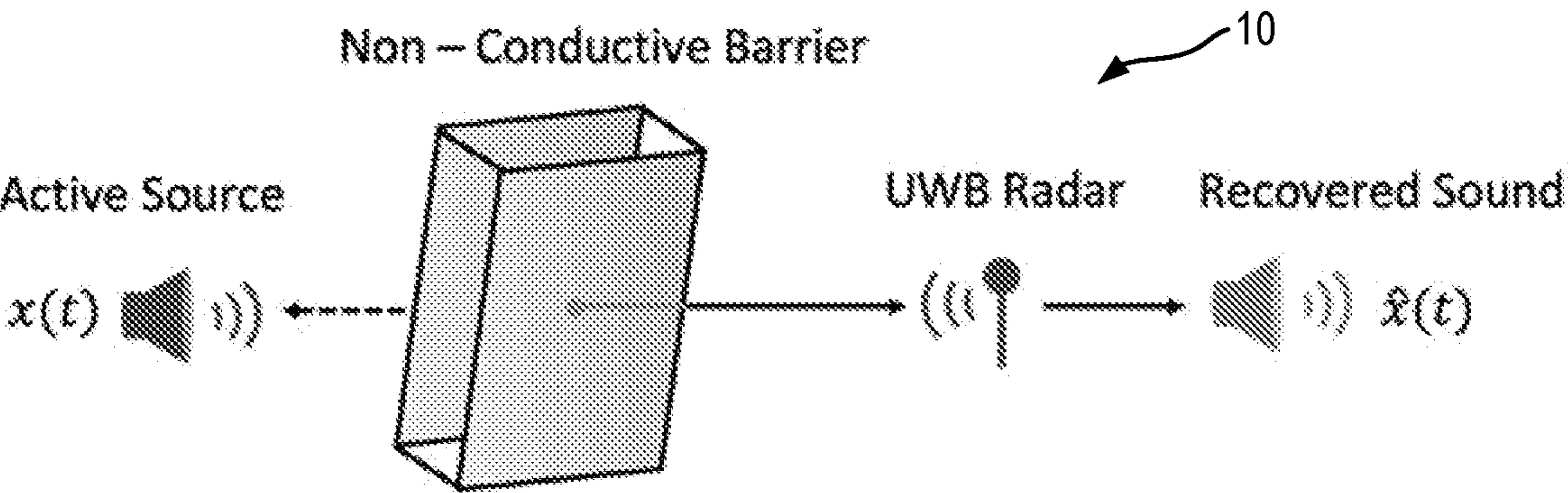


FIG. 1C

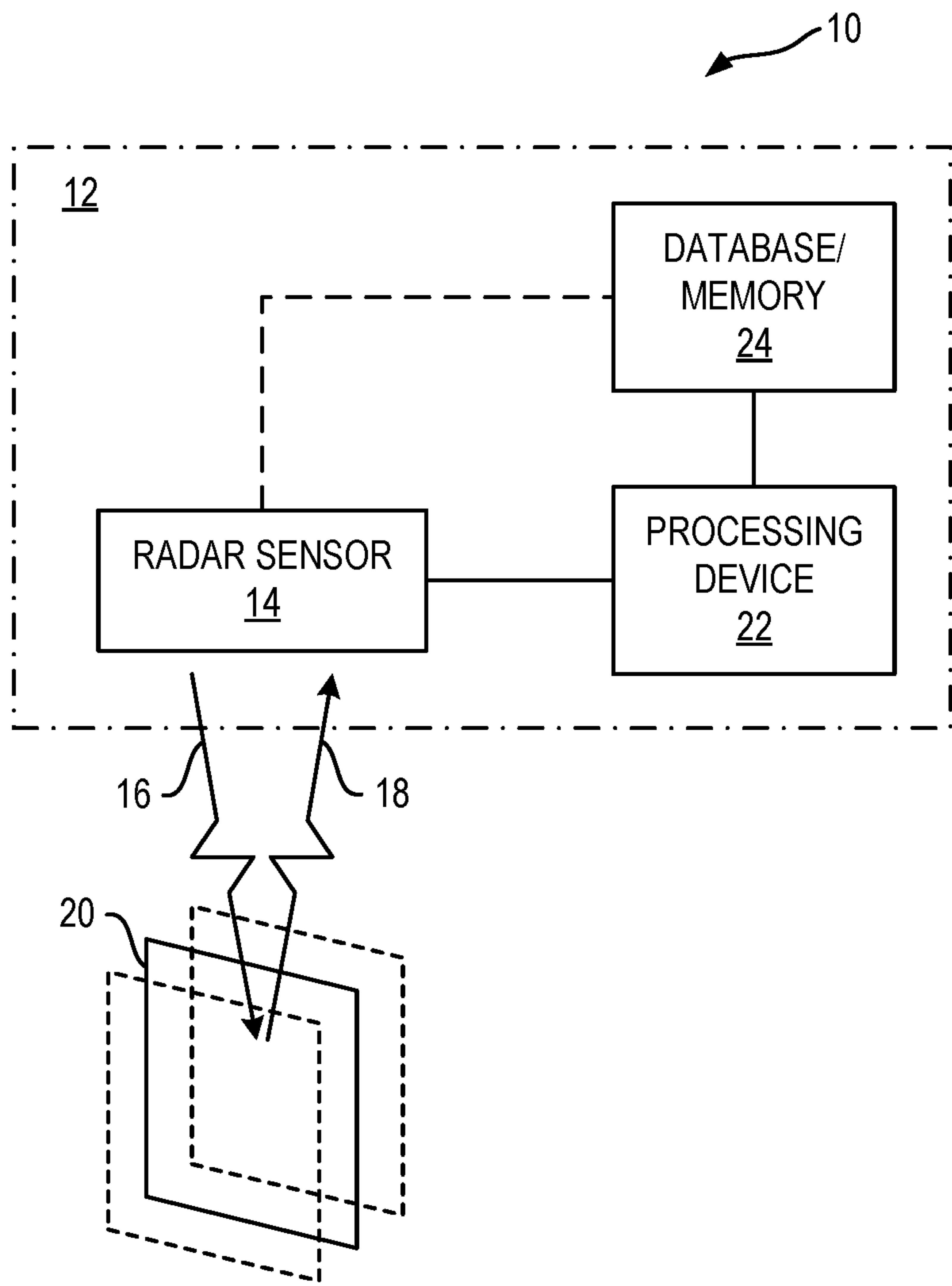


FIG. 2

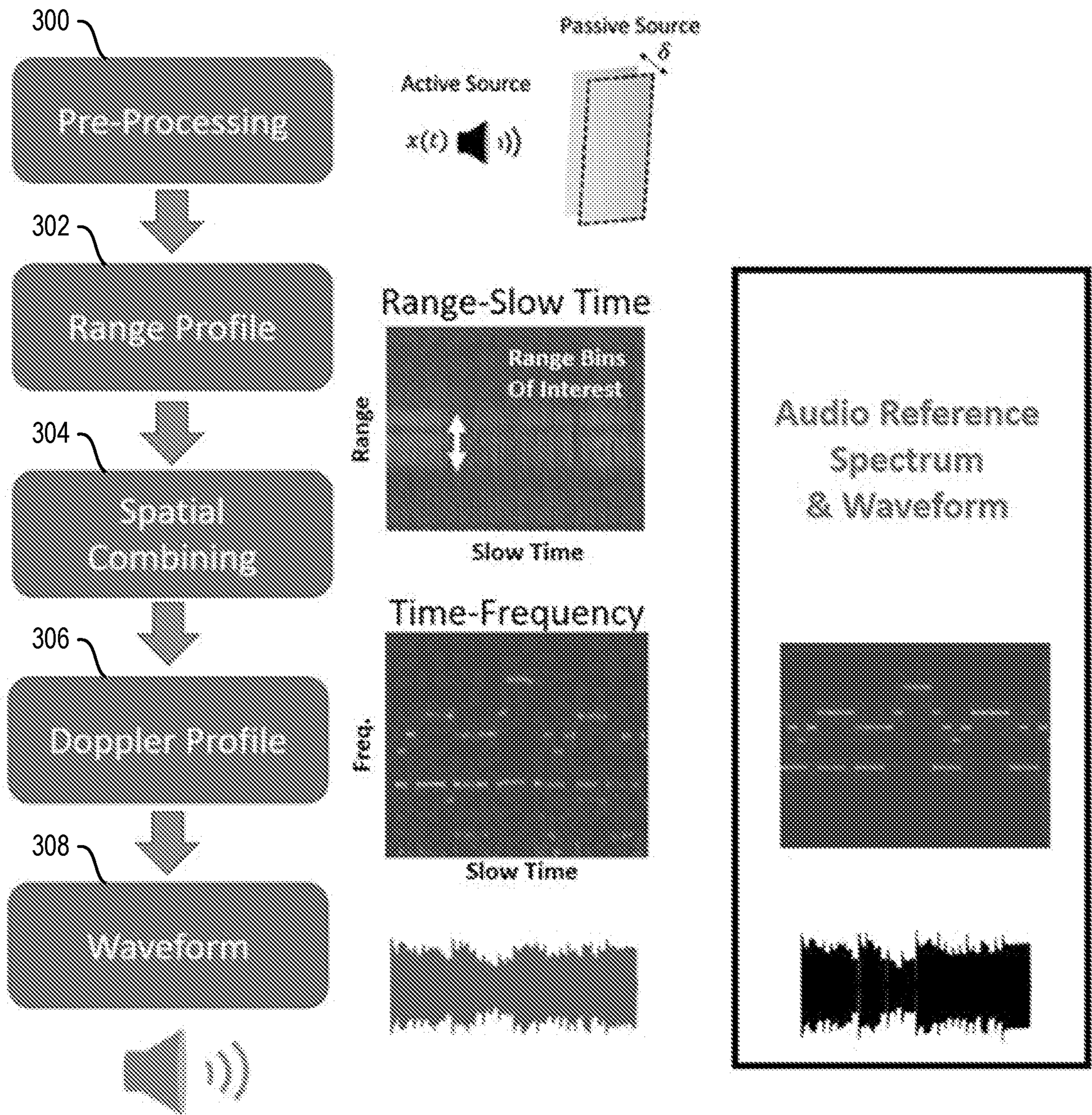


FIG. 3

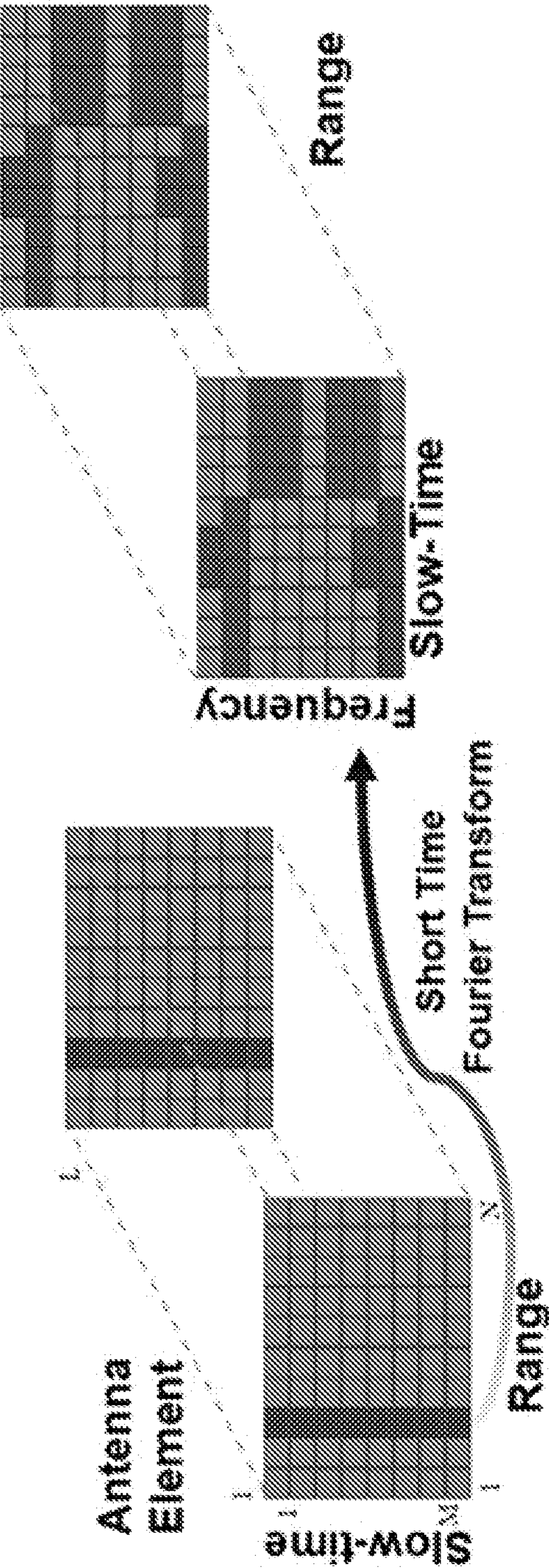


FIG. 4

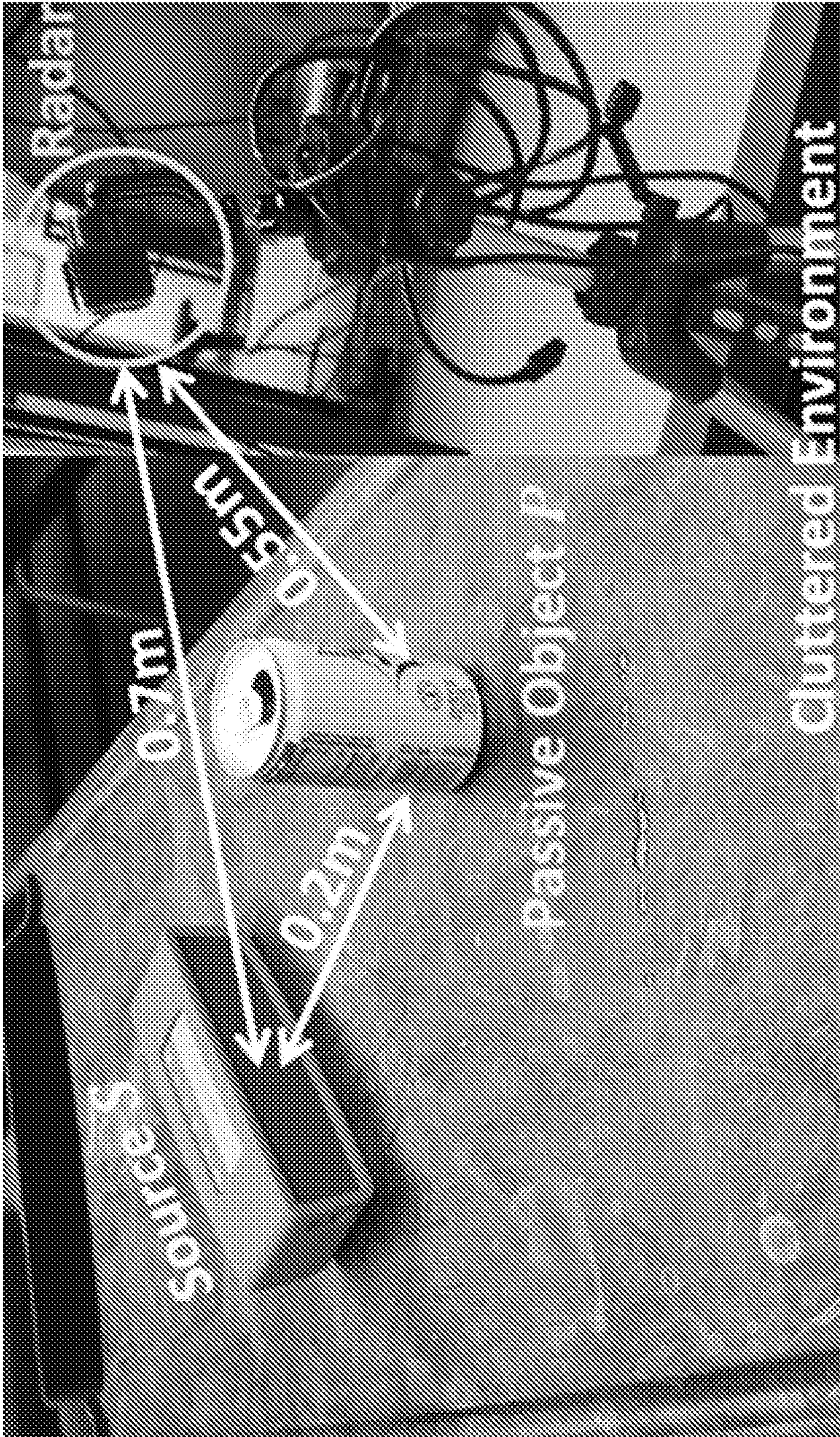


FIG. 5

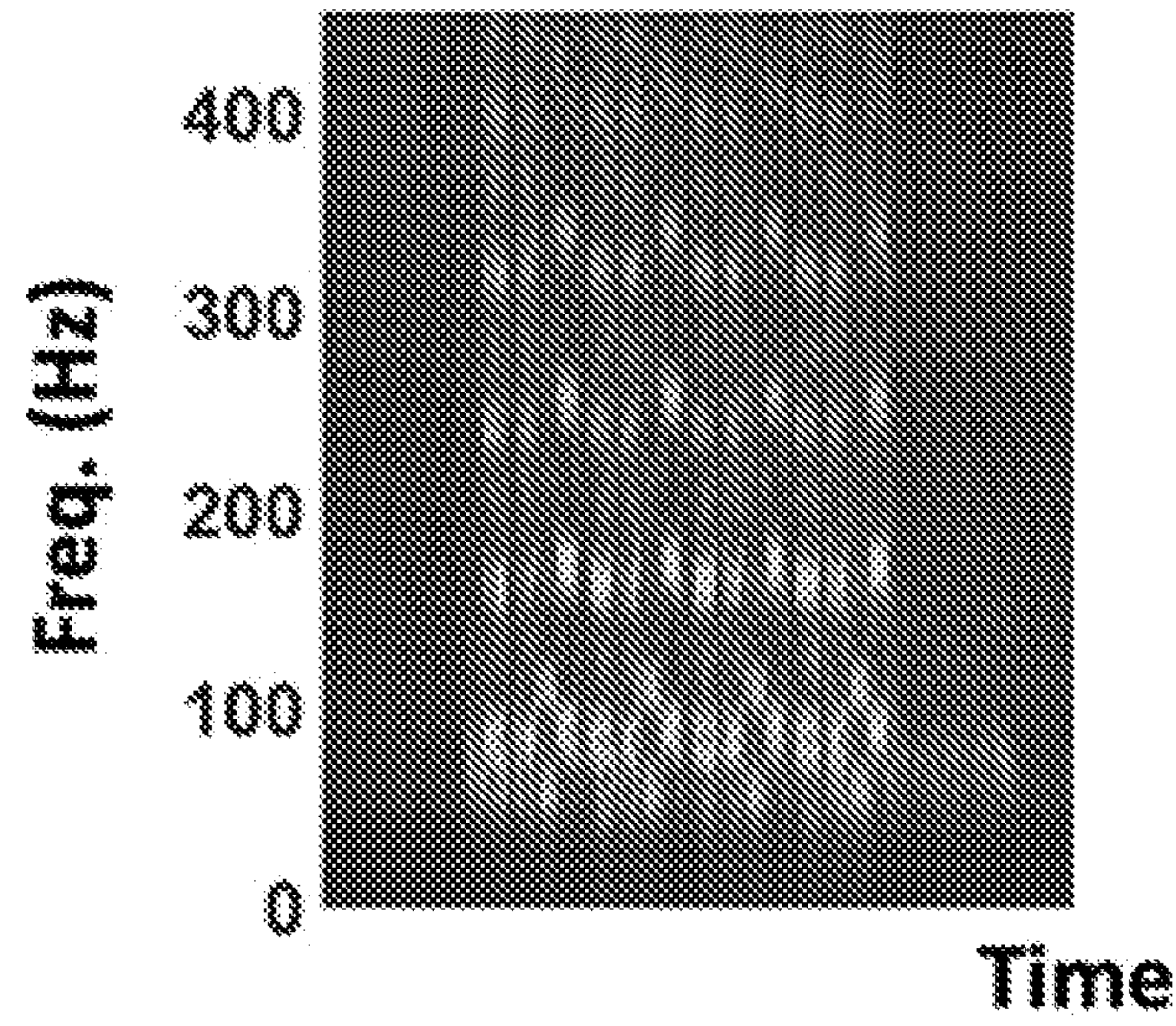


FIG. 6A

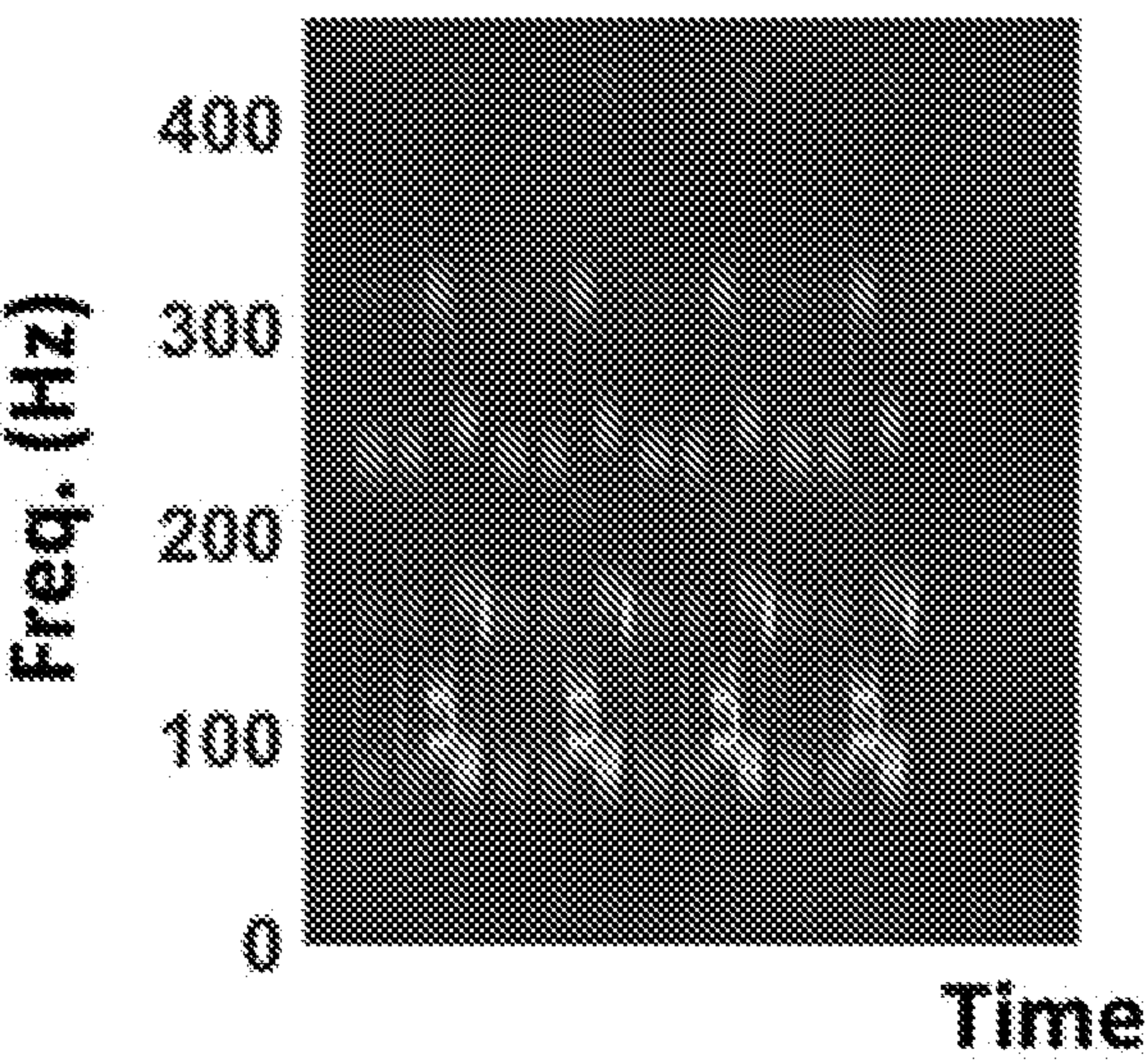


FIG. 6B

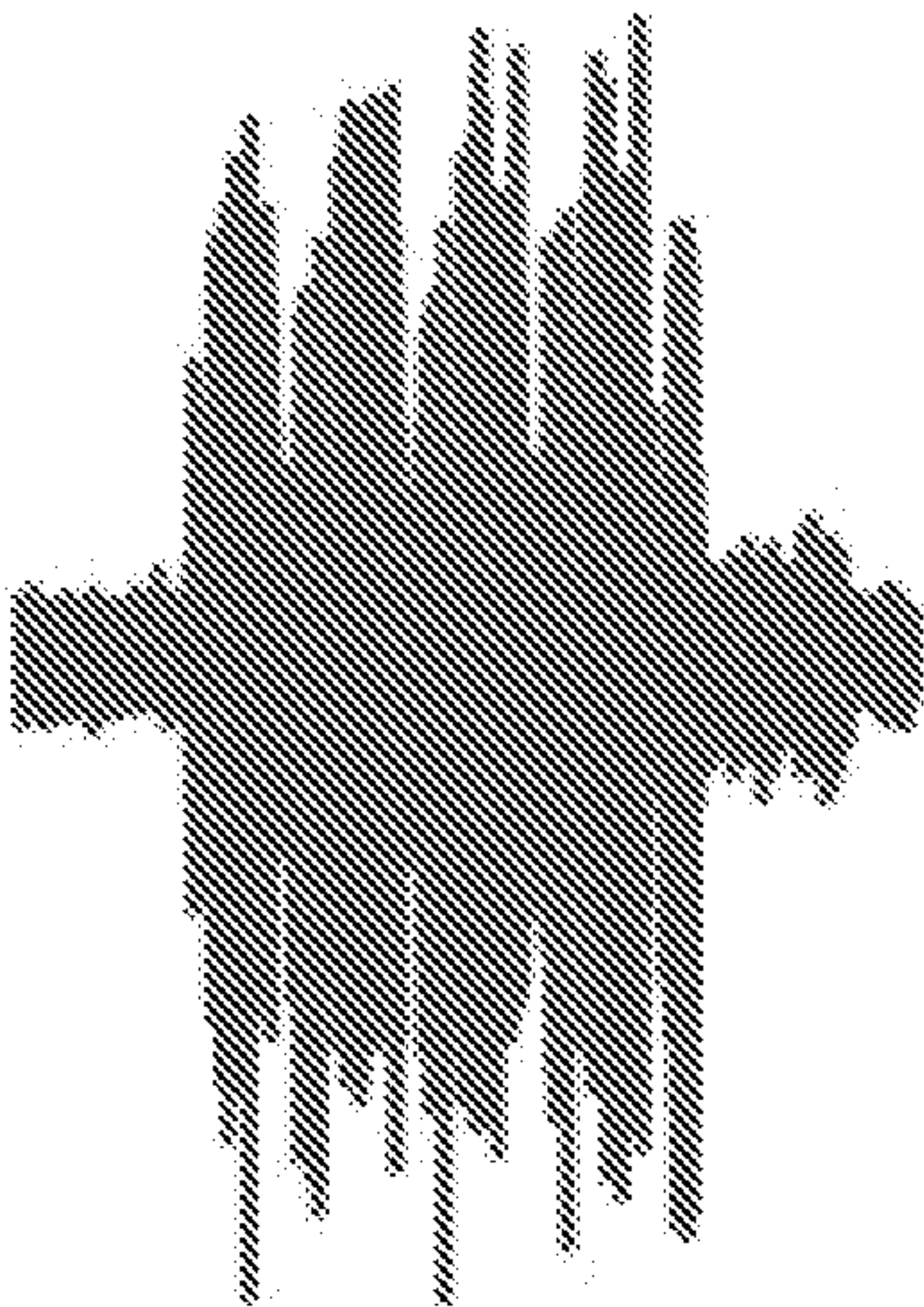


FIG. 6C



FIG. 6D

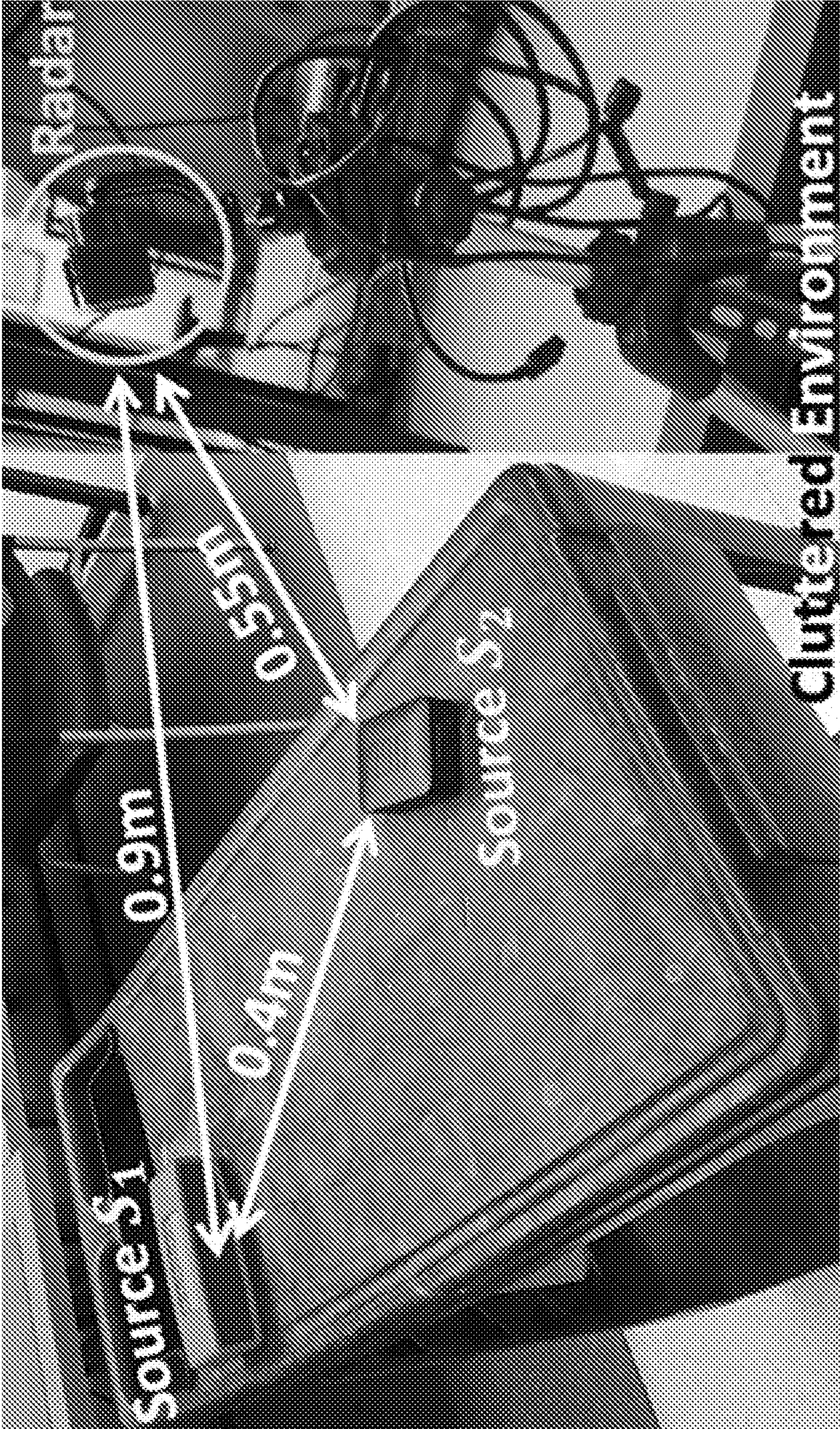


FIG. 7

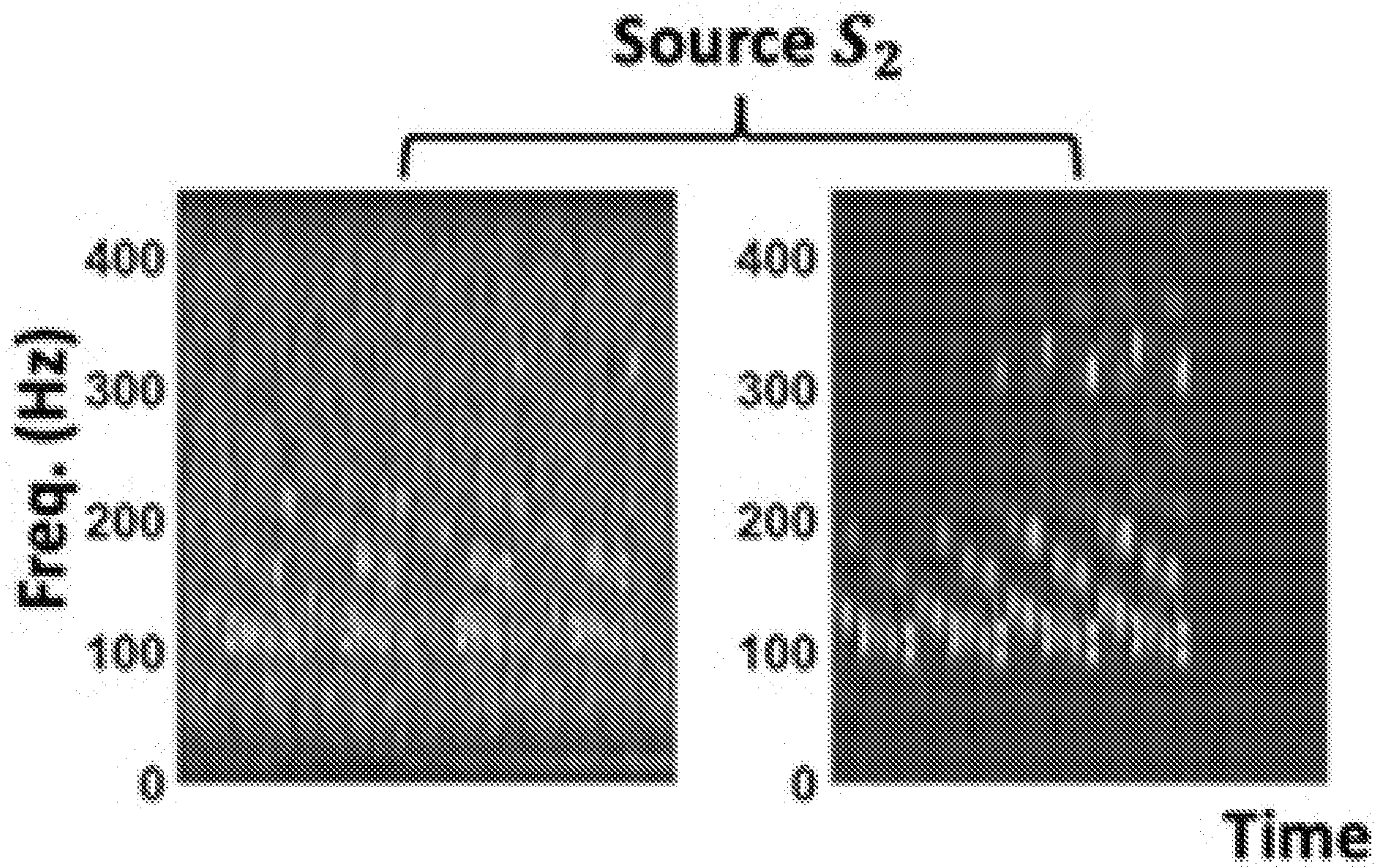


FIG. 8A

FIG. 8B

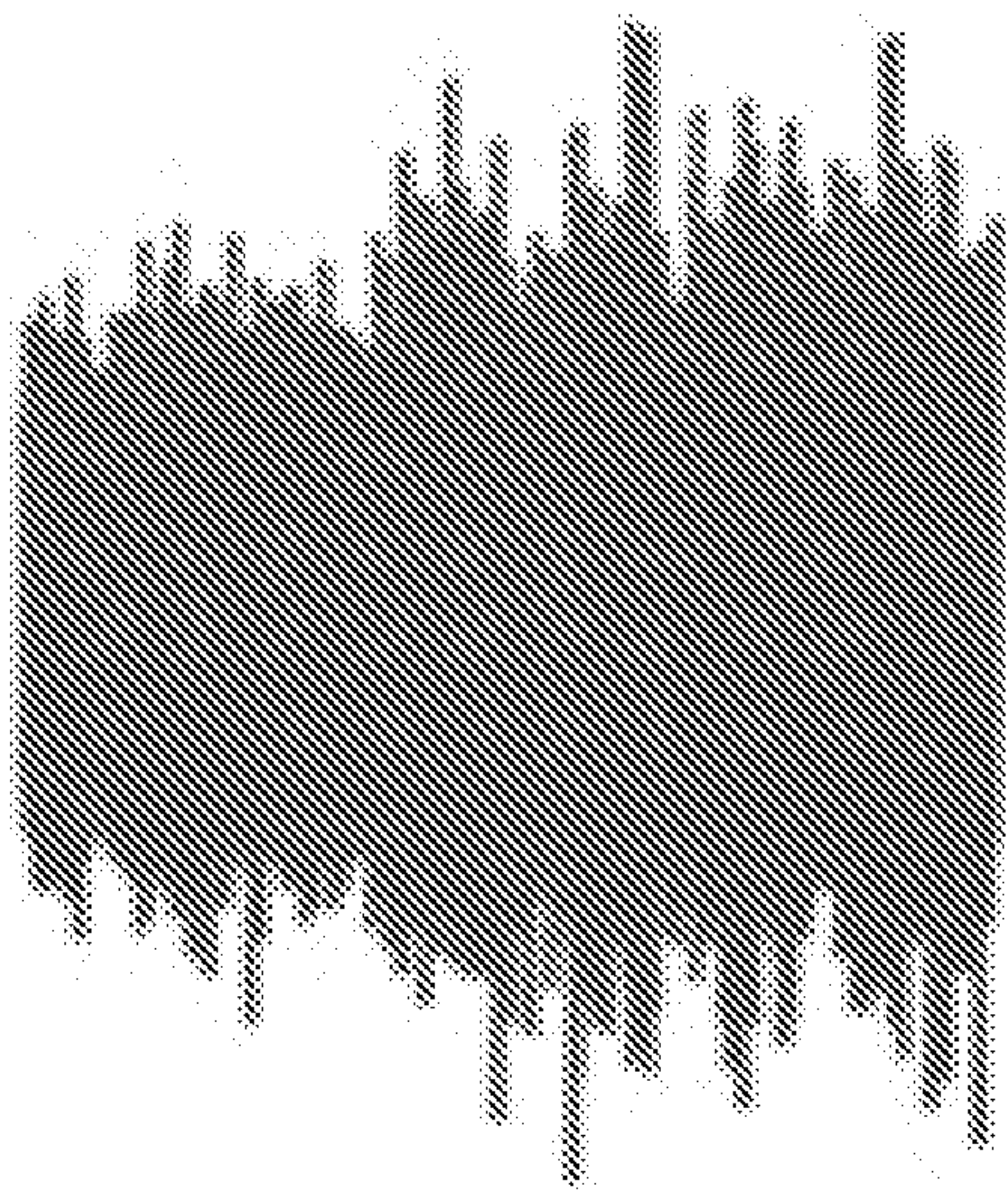


FIG. 8C

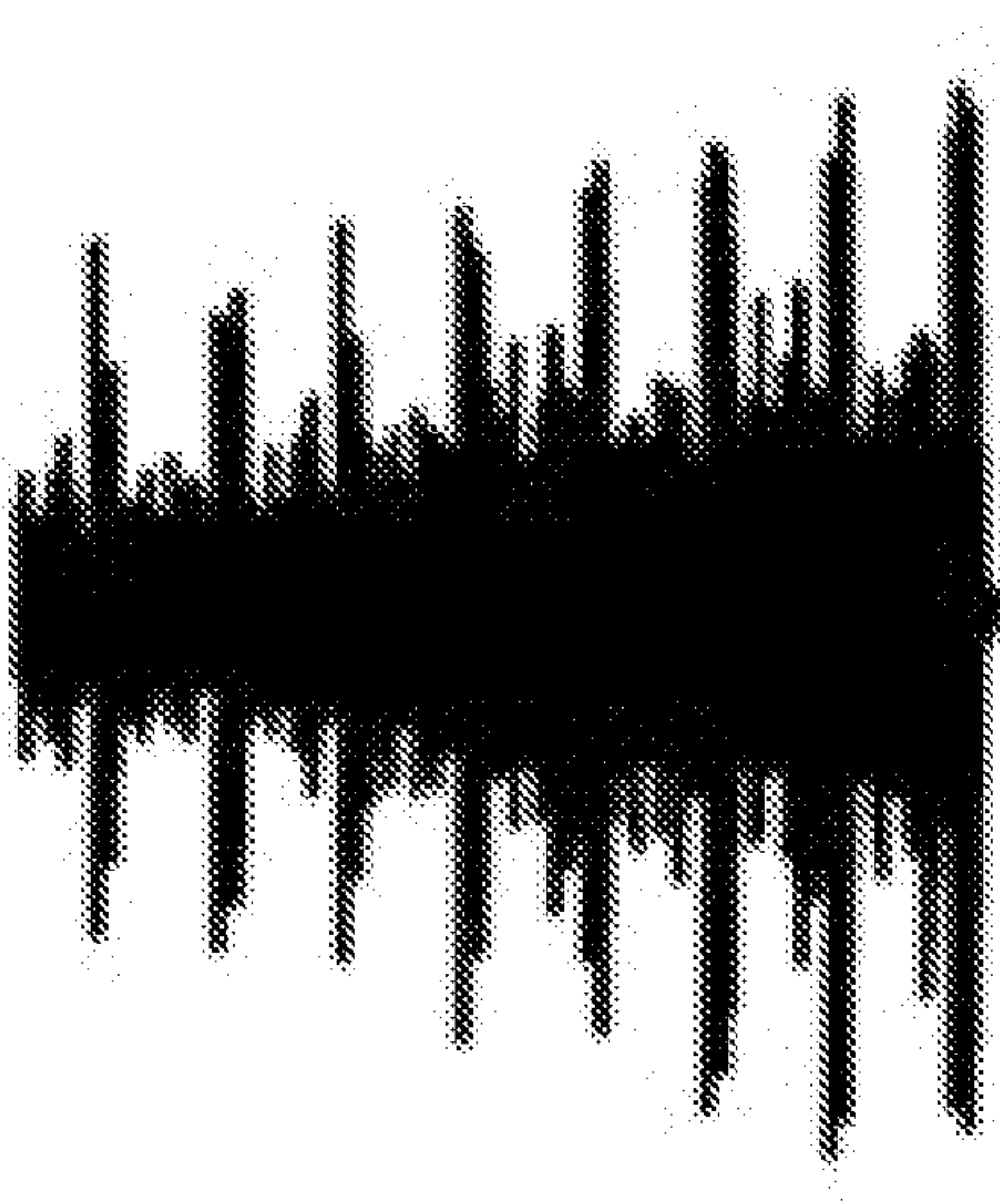


FIG. 8D

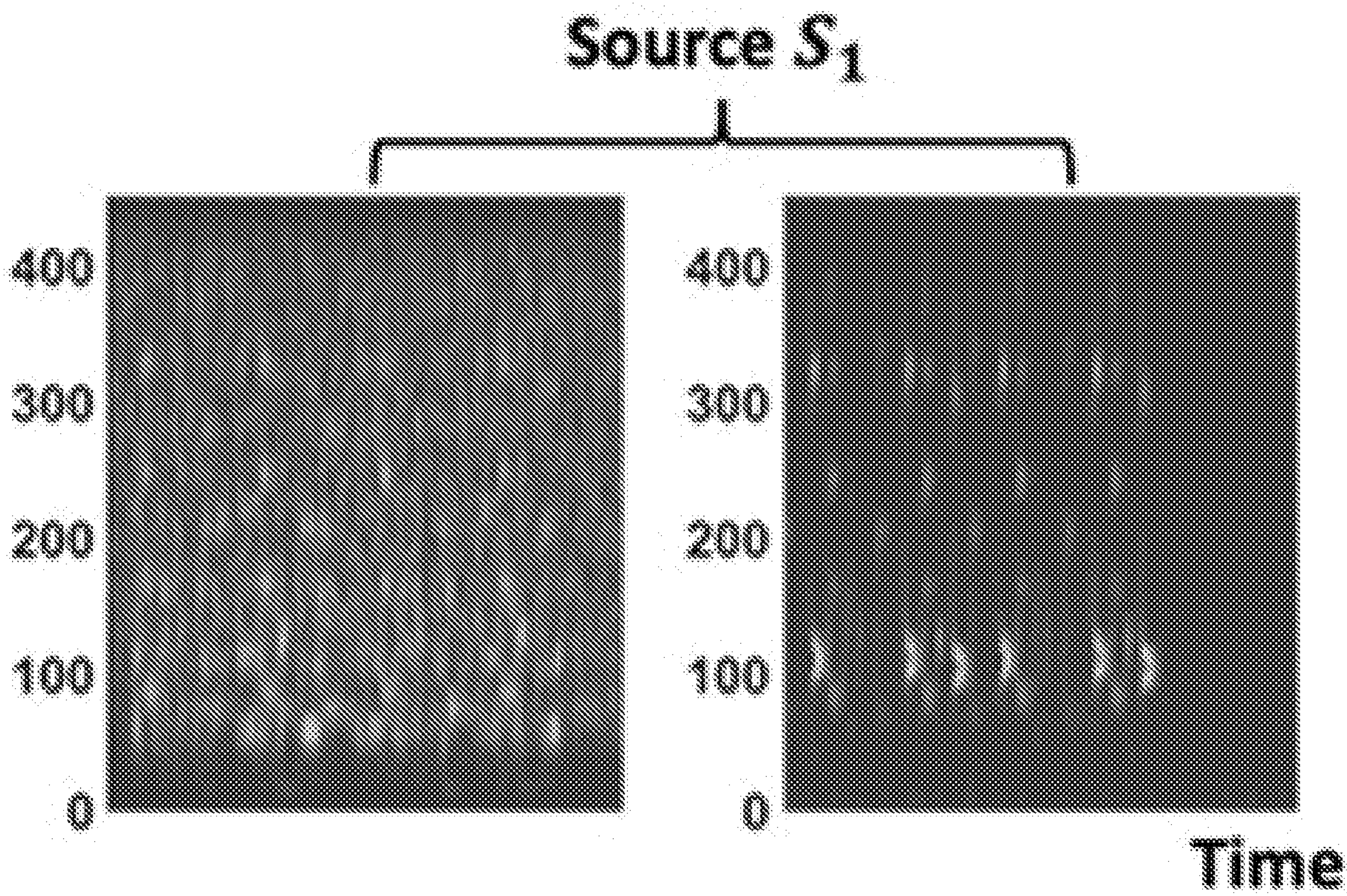


FIG. 8E

FIG. 8F

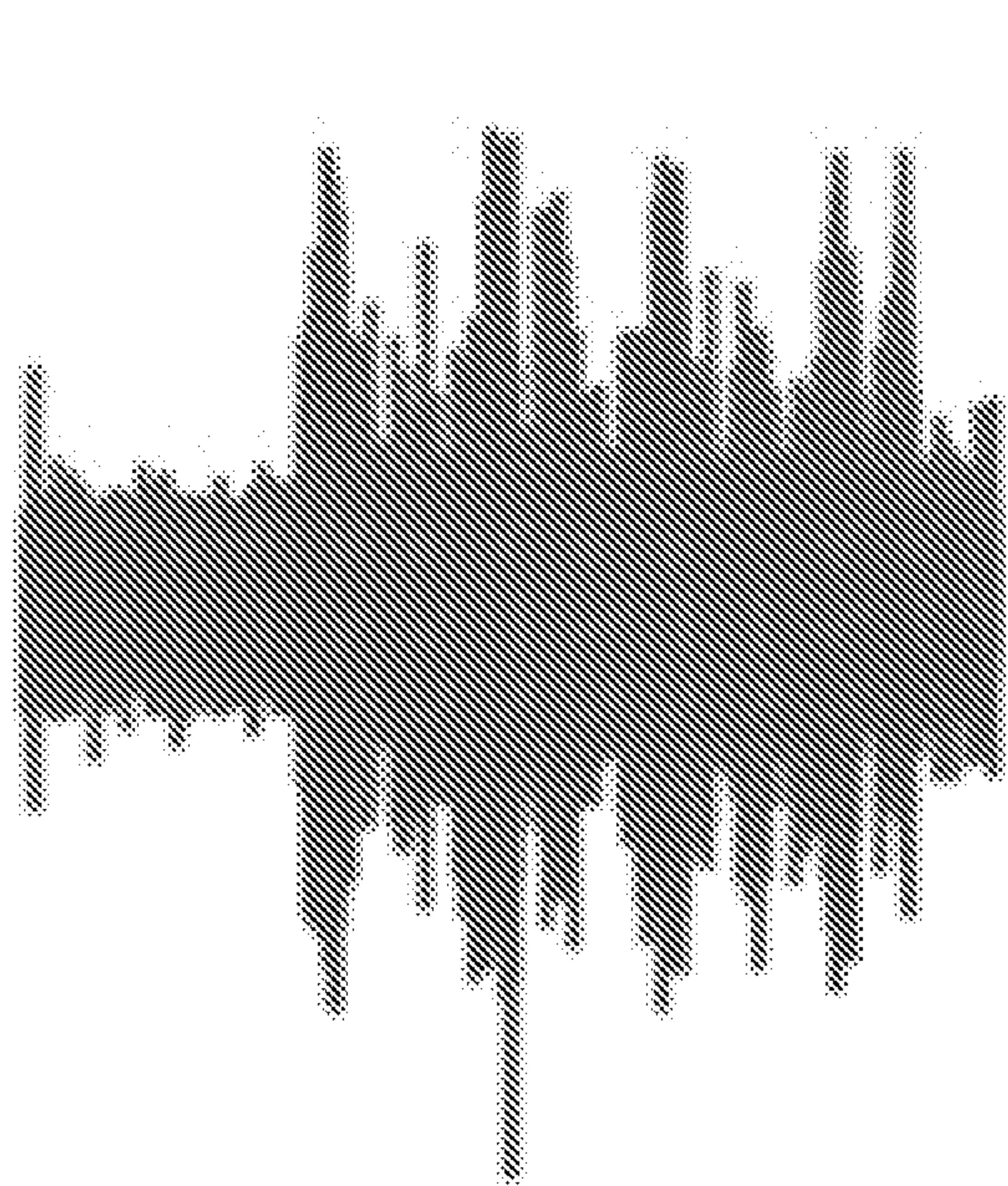


FIG. 8G



FIG. 8H

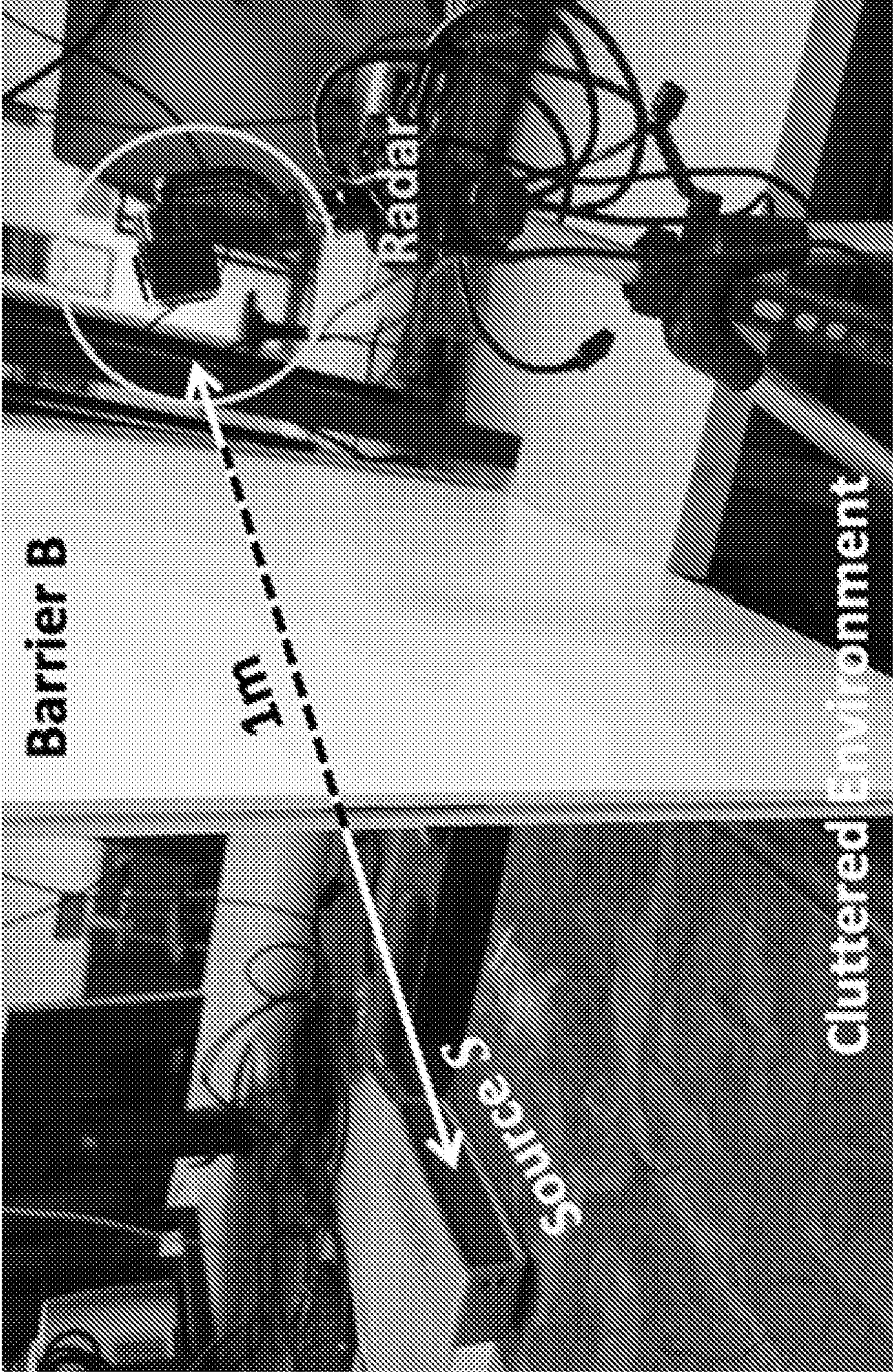


FIG. 9

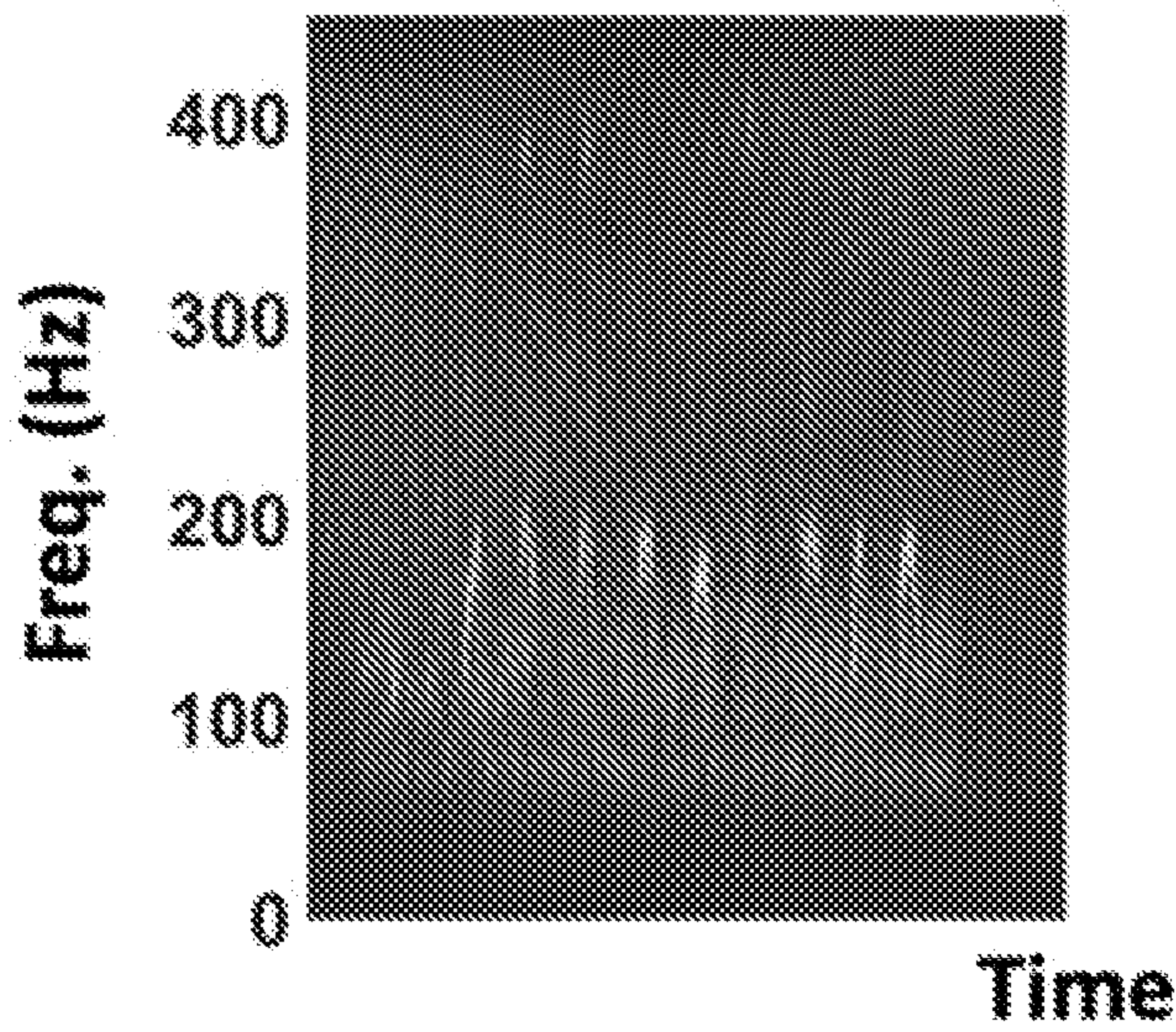


FIG. 10A

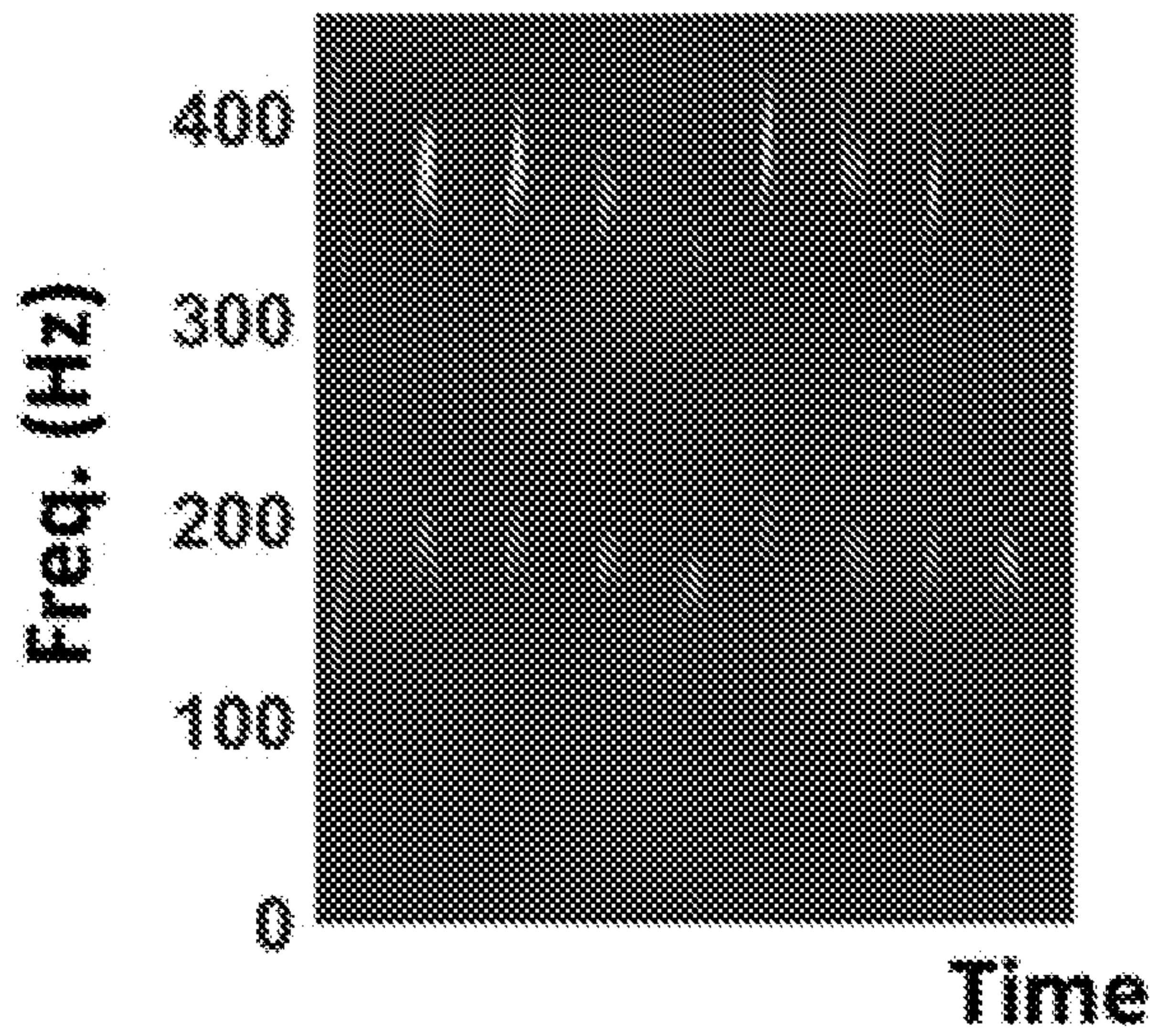


FIG. 10B

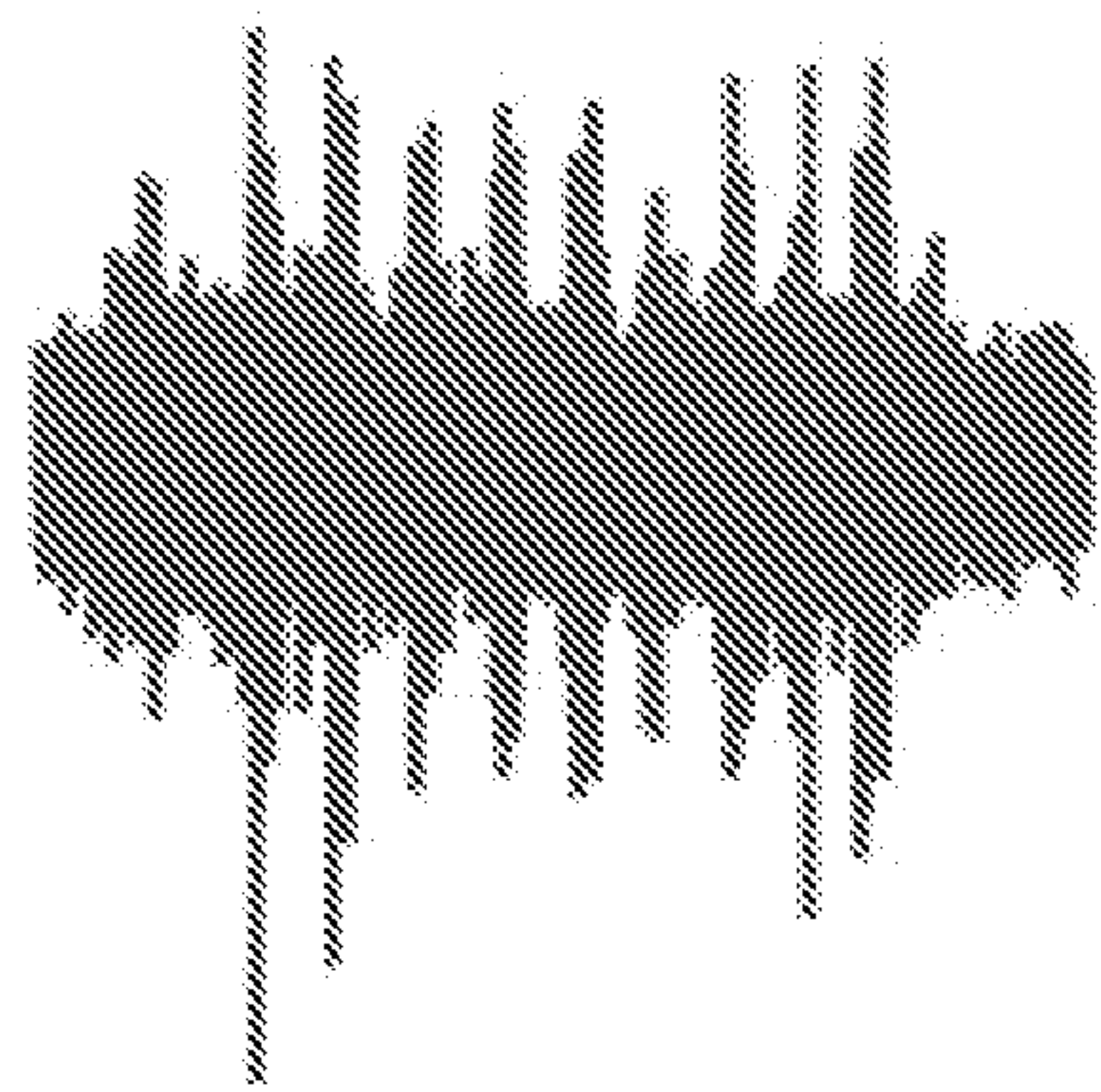


FIG. 10C

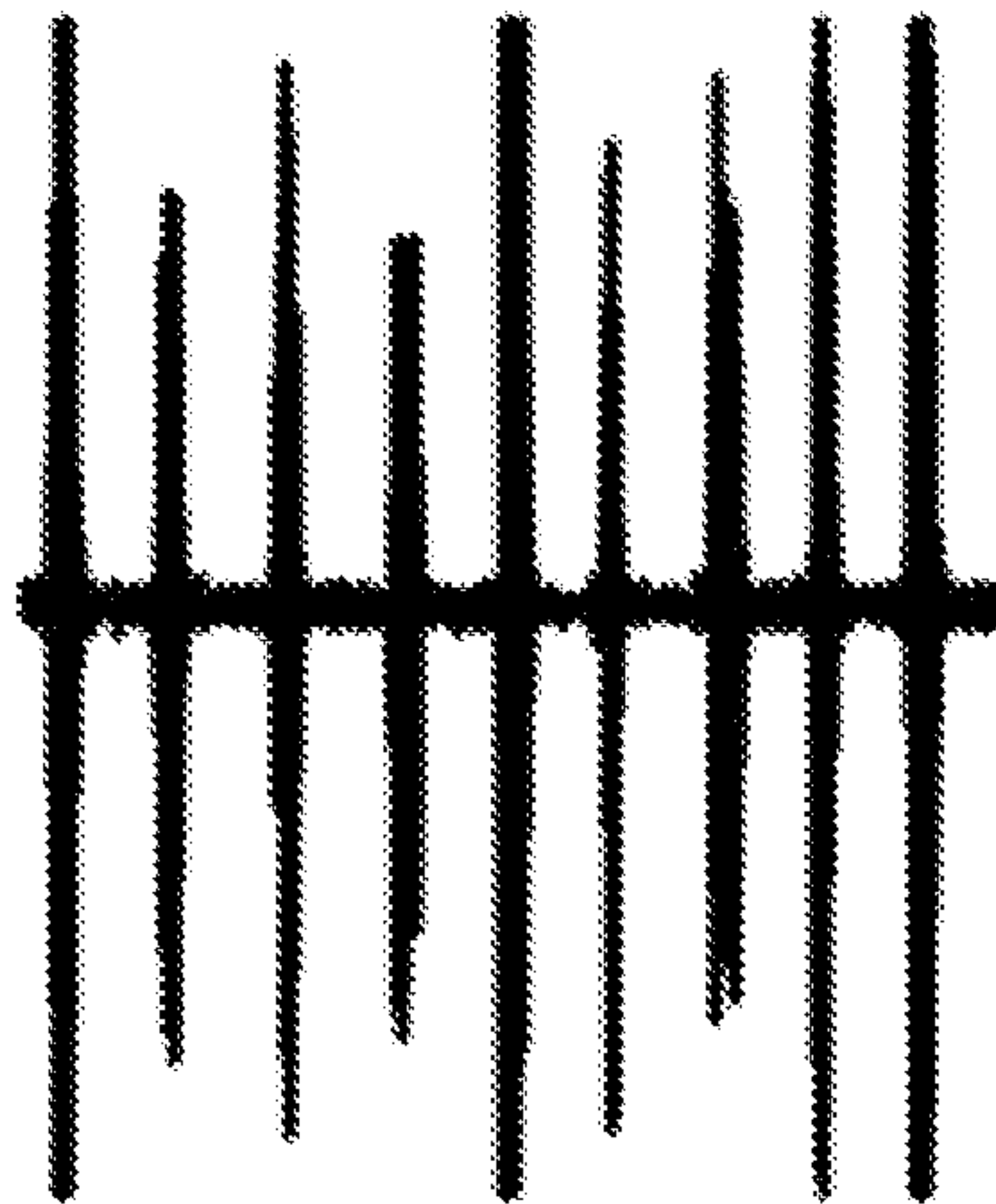
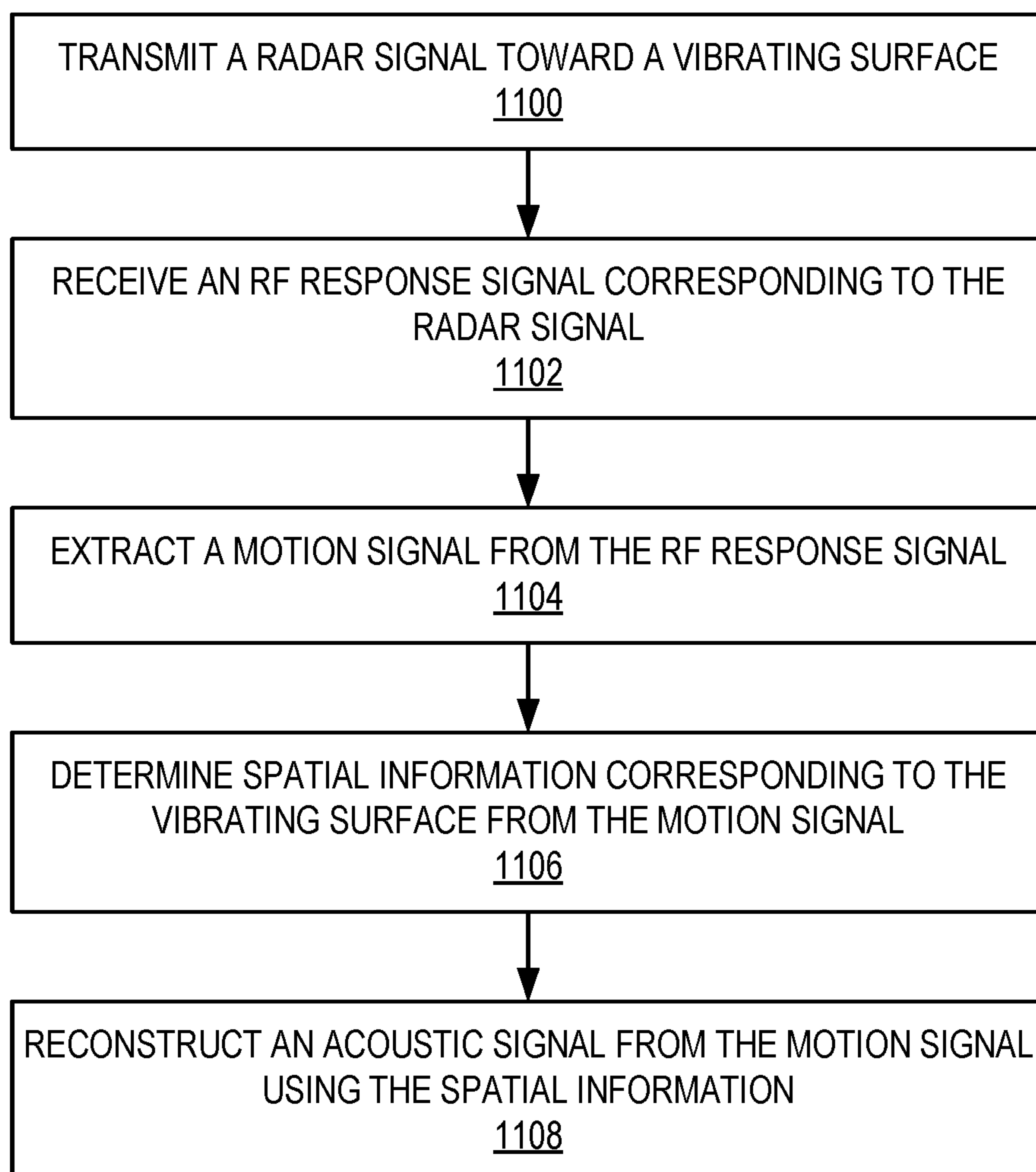


FIG. 10D

12/13

**FIG. 11**

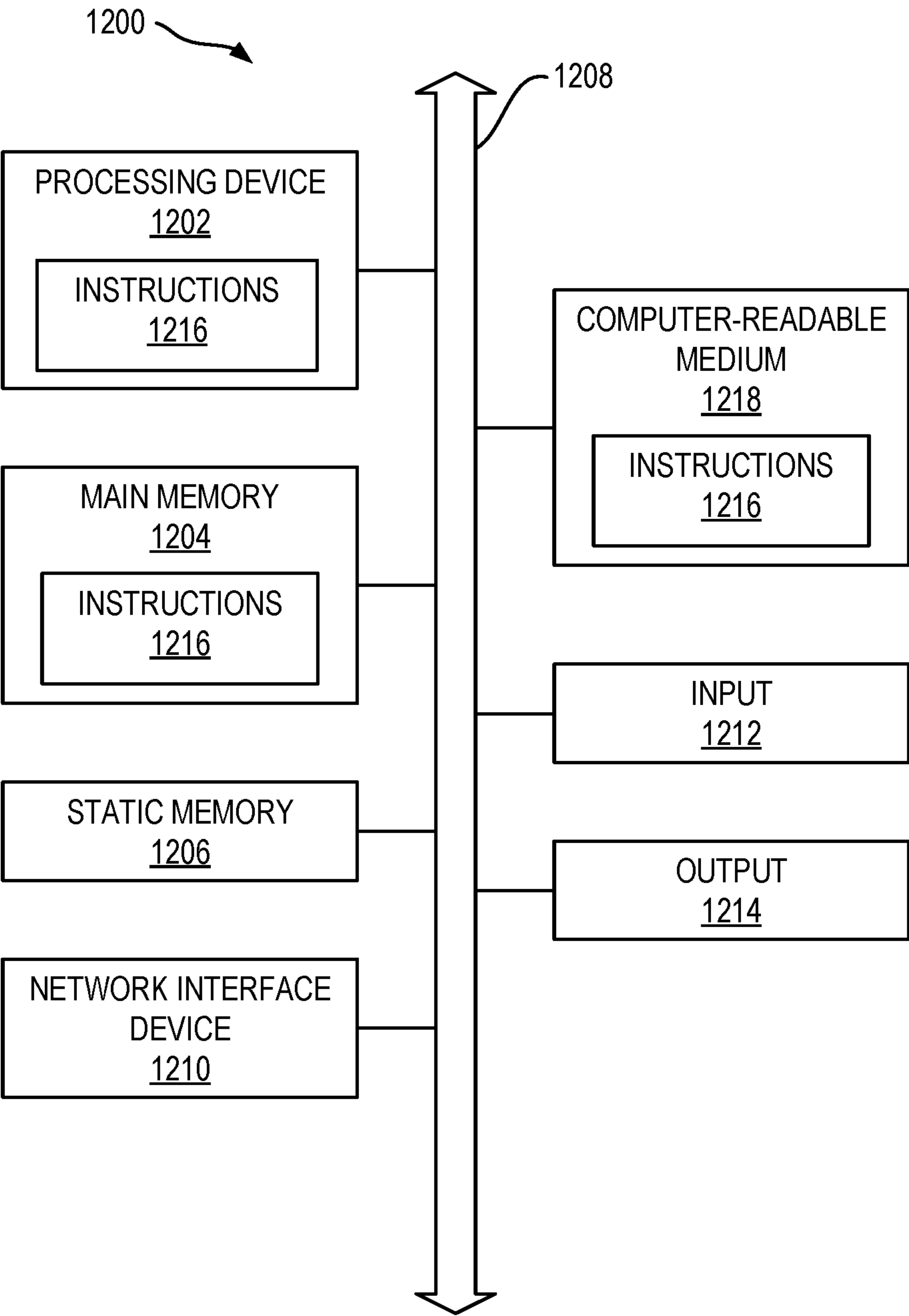


FIG. 12

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2020/058326

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - G01S 13/50; G01S 13/56; G01S 15/02; G01S 15/04; G01S 13/88 (2020.01)

CPC - G01S 13/50; G01S 15/02; G01S 15/04; G01S 13/66; A61B 2562/0204 (2020.08)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

see Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

see Search History document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

see Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2008/0077015 A1 (BORIC-LUBECKE et al) 27 March 2008 (27.03.2008) entire document	1-5, 16-20
A	US 2014/0194793 A1 (KAI MEDICAL, INC.) 10 July 2014 (10.07.2014) entire document	1-5, 16-20
A	WO 2018/050913 A1 (RESMED SENSOR TECHNOLOGIES LIMITED) 22 March 2018 (22.03.2018) entire document	1-5, 16-20
A	US 6,026,340 A (CORRADO et al) 15 February 2000 (15.02.2000) entire document	1-5, 16-20
A	US 2005/0168336 A1 (DONSKOY et al) 04 August 2005 (04.08.2005) entire document	1-5, 16-20
A	US 2014/0212986 A1 (FLUIDION SAS) 31 July 2014 (31.07.2014) entire document	1-5, 16-20
A	US 2010/0011845 A1 (LAUGHARN, JR. et al) 21 January 2010 (21.01.2010) entire document	1-5, 16-20
A	RAHMATI et al., "SSFB: Signal-Space-Frequency Beamforming for Underwater Acoustic Video Transmission", IEEE, 2017, retrieved on [02.01.2021]. Retrieved from the internet <URL: http://coewww.rutgers.edu/www4/cacweb/sites/all/files/Biblio%20Papers/2324a180_Mehdi%20SSFB%29.pdf > entire document	1-5, 16-20

☐ Further documents are listed in the continuation of Box C.

☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"D" document cited by the applicant in the international application

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

03 January 2021

Date of mailing of the international search report

03 FEB 2021

Name and mailing address of the ISA/US

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Authorized officer

Blaine R. Copenheaver

Telephone No. PCT Helpdesk: 571-272-4300

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2020/058326

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☒ Claims Nos.: 6-15
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.